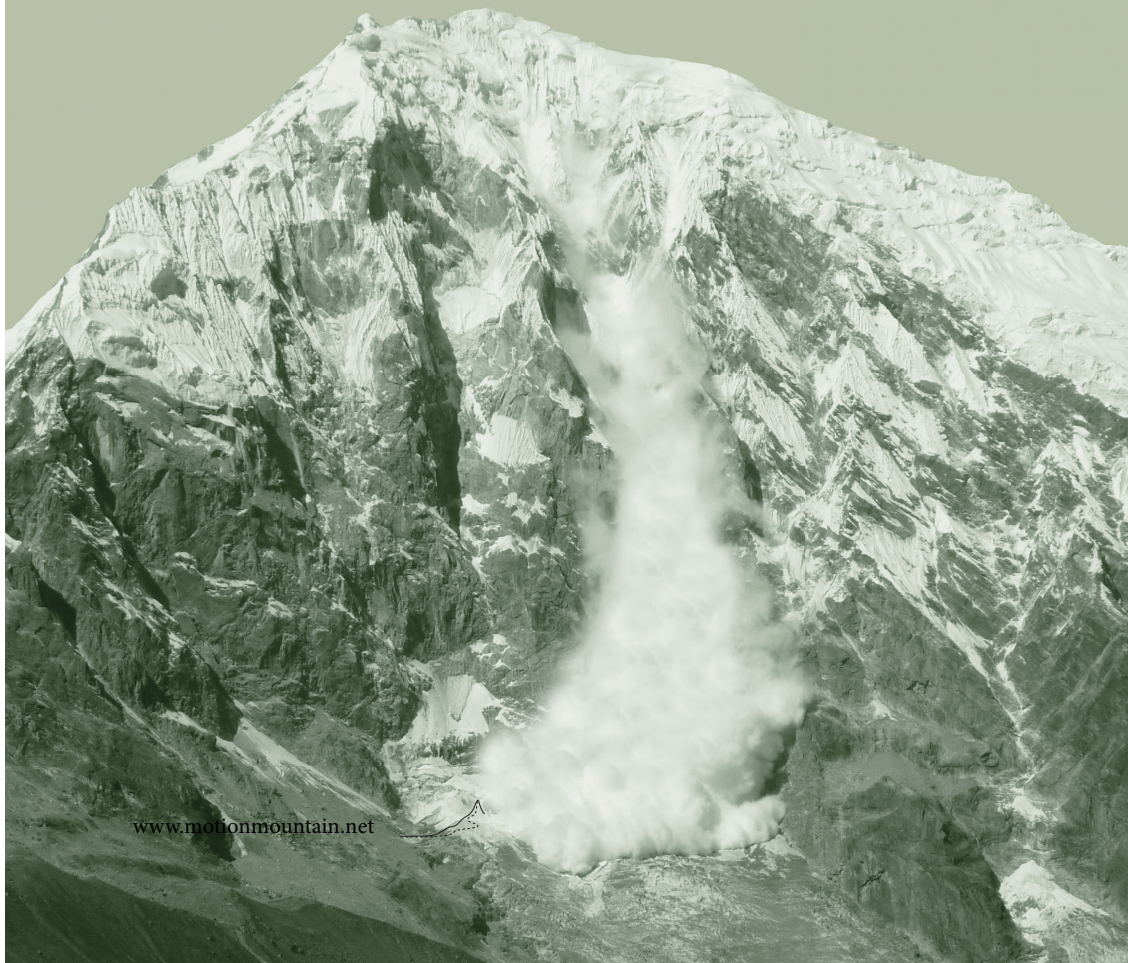
Christoph Schiller

MOTION MOUNTAIN

THE ADVENTURE OF PHYSICS – VOL. V

MOTION INSIDE MATTER – PLEASURE, TECHNOLOGY AND STARS

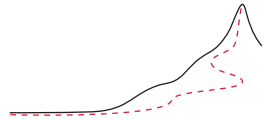


www.motionmountain.net



Christoph Schiller

Motion Mountain



The Adventure of Physics
Volume V

Motion Inside Matter – Pleasure, Technology and Stars

Edition 29, available as free pdf
with films at www.motionmountain.net

Editio trigesima.

Proprietas scriptoris © Chrestophori Schiller
secundo anno Olympiadis trigesimae primae.

Omnia proprietatis iura reservantur et vindicantur.
Imitatio prohibita sine auctoris permissione.
Non licet pecuniam expetere pro aliqua, quae
partem horum verborum continet; liber
pro omnibus semper gratuitus erat et manet.

Thirtieth edition.

Copyright © 1990–2018 by Christoph Schiller,
from the third year of the 24th Olympiad
to the second year of the 31st Olympiad.

This pdf file is licensed under the Creative Commons
Attribution-Noncommercial-No Derivative Works 3.0 Germany
Licence, whose full text can be found on the website
creativecommons.org/licenses/by-nc-nd/3.0/de,
with the additional restriction that reproduction, distribution and use,
in whole or in part, in *any* product or service, be it
commercial or not, is not allowed without the written consent of
the copyright owner. The pdf file was and remains free for everybody
to read, store and print for personal use, and to distribute
electronically, but only in unmodified form and only at no charge.

MOTION MOUNTAIN

The Adventure of Physics – Vol. V

Motion inside Matter – Pleasure, Technology and Stars



Which quantum effects are at the basis of life?
How many motors does a human contain?
How do our senses work?
What crystals are used in everyday life?
What is vacuum energy?
How does magnetic resonance work?
Where do the atoms in our body come from?
Why do stars shine?
Which problems in physics are unsolved?

Answering these and other questions on motion, this series gives an entertaining and mind-twisting introduction into modern physics – one that is surprising and challenging on every page. Starting from everyday life, the adventure provides an overview of modern results in mechanics, heat, electromagnetism, relativity, quantum physics and unification.

Christoph Schiller, PhD Université Libre de Bruxelles, is a physicist and physics popularizer. He wrote this book for his children and for all students, teachers and readers interested in physics, the science of motion.

Pdf file available free of charge at
www.motionmountain.net

introduction 241
Z boson mass 315, 336
Zeno effect
quantum 50
zepto 327
zero-body problem 134
zero-point fluctuations 124
Zetta 327
zinc 356
zirconium 356
zoo
particle 220



Z

Z

To Britta, Esther and Justus Aaron

τῷ ἐμοὶ δαίμονι

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Die Menschen stärken, die Sachen klären.

U

UNIT

what for 323
unit
astronomical 338
units 325
natural 328
non-SI 328
Planck's 328
provincial 328
SI, definition 325
units, true natural 330
universe 134
multiple 322
unpredictability
practical 46
Unruh effect 146
Unruh radiation 129
illustration about 148
up quark 223, 263
up quark mass 335
uranium 165, 185, 356

V

vacuum
energy density 317
permeability 334
permittivity 334
wave resistance 336
vacuum as bath 131
vacuum permeability 264
vacuum permittivity 264
vacuum polarization 133
vacuum temperature 146
vacuum, swimming through 291
Van-der-Waals interaction 220
vanadium 356
vanilla ice cream 52
variance 332
vector boson
weak, introduction 241
vector coupling 255
Vela satellites 397
velocity
Planck 329
vendeko 327
Vendekta 327
ventral tegmental area 54, 56
Viagra 352
video
bad for learning 9
viroids 377
virtual particles 122
virus 17
virus crystallization 377
virusoids 377
viscosity 281
kinematic 285
viscosity, kinematic 281
viscosity,dynamic 281
vitamin B_{12} 348
vodka 114
volt 327
vortex 294
in superfluids 105
vortex evolution 295
vortex filaments 295
vortex tubes 295

W

W boson 243, 262
introduction 241
W boson mass 335
Waals, van der
force in living being 90
warming, global 93
warp drive 159
water
properties 343
water density 315
water drops and droplets 308
water waves 123
waterspout 295
watt 327
wave
terahertz 390
wave function phase in gravity 142
wavelength
de Broglie 326
waves, terahertz 84, 91
weak charge 250, 255, 264
weak interaction
curiosities 255
weakness of 241
weak intermediate bosons 242
weak isospin 250, 255, 264
weak mixing angle 252, 265, 269, 335
weak vector bosons 242
weapons
nuclear 197
weber 327
weko 327
Wekta 327
whale brain size 41
whales 41
wheel, paddle 26
wheels and propellers 283
Wien's displacement constant 315, 338
Wikipedia 375
wine 75
wine, dating of 197
wing
membrane 281
wings
fixed 281
flapping 281
wood 88
World Geodetic System 340
worm holes 159
wound healing 22
writhe
definition 308
quasi quantization 308

X

X bosons 269
X-ray binaries 217
X-rays 84
Xe 110
xenno 327
xenon 109, 356
Xenta 327

Y

Yang–Mills theory 224
yawning 54
yocto 327
Yotta 327
ytterbium 356
yttrium 356
Yukawa coupling 253

Z

Z boson 243, 262

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

S

SWIMMING

macroscopic 284
microscopic 284
science of human 306
swimming through curved space-time 291
swords in science fiction 130
symmetry
and unification 268
beyond the standard model 271–277
symmetry, conformal 273
symmetry, external 272
symmetry, internal 272
synapses 41
Système International d'Unités (SI) 325
system
metastable 180

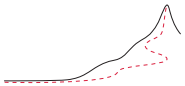
T

T duality 274
T violation 250
table
periodic, illustration of 60
periodic, with photographs 61
table tennis with neutrons 140
Talitrus saltator 43
Taningia danae 110
tantalum 355, 410
properties 343
tape, adhesive 97
tape, sticky 97
tardigrade 377
taste 40
tau 242, 263
tau mass 335
tau neutrino 242, 263
tax collection 325
teaching
best method for 9
teapot, unknown properties of 323
technetium 355
teeth 79
and plasmas 91
telephathy 118
teleportation 118
tellurium 355
telomeres 42
temperature
Planck 329
temperature, human 34
tennessine 355
Tera 327
terahertz
waves 390
terahertz waves 84, 91
terbium 355
tesla 327
tetrahedral skeletons 60
tetraquark 402
tetraquarks 237
thallium 355
thermometer 147
thorium 185, 356
three-body problem 134
thrips 282
thulium 356
thunderstorms 195
Ti:sapphire laser 393
tie knots 308
time
of observation 49
Planck 329
time inversion violation 250
time machines 159
tin 356
titanium 356
TmI_5 109
TNT energy content 338
toilet brushes 282
tokamak 212
tongue 40
tonne, or ton 327
tooth decay 83
tooth paste 311
top quark 223, 263
top quark mass 335
topness 264
topoisomerases 307
topological invariant 307
topological space 364
topology 364
tornado 295
torus, *n*- 366
touch sensors 38
tourmaline 76
transformation
of particles 240
transformations, linear 359
transistor 100
transpiration-cohesion-tension model 33
tree 344
definition 33
fighting 36
growth 33
image of 160
motion of 36
tree growth 34
trees
and gravity 143
trefoil knot 303
triple-α process 210
tritium 211, 240
trivial knot 302
tropical year 338
trousers 363
trout 40
truth 264
truth quark 223
tungsten 62, 73, 109, 356
atoms, images of 74
tuning, fine 322
tunnelling rate 314
Turin shroud 184
twins as father(s) 30
two-body problem 134
two-dimensional crystals 98

U

udeko 327
Udekta 327
ultrasound 41
ultrasound imaging 84
umami 40
uncertainty
relative 333
total 333
unification
delusions about 320
incorrect graph on 275
lack of electroweak 252
search for 268
the dreom of 268–277

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



PREFACE

Primum movere, deinde docere.*

Antiquity

This book series is for anybody who is curious about motion in nature. How do hings, people, animals, images and empty space move? The answer leads o many adventures, and this volume presents those about motion inside everyday matter, inside people and animals, and inside stars and nuclei.

Motion *inside bodies* – dead or alive – is tiny: thus it is described by quantum theory. Quantum theory describes all motion with the quantum of action $\hbar$, the smallest change observed in nature. Building on this basic idea, the text first shows how to describe life, death and pleasure. Then, the text explains the observations of chemistry, materials science, astrophysics and particle physics. In the structure of physics, these topics correspond to the three 'quantum' points in Figure 1. The story of motion found inside living cells, inside the coldest gases and throughout the hottest stars is told here in a way that is simple, up to date and captivating.

In order to be *simple*, the text focuses on concepts, while keeping mathematics to the necessary minimum. Understanding the concepts of physics is given precedence over using formulae in calculations. The whole text is within the reach of an undergraduate.

In order to be *up to date*, the text is enriched by the many gems – both theoretical and empirical – that are scattered throughout the scientific literature.

In order to be *captivating*, the text tries to startle the reader as much as possible. Reading a book on general physics should be like going to a magic show. We watch, we are astonished, we do not believe our eyes, we think, and finally we understand the trick. When we look at nature, we often have the same experience. Indeed, every page presents at least one surprise or provocation for the reader to think about. Numerous interesting challenges are proposed.

The motto of the text, *die Menschen stärken, die Sachen klären*, a famous statement on pedagogy, translates as: 'To fortify people, to clarify things.' Clarifying things – and adhering only to the truth – requires courage, as changing the habits of thought produces fear, often hidden by anger. But by overcoming our fears we grow in strength. And we experience intense and beautiful emotions. All great adventures in life allow this, and exploring motion is one of them. Enjoy it.

Christoph Schiller

* 'First move, then teach.' In modern languages, the mentioned type of *moving* (the heart) is called *motivating*; both terms go back to the same Latin root.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

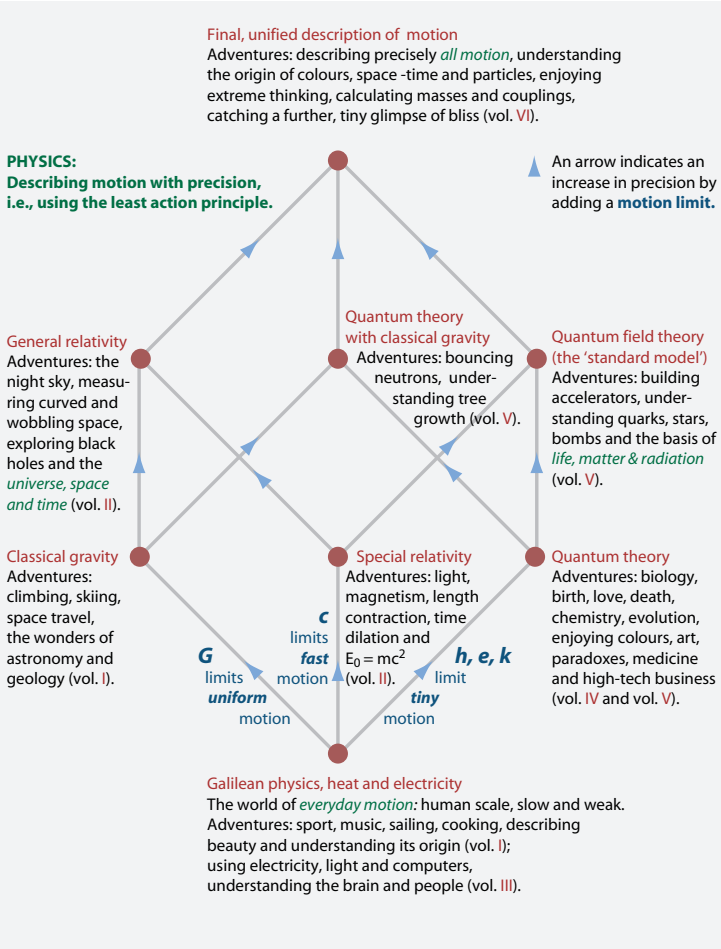


FIGURE 1 A complete map of physics, the science of motion, as first proposed by Matvei Bronshtein (b. 1907 Vinnytsia, d. 1938 Leningrad). The Bronshtein cube starts at the bottom with everyday motion, and shows the connections to the fields of modern physics. Each connection increases the precision of the description and is due to a limit to motion that is taken into account. The limits are given for uniform motion by the gravitational constant G, for fast motion by the speed of light c, and for tiny motion by the Planck constant h, the elementary charge e and the Boltzmann constant k.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

S

SMOKY

cancer due to radioactivity 194, 195
smoky quartz 75
snakes 40
sneeze 30
snow flakes 74
sodium 355
sodium lamps 109
Sokolov–Ternov effect 147, 396
solar constant
variation 210
solar cycle 210
solar flare 204
solar storms 204
soliton 87
solitons 275
soul 312
space-time
non-commutative 273
space-time duality 274
space-time foam 159
space-time, fluid 298
space-time, solid 299
space-time, swimming through curved 291
spark chambers 174
sparticles 272
special relativity 128
special relativity and dislocations 299
spectrum 359
spectrum of hot objects 315
speed
of light *c*
physics and 8
speed of light
inside the Sun 203
sperm 286
sphere packing 73
spinach 56
spinor
as conserved quantity 272
spirits 312
spirochaetes 287
Spiroplasma 287
sponsor
this book 10
spontaneous fission 181
spores 282
squark 412
squid 110
stalk 91
standard deviation 332
illustration 333
standard model
open questions 265
summary 261–265
standard quantum limit for clocks 46
stannum 356
star
collapse of 210
neutron 68, 69
pressure in 210
quark 69
shining of 208
size 68
surface 68
temperature sensitivity 210
star algebra 359
stardust 216
stars 109, 110
Stefan–Boltzmann black body radiation constant 150, 315, 338
steradian 326
stibium 347
stimulated emission 114
stokes (unit) 281
stone
age of a 69
stone formation 69
stones 311
strange quark 223, 263
strange quark mass 335
Streptococcus mitis 31
striatum 44
stroke
motion 289
strong coupling constant 225, 265, 335
strong CP problem 238
strong interaction
feeble side 219
introduction 219
strontium 355
structure constants 226, 361
SU(3)
in nuclei 199
subalgebra 361
sulfates 75
sulphur 355
Sun 200–208
collapse of 210
convection inside the 204
corona photograph 205
energy source in 200
formation 216
images at different wavelengths 201
lifetime remaining 202
motion in 204
neutrino flux 217
pressure 68
Sun's age 339
Sun's lower photospheric pressure 339
Sun's luminosity 339
Sun's mass 339
Sun's surface gravity 339
superconducting
supercollider 258
superconductivity 103, 235, 316
superfluidity 103, 120, 315
supergravity 272
supernova 153, 215
cosmic radiation and 175, 177, 178
debris dating 183
definition 216
matter distribution and 216
neutron star and 186
Sun, Earth and 216
supersymmetry 268, 270–273
support
this book 10
surface 303
of a star 68
surface, compact 366
surfaces of genus *n* 366
swimming 282–287
and atoms 282
interfacial 287
lift-based 284

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

R

RAINBOW

photograph of 138
rainbow due to gravity 157
raindrops 308
rainforest 99
ratchet 24
classical 25
picture of 24
ratchet, quantum 25
rays, alpha *see* α rays
rays, beta *see* β rays
rays, cosmic *see* cosmic rays
reaction
nuclear 188
reaction rate
chemical 315
reactor
for nuclear power 196
natural nuclear 196
reactor, nuclear 191
red giants 68
red-shift values 152
Regge trajectory 230
relativity, special, and
dislocations 299
rem (unit) 194
renormalization 127
of quantum field theory
275
reproduction 18
reproduction as proof of
existence of atoms 19
research fraud 346
reset mechanism 42
Reynolds number 281, 405
definition 285
rhenium 62, 73, 354
rhodium 354
Rhodospirillum rubrum 287
rock cycle 69
rock types 71
rocks 69
rods 38
roentgenium 354
rotational motors 22
rotons 87
rubber 301
rubidium 354
ruby 76
ruthenium 354
rutherfordium 354
Rydberg atom 294
Rydberg constant 315, 331, 337
röntgen (unit) 194

S

S duality 274
s-process
definition 213
Salmonella 286
salt-formers 346
Salticidae 90
samarium 354
sand 380
sapphire 76
satellites 151
scaling 97
scallop
swimming 285
scallop theorem 285
scandium 354
scattering
nuclear 187
scattering experiment 167
Schrödinger equation,
complex numbers in 297
Schrödinger equation, for
extended entities 296
Schrödinger's equation 58
Schwarzschild radius as
length unit 330
ScI_3 109
science fiction, not in
quantum gravity 159
Scoville heat unit 332
screw dislocations 299
seaborgium 354
second 327
definition 325, 340
second principle of
thermodynamics 149
secret service 91
sedimentary rocks 69
sedimentites 71
see
through clothes 390
selectron 272
selenium 354
self-acceleration 157
self-reproduction 18
semiconductor
garlic-smelling 355
semisimple 362
sense of smell 40
sense of taste 40
sensors
of touch, illustration of 39
sensors, animal 40
sexes, number of 30
shadow of the Moon by
cosmic rays 177
sharks 40
sheets, thinnest, in nature 97
shells 58
shoe laces 308
showers
cosmic ray 178
shroud, Turin 184
shuttlecocks 88
SI
new 328
prefixes
table of 327
units 325, 334
SI units
definition 325
prefixes 327
supplementary 326
siemens 327
sievert 194, 327
sievert (SI unit) 193
signal distribution 42
silent holes 151
silica 71
silicon 79, 355
silver 80, 355
simple 362
simply connected 365
single atom 46, 114
singular point 385
skatole 52
skyrmions 275
slime eel 306
smartphone
bad for learning 9
smell
sense of 52
smoking

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Using this book

Marginal notes refer to bibliographic references, to other pages or to challenge solutions. In the colour edition, marginal notes, pointers to footnotes and links to websites are typeset in green. Over time, links on the internet tend to disappear. Most links can be recovered via www.archive.org, which keeps a copy of old internet pages. In the free pdf edition of this book, available at www.motionmountain.net, all green pointers and links are clickable. The pdf edition also contains all films; they can be watched directly in Adobe Reader.

Solutions and hints for *challenges* are given in the appendix. Challenges are classified as easy (e), standard student level (s), difficult (d) and research level (r). Challenges for which no solution has yet been included in the book are marked (ny).

Advice for learners

Learning allows us to discover what kind of person we can be. Learning widens knowledge, improves intelligence and provides a sense of achievement. Therefore, learning from a book, especially one about nature, should be efficient and enjoyable. Avoid bad learning methods like the plague! Do not use a marker or a pencil to highlight or underline text on paper. It is a waste of time, provides false comfort and makes the text unreadable. And do not learn from a screen. In particular, never, ever, learn from the internet, from videos, from games or from a smartphone. Most of the internet, almost all videos and all games are poisons and drugs for the brain. Smartphones are dispensers of drugs that make people addicted and prevent learning. Nobody putting marks on paper or looking at a screen is learning efficiently or is enjoying doing so.

In my experience as a pupil and teacher, one learning method never failed to transform unsuccessful pupils into successful ones: if you read a text for study, summarize every section you read, *in your own words and images, aloud*. If you are unable to do so, read the section again. Repeat this until you can clearly summarize what you read in your own words and images, aloud. And *enjoy* the telling aloud! You can do this alone or with friends, in a room or while walking. If you do this with everything you read, you will reduce your learning and reading time significantly; you will enjoy learning from good texts much more and hate bad texts much less. Masters of the method can use it even while listening to a lecture, in a low voice, thus avoiding to ever take notes.

Advice for teachers

A teacher likes pupils and likes to lead them into exploring the field he or she chose. His or her enthusiasm is the key to job satisfaction. If you are a teacher, before the start of a lesson, picture, feel and tell yourself how you enjoy the topic of the lesson; then picture, feel and tell yourself how you will lead each of your pupils into enjoying that topic as much as you do. Do this exercise consciously, every day. You will minimize trouble in your class and maximize your teaching success.

This book is not written with exams in mind; it is written to make teachers and students *understand* and *enjoy* physics, the science of motion.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Feedback

The latest pdf edition of this text is and will remain free to download from the internet. I would be delighted to receive an email from you at fb@motionmountain.net, especially on the following issues:

Challenge 1 s
— What was unclear and should be improved?
— What story, topic, riddle, picture or film did you miss?

Also help on the specific points listed on the www.motionmountain.net/help.html web page is welcome. All feedback will be used to improve the next edition. You are welcome to send feedback by mail or by sending in a pdf with added yellow notes, to provide illustrations or photographs, or to contribute to the errata wiki on the website. If you would like to translate a chapter of the book in your language, please let me know.

On behalf of all readers, thank you in advance for your input. For a particularly useful contribution you will be mentioned – if you want – in the acknowledgements, receive a reward, or both.

Support

Your donation to the charitable, tax-exempt non-profit organisation that produces, translates and publishes this book series is welcome. For details, see the web page www.motionmountain.net/donation.html. The German tax office checks the proper use of your donation. If you want, your name will be included in the sponsor list. Thank you in advance for your help, on behalf of all readers across the world.

The paper edition of this book is available, either in colour or in black and white, from www.amazon.com or www.createspace.com. And now, enjoy the reading.



Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

P

PRIONS

anthropic 322
simian 322
prions 377
Prochlorococcus 36
projective planes 366
promethium 353
propeller 282
fish have none 283
protactinium 353
proton 170
Compton wavelength 337
g factor 337
gyromagnetic ratio 337
in magnetic resonance imaging 162
is composed 219
lifetime 315
magnetic moment 337
mass 315, 336
properties 171, 342
quark content 223
specific charge 337
proton decay 269
proton emission 181
proton lifetime 269
proton mass 233
proton shape, variation of 234
proton, magnetic moment 227
protons 170
protonvolt 330
psychology 262
Puffinus griseus 30
pullovers 363
pump
molecular 21
pungency 332
puzzle
animal symmetry 31
pyrite 80
pyroxenes 72

Q

QAD 259
QED 126
QED, open questions in 137
quality factor 122
quanton, elementary 312
quantons 311
quantum asthenodynamics 259
essence 313
quantum chromodynamics 224
essence 313
essence of 224
Lagrangian 224
quantum electrodynamics 126
essence 313
quantum field theory
collective aspects 274–275
definition 313
emotions of 320
essence of 274
intensity of 320
perturbative aspect of 314
topological 273
quantum groups 273
quantum Hall effect 107
quantum machines 19
quantum number
principal, illustration of 59
quantum numbers
list of 263
quantum of action
precise value 264, 334
quantum of circulation 337
quantum particle
elementary 312
quantum physics
in a nutshell 311–324
quantum systems in gravity 140
quantum theory
in three sentences 311
millennium issues and 316–317
open questions 316
precision of 314
quantum Zeno effect
radioactivity and 180
quark
mixing matrix 265, 335
table of 223
types 223
quark confinement 224, 229
quark mass 233
quark masses 233
quark mixing
definition 251
quark model 220–223
quark stars 69
quarks 108, 219, 223
quartz 72, 75
quartz, transparency of 86
quasars 153
quasicrystal, natural 81
quasiparticle 86–87
definition of 86
quaternions 360

R

r-process 215
Rad (unit) 194
radian 326
radiation 342
cosmic *see* grand unification, 174
radiation exposure 178
radiation pressure 210
radiative decay 314
radioactive dose 193
radioactive material
amount of 193
radioactivity 165, 180, 193
and hell 185
dangers of 195, 197
discovery of 165
measurement of 193
of Earth 185
of human body 181
of lava 185
types of 166
units 194
radioactivity, artificial 192
Radiocarbon dating 184
radiocarbon dating 184
radiocarbon dating method 184
radiometric dating 182–184
radium 353
radius, covalent 357
radius, ionic 357
radon 354
rain on demand 309
rainbow
and fine structure constant 138

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

P

PALLADIUM

palladium 352
paraffin
  dangers of 64
Paramecium 286
parameter space 273
parity 263
parity violation 245, 246
parity violation in electrons 246
parsec 338
particle
  elementary, definition 312
  limit to localization 313
  transformation 240
  virtual, and Lamb shift 125
  zoo 220
Particle Data Group 401
particle pairs
  virtual 130
particle reactions 313
particle transformations 313
particle, alpha *see* α particle
particle, beta *see* electron
particle, virtual
  in nuclear physics 188
particles, virtual 122
pascal 327
Pauli pressure 68, 210
Pauli spin matrices 225
Pauli's exclusion principle 67
PbNO 66
PbI 378
pencil 375
pencils 98
Penrose process 153
pentaquarks 237, 403
people 210
perception research 38
perigee 338
perihelion 339
periodic table 344
  with videos 59
periodic table of the elements 59, 345
permeability
  vacuum 334
permeability, vacuum 264
permittivity
  vacuum 334
permittivity, vacuum 264
perovskite 78
perturbation theory 136
  and quantum field theory 314
  definition 131
Peta 327
PETRA collider 236
phanerophyte, monopodal 33
phase of wave function in gravity 142
pheasants 280
Philips 124
phonon Hall effect 97
phonons 86
phosphorus 352
photino 272
photoacoustic effect 378
photon 254, 262
  hitting photon 130
  number density 341
photon hall effect 392
photon mass 335
photon-photon scattering 315
photonic Hall effect 96
photoperiodism 43, 56
physics
  map of 8
  mathematical, limits of 277
  nuclear 162
physics cube 8, 318
phytochrome system 56
pico 327
pigeons 40
pigs 210
pion 172
  properties 342
plagioclase 72
Planaria 31
Planck constant
  value of 264, 334
Planck length 128
Planck stroll 331
Planck time 144
Planck units
  as limits 330
  table of 329
Planck units, corrected 330
Planck's natural units 328
plankton 286
plasma 91, 212
plasmons 86
platinum 352
pleasure system 54
  illustration of 55
plumbum 350
plutonium 195, 353
Poincaré algebra 363
points 364
poise 281
poisons 63
polaritons 87
polarons 87
poliomyelitis 259
pollen 282
polonium 64, 195, 353
polymer
  electroactive 33
polymer, DNA as 62
Pontecorvo–Maki–Nakagawa–Sakata mixing matrix 251, 254
positron charge
  specific 337
  value of 264, 334
positron tomography 51
positrons 84
potassium 185, 353
potatoes irradiation 198
praeseodymium 353
precision 332
  limits to 334
predictions
  difficulties for 46
prefixes 327, 409
  SI, table 327
prefixes, SI 327
present
  takes time 49
  Zeno and the absence of the 48
pressure, negative
  in trees 117
primal scream of a black hole 153
prime knots 303
principal quantum number 58
principle

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Contents

15 1 Motion for enjoying life

15 **From quantum physics to biological machines and miniaturization**
Reproduction 18 • Quantum machines 19 • How do we move? – Molecular motors 21 • Linear molecular motors 23 • A rotational molecular motor: ATP synthase 25 • Rotational motors and parity breaking 27 • Curiosities and fun challenges about biology 29

37 **The physics of pleasure**
The nerves and the brain 41 • Living clocks 42 • When do clocks exist? 44 • The precision of clocks 45 • Why are predictions so difficult, especially of the future? 46 • Decay and the golden rule 47 • The present in quantum theory 48 • Why can we observe motion? 49 • Rest and the quantum Zeno effect 50 • Consciousness – a result of the quantum of action 50 • Why can we observe motion? – Again 51 • Curiosities and fun challenges about quantum experience 52 • Summary on biology and pleasure 57

58 2 Changing the world with quantum effects

58 **Chemistry – from atoms to DNA**
Atomic bonds 59 • Ribonucleic acid and deoxyribonucleic acid 62 • Curiosities and fun challenges about chemistry 63

67 **Materials science**
Why does the floor not fall? 67 • Rocks and stones 69 • Crystal formation 72 • Some interesting crystals 75 • How can we look through matter? 83 • What is necessary to make matter invisible? 85 • What moves inside matter? 86 • Curiosities and fun challenges about materials science 87

100 **Quantum technology**
Transistors 100 • Motion without friction – superconductivity and superfluidity 103 • The fractional quantum Hall effect 107 • How does matter behave at the lowest temperatures? 108 • Lasers and other spin-one vector boson launchers 108 • From lamps to lasers 113 • The three lightbulb scams 114 • Applications of lasers 115 • Challenges, dreams and curiosities about quantum technology 116 • Summary on changing the world with quantum effects 120

122 3 Quantum electrodynamics – the origin of virtual reality
Ships, mirrors and the Casimir effect 122 • The Lamb shift 125 • The QED Lagrangian and its symmetries 126 • Interactions and virtual particles 127 • Vacuum energy: infinite or zero? 128 • Moving mirrors 128 • Photons hitting photons 130 • Is the vacuum a bath? 131 • Renormalization – why is an electron so light? 131 • Curiosities and fun challenges of quantum electrodynamics 132 • How can one move on perfect ice? – The ultimate physics test 134 • A summary of quantum electrodynamics 135 • Open questions in QED 137

140 4 Quantum mechanics with gravitation – first steps
Falling atoms 140 • Playing table tennis with neutrons 140 • The gravitational phase of wave functions 142 • The gravitational Bohr atom 143 • Curiosities about quantum theory and gravity 143 • Gravitation and limits to disorder 145 • Measuring acceleration with a thermometer: Fulling–Davies–Unruh radiation 146 • Black holes aren't black 147 • The lifetime of black holes 150 • Black holes are all over the place 151 • Fascinating gamma-ray bursts 151 • Material properties of

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

black holes 154 • How do black holes evaporate? 155 • The information paradox of black holes 155 • More paradoxes 156 • Quantum mechanics of gravitation 157 • Do gravitons exist? 157 • Space-time foam 158 • Decoherence of space-time 159 • Quantum theory as the enemy of science fiction 159 • No vacuum means no particles 160 • Summary on quantum theory and gravity 161

162 5 The structure of the nucleus – the densest clouds

A physical wonder – magnetic resonance imaging 162 • The size of nuclei and the discovery of radioactivity 164 • Nuclei are composed 169 • Nuclei can move alone – cosmic rays 172 • Nuclei decay – more on radioactivity 180 • Radiometric dating 182 • Why is hell hot? 184 • Nuclei can form composites 185 • Nuclei have colours and shapes 186 • The four types of motion in the nuclear domain 187 • Nuclei react 188 • Bombs and nuclear reactors 191 • Curiosities and challenges on nuclei and radioactivity 192 • Summary on nuclei 199

200 6 The sun, the stars and the birth of matter

The Sun 200 • Motion in and on the Sun 203 • Why do the stars shine? 208 • Why are fusion reactors not common yet? 211 • Where do our atoms come from? 213 • Curiosities about the Sun and the stars 216 • Summary on stars and nucleosynthesis 218

219 7 The strong interaction – inside nuclei and nucleons

The feeble side of the strong interaction 219 • Bound motion, the particle zoo and the quark model 220 • The essence of quantum chromodynamics 224 • The Lagrangian of quantum chromodynamics 225 • Experimental consequences of the quark model 227 • Confinement of quarks – and elephants 229 • Asymptotic freedom 231 • The sizes and masses of quarks 233 • The mass, shape and colour of protons 234 • Curiosities about the strong interaction 235 • A summary of QCD and its open issues 238

240 8 The weak nuclear interaction and the handedness of nature

Transformation of elementary particles 240 • The weakness of the weak nuclear interaction 241 • Distinguishing left from right 245 • Distinguishing particles and antiparticles, CP violation 248 • Weak charge and mixings 250 • Symmetry breaking – and the lack of electroweak unification 252 • The Lagrangian of the weak and electromagnetic interactions 253 • Curiosities about the weak interaction 255 • A summary of the weak interaction 259

261 9 The standard model of particle physics – as seen on television

Summary and open questions 265

268 10 Dreams of unification

Grand unification 268 • Comparing predictions and data 269 • The state of grand unification 270 • Searching for higher symmetries 271 • Supersymmetry 271 • Other attempts 273 • Dualities – the most incredible symmetries of nature 273 • Collective aspects of quantum field theory 274 • Curiosities about unification 275 • A summary on unification, mathematics and higher symmetries 276

278 11 Bacteria, flies and knots

Bumblebees and other miniature flying systems 278 • Swimming 282 • Rotation, falling cats and the theory of shape change 287 • Swimming in curved space 291 • Turning a sphere inside out 292 • Clouds 293 • Vortices and the Schrödinger equation 294 • Fluid space-time 298 • Dislocations and solid space-time 298 •

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

N

NEUTRINIUM

interaction 254
neutrinium 258
neutrino 196, 257
atmospheric 256
cosmic 256
Earth 256
fossil 256
man-made 256
masses 335
PMNS mixing matrix 252, 265, 335
prediction 241
solar 256
neutrino flux on Earth 256
neutrino mixing
definition 251
neutrino oscillations 257
neutrino, electron 263
neutrinos 84, 396
neutron
Compton wavelength 337
is composed 219
levitation 171
magnetic moment 338
mass 336
properties 171, 343
quark content 223
neutron capture 208, 213
neutron emission 181
neutron interferomtry 142
neutron mass 233
neutron star 68, 185–186
size of 186
neutron star mergers 215
neutron stars 210
neutron trap 171
neutron, magnetic moment 227
neutrons 84, 170
and table tennis 140–142
newton 327
nickel 351
nihonium 351
niobium 352
nitrogen 352
NMR 162
Nobel Prizes, scientists with two 103
nobelium 352
noble gases 59, 346
node, on embryo 28
non-singular matrix 370
nose 40
nova 215
nuclear magnetic resonance 162, 164
nuclear magneton 337
nuclear motion
bound 188
nuclear physics 162
nuclear reaction 238
nuclear reactor
as power plant 196
natural 196
nuclei
history of 200
nucleon
definition 172
is composed 219
nucleosynthesis 213–216
primordial 213
nucleus
colour of 186
discovery of 169
fission 188
free motion of 172
in cosmic rays 172
is usually composed 169
mass limit 185
shape of 186–187
shape oscillations 199
size of 164
spin 172
spin of 164
strong force in 172
tranformation with lasers 259
nucleus accumbens 55, 56
nuclide
definition 172
nuclides 343
nymphs 312

O

oak, fighting 36
object
wobbly 309, 310
object, full list of properties 262
objects are made of particles 311
observation
takes tine 49
ocean floors 71
octonions 360
octopus
and knots 305
Oganesson 343
oganesson 352
ohm 327
oil tanker 169
Oklo 196
olivine 72
Olympus mons 88
omega
properties 343
one million dollar prize 375
one-body problem 134
onyx 75
open questions
in quantum theory and general relativity 316
open questions in QED 137
open set 364
opiorphin 54
optical black holes 151
optical coherence
tomography 115
orbifold 368
orchid 19
ore-formers 346
organelles 22
orientation sensors 40
orthoclase 72
oscillator 42
osmium 352
ovule
picture of 23
oxygen 352

P

P violation 245
p–p cycle 201, 208
packing of spheres 73
paddle wheel 26
pain sensors 40
pair creation 314

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

M

MERCURY

mercury lamps 109
meson
  diagram 222
meson table 345
mesons 222
metabolism 18
metacentric height 122
metal halogenide lamps 109
metals 346
  heavy 346
  transition 346
metamaterials 86
metamorphic rocks 69
metamorphites 71
metastability 180
metre
  definition 325
micro 327
microorganism
  swimming 285–287
microwave background
  temperature 341
migration 206
mile 328
military 151
Milky Way
  age 339
  mass 339
  size 339
millennium list 316
  of open issues 316
milli 327
mineral
  rock-forming 71
minerals 71
mines, detection of 85
miniaturization
  feats of living beings 17
Minion Math font 413
minute 327
  definition 340
mirror 147
  accelerated 129
  light emission from 129
mirror and source
  motion of 128
mirror molecules 31
mirrors 124, 128
mitochondria 25
mixing
  of neutrinos 251
  of quarks 251
mixing matrix
  CKM quark 265, 335
  PMNS neutrino 252, 265, 335
MnO 108
mobile
  neurochemical 54
moduli space 273
molar volume 337
mole
  definition 325
molecular motors 23
molecular pumps 22
molecule
  mirror 31
  most tenuous 66
molecule size 315
molybdenum 351
momentum
  Planck 329
monopole, magnetic 269
Monster group 368
monster group 369
Moon
  density 339
  properties 338
MoS_2 97
moscovium 351
moss 100
motion
  and measurement units 326
  as illusion 52
  is fundamental 326
  reasons for existence 51
  reasons for observability 51
  symmetry 31
  through strokes 289
  with limbs 31
  wobbly 309, 310
motion inversion violation 250
Motion Mountain
  aims of book series 7
  helping the project 10
  supporting the project 10
  top of 324
motor
  ciliary 30
  linear, film of 22
  molecular 21
  ultrasound 25
motors, molecular 19
MRI 162
multiverse 322
muon 172, 242, 263
  g-factor 337
muon magnetic moment 337
muon mass 335
muon neutrino 242, 263
muons 84
Musca domestica 43, 279
muscle
  working of 21
muscle motion 21
muscovite 72
music and mathematics 277
mycoplasmas 45
myosin 23
Myxine glutinosa 306
Möbius strip 365

N

Na 109, 110
NaI 109
nano 327
NASA 119
natural unit 336
navel
  in birds 31
$NbSe_2$ 97
neighbourhood 364
Nelumbo nucifera 99
neodymium 351
neon 351
Neonothopanus gardneri 110
neptunium 351
nerve cell
  blue whale 344
neurology 51
neurosciences 262
Neurospora crassa 43
neurotransmitters
  important types 55
neutral weak current

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Polymers 300 • Knots and links 302 • The hardest open problems that you can tell your grandmother 304 • Curiosities and fun challenges on knots and wobbly entities 305 • Summary on wobbly objects 309

311 12 Quantum physics in a nutshell – again
Quantum field theory in a few sentences 311 • Achievements in precision 314 • What is unexplained by quantum theory and general relativity? 316 • The physics cube 318 • The intense emotions due to quantum field theory and general relativity 320 • What awaits us? 323

325 A Units, measurements and constants
SI units 325 • The meaning of measurement 328 • Planck's natural units 328 • Other unit systems 330 • Curiosities and fun challenges about units 331 • Precision and accuracy of measurements 332 • Limits to precision 334 • Physical constants 334 • Useful numbers 341

342 B Composite particle properties

358 C Algebras, shapes and groups
358 **Algebras**
Lie algebras 361 • Classification of Lie algebras 362
363 **Topology – what shapes exist?**
Topological spaces 364 • Manifolds 365 • Holes, homotopy and homology 367
368 **Types and classification of groups**
Lie groups 369 • Connectedness 370 • Compactness 370
375 **Mathematical curiosities and fun challenges**

377 Challenge hints and solutions

386 Bibliography

412 Credits
Acknowledgements 412 • Film credits 413 • Image credits 413

417 Name index

427 Subject index





Motion Inside Matter – Pleasure, Technology and Stars

In our quest to understand how things move
as a result of a smallest change value in nature, we discover
how pleasure appears,
why the floor does not fall but keeps on carrying us,
that interactions are exchanges of radiation particles,
that matter is not permanent,
how quantum effects increase human wealth and health,
why empty space pulls mirrors together,
why the stars shine,
where the atoms inside us come from,
how quantum particles make up the world,
and why swimming and flying is not so easy.

L

LEARNING

from Roman times 196
radioactivity of natural 196
learning
best method for 9
without markers 9
without screens 9
length
Planck 329
lepton number
definition 189
levitation
neutron 171
lie
on invisibility 86
Lie algebra 361, 371
Lie algebra,
finite-dimensional 362
Lie algebra, solvable 362
Lie algebras 371
Lie group 369
Lie group, compactness of 370
Lie group, connectedness of 370
Lie group, linear 369
Lie groups 268
Lie multiplication 361
lie, biggest in the world 258
life 15, 19
definition of 17
life time
definition 180
life's basic processes 18
life's chemical formula 346
lifetime
relation to half-life 263
lifetime, atomic 315
light
speed inside the Sun 203
light bulb
scams 114–115
light can hit light 130
light emitting diodes 110
light swords 130
light year 338, 340
lightning
cosmic rays and 178
lightning rods, laser 115
limit, definition of 365
limits
to precision 334
line 303
linear motors 22
link 305
classification 305
links, long 305
lipoid pneumonia 64
liquid crystals, colours in 95
lithium 213, 350, 357
litre 327
livermorium 351
living being 15
construction plan 18
definition of 17
living thing, heaviest 344
localization
limits to particle 313
looking through matter 83
Lorentz group 370
Loschmidt's number 337
lotus effect 99
love
romantic 56
love, making 164
lumen 327
lung cancer 195
lutetium 351
lux 327

M

machine
definition of 19
molecular 21
machines, quantum 19
magma
radioactivity of 185
magmatites 71
magnesium 351
magnetic charge 273
magnetic domain walls 87
magnetic field, critical 133
magnetic flux quantum 337
magnetic monopoles 275
magnetic resonance imaging 51, 84, 162
magneton, nuclear 337
magnons 87
manganese 351
manifold 365
analytic 369
manifold, connected 365
manifolds 363
manta 286
marble 69
marker
bad for learning 9
Mars 88
Mars trip 178
masers 114
mass
Planck 329
mass ratio
muon–electron 337
neutron–electron 337
neutron–proton 337
proton–electron 337
materials science 262
Mathieu groups 368
matter
birth of 200
history of 213
looking through 83
matter is not made of atoms 179
matter, composite 342
Mauna Kea 88
maximal ideal 361
Maxwell equations 254
Mayak 195
measurement
comparison 328
definition 325, 328
error definition 332
irreversibility 328
meaning 328
process 328
medicine 262
holistic 34
medicines 63
Mega 327
meitnerium 351
Melanophila acuminata 40
memory
and reproduction 19
Mendel's 'laws' of heredity 18
mendelevium 351
menthol 39
mercury 66, 351

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

H

HYPERICUM

Hypericum 67
hypernova 153

I
ideal 361
igneous rocks 69
ignition 212
illusion
  of motion 39
imaging
  magnetic resonance 51, 162
indium 350
infinite-dimensional 363
infrasound 41
InGaAsP laser 113
ink fish 286
insects 279
inside 167
instanton 275
interaction
  strong nuclear 200
  weak 240–260
  weak, curiosities 255
  weak, summary 259
interference 130
interferometer, neutron 142
interferometers 142
internal conversion 181
International Astronomical Union 340
International Geodesic Union 340
intrinsic properties 312
invariant, link 307
invariant, topological 307
inversion 293
invisibility 85–86
invisibility cloak 85
involution 360
iodine 350
ion channel 53
ionic radii 357
iridium 350
iron 350
  fission and 208
  fusion and 208
isomeric transition 181
isotope
  definition 172
isotopes 346, 410
IUPAC 410
IUPAC 411
IUPAP 410

J
Jacobi identity 361
Janko groups 368
Jarlskog invariant 251, 265, 335
JET, Joint European Torus 211
Joint European Torus 211
Josephson constant 315
Josephson effect 326
Josephson frequency ratio 337
joule 327
junk DNA 53
Jupiter 68
  properties 339

K
kaon 172
  properties 342
Karachay, Lake 35, 195
kefir grains 30
kelvin
  definition 325
Killing form 362
kilo 327
kilogram
  definition 325
kilonova 215
kinesin 25
KJ 66
Klein bottles 366
Klitzing, von – constant 315, 337
knot
  and particles 309
  in plants 305
  no in octopus arms 305
  tight
  illustration of 304
Knot Atlas 302
knot fish 306
knot invariants 303
knot problem, simplest 304
knot shapes 304
knot theory 137
knot, mathematical 302
KnotPlot 302
knotted protein 307
krypton 350

L
lady's dress 292
Lagrangian,QED 126
Lamb shift 125–126, 133, 315
lamp 108
lamp, ideal 110
lamps 109
  gas discharge 108
  incandescent 108
  recombination 108
lamps, sodium 110
lamps, xenon 110
land mines, detection of 85
lanthanoids 346
lanthanum 350
large number hypothesis 144
laser 114, 315
  list of types 109
laser mosquito killers 115
laser sword 130
laser umbrella 115
laser weapon 111
laser, CO_2 111
laser, argon 110
laser, beer 112
laser, cadmium 111
laser, copper 111
laser, gold 111
laser, helium-neon 110
laser, krypton 111
laser, lead salt 113
laser, nitrogen 111
laser, quantum cascade 113
laser, semiconductor 113
laser, vodka 112
laser, water 111
laser, xenon 111
latex 88
lattice QCD 231
lattice gauge theory 231
lava 184
  radioactivity of 185
lawrencium 350
Lawson criterion 212
lead 350

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

CHAPTER 1

MOTION FOR ENJOYING LIFE

"Homo sum, humani nil a me alienum puto.**"
Terence

Since we have explored quantum effects in the previous volume, let us now have some serious fun with *applied* quantum physics. The quantum of action $\hbar$ has significant consequences for medicine, biology, chemistry, materials science, engineering and the light emitted by stars. Also art, the colours and materials it uses, and the creative process in the artist, are based on the quantum of action. From a physics standpoint, all these domains study *motion inside matter*.

Vol. IV, page 15

Inside matter, we observe, above all, tiny motions of quantum particles.*** Therefore the understanding and the precise description of matter requires *quantum physics*. In the following, we will only explore a cross-section, but it will be worth it. We start our exploration of motion inside matter with three special forms that are of special importance to us: life, reproduction and death. We mentioned at the start of quantum physics that none of these forms of motion can be described by classical physics. Indeed, life, reproduction and death are quantum effects. In addition, every perception, every sense, and thus every kind of pleasure is a quantum effect. The same is true for all our actions. Let us find out why.

FROM QUANTUM PHYSICS TO BIOLOGICAL MACHINES AND MINIATURIZATION

We know that all of quantum theory can be resumed in one sentence:

▷ In nature, action or change below $\hbar = 1.1 \cdot 10^{-34}$ Js is not observed.

In the following, we want to understand how this observation explains life, pleasure and death. An important consequence of the quantum of action is well-known.

▷ If it moves, it is made of quantons, or quantum particles.

** 'I am a man and nothing human is alien to me.' Terence is Publius Terentius Afer (b. *c.* 190 Carthago, d. 159 BCE Greece), the important roman poet. He writes this in his play *Heauton Timorumenos*, verse 77.
*** The photograph on page 14 shows a soap bubble, the motion of the fluid in it, and the interference colours; it was taken and is copyright by Jason Tozer for Creative Review/Sony.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Starting size: the dot on the letter i – final size:

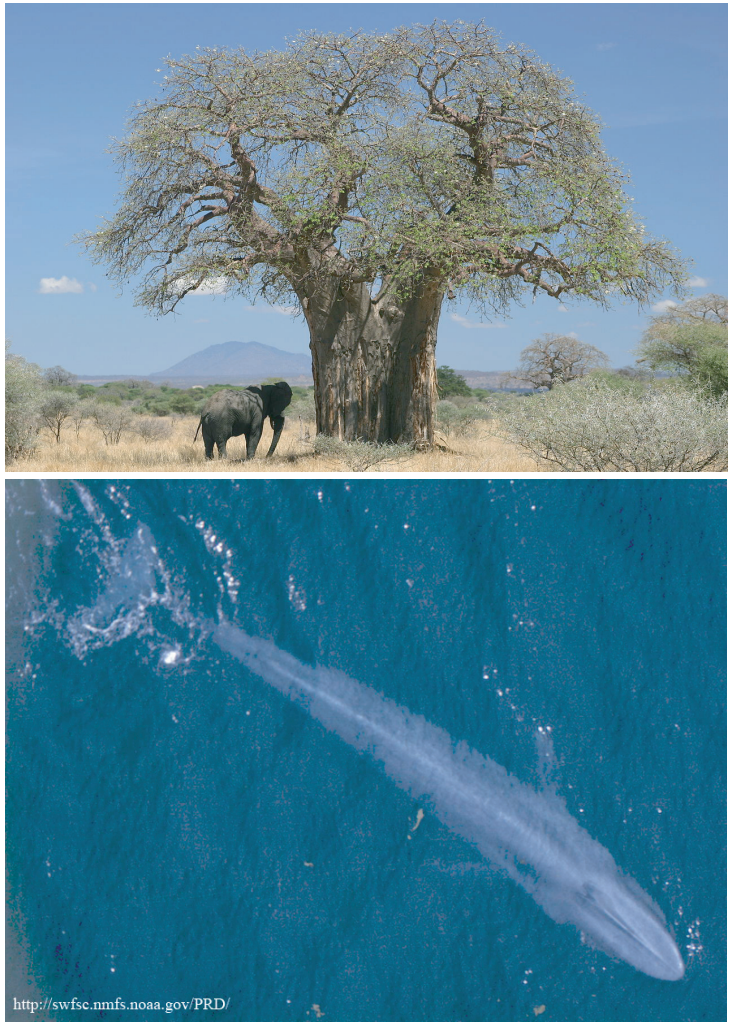


FIGURE 2 Metabolic growth can lead from single cells, about 0.1 mm in diameter, to living beings of 25 m in size, such as the baobab or the blue whale (© Ferdinand Reus, NOAA).

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

G

GAUGE

gauge theory
and shape change 289
from falling cats 287
gauge transformations 370
gauge-dependent 290
gauge-invariant 290
Gaussian distribution 332
Gaussian unit system 330
gecko 90
Geiger–Müller counters 174
Geigerpod 176
Gell-Mann matrices 227
gemstones 75
general relativity
millennium issues and 317–318
open quastions 316
generators 361
genes 22, 53
geologist 69
geology 69, 262
geosmin 56
germanium 350
ghosts 312
Giant's Causeway 71
giant, red 68
Giga 327
global warming 93
glucose 66
glueball 236, 343
definition 237
gluinos 272
gluon 262, 336
absorption 224
definition 224
emission 224
scattering 224
gluon jets 236
goblin 348, 351
god 356
goddess 312, 348, 352, 356
gods 312
gold 80, 99, 350
gold foil experiment 167
golden rule 48
grand unification 268–271
grand unified theory 269
grandmother: a hard problem 304
grape sugar 66
graphene 97, 98, 108
grasshopper 17
gravitational Bohr radius 143
gravitational constant 264, 335
geocentric 338
heliocentric 339
gravitational constant *G*
physics and 8
gravitational coupling constant 264, 335
graviton
definition of 158
gravity measurement with a thermometer 147
gray 327
gray (SI unit) 193
greenhouse effect 93
group of components 375
group, monster 369
group, simple 368
groups
gauge and Lie 268
growth
in living beings 16
growth of trees 34
growth rings 99
GUT 269
gypsum 75
gyromagnetic ratio of the electron 315

H

hadron
large number of 222
hadrons 222
hafnium 350
hagfish 306
hahnium 349
half-life
definition 180
relation to lifetime 263
Hall effect 95, 380
Hall effect, fractional quantum 107
Hall effect, phonon 97
Hall effect, photonic 96
Hall probes 95
halogens 346
handcuff puzzle 363
hassium 350
Hausdorff space 365
heart
position 27
heat capacity of diatomic gas 315
heat capacity of metals 315
Heaviside–Lorentz unit system 330
heavy ion emission 181
hecto 327
helioseismology 210, 217
helium 120, 320, 321, 343, 350
helium burning 210
helix 297
hell
hotness of 184
henry 327
hertz 327
Higgs 263
Higgs boson 253, 258
Higgs mass 336
Hiroshima bomb 194
history
of matter 200
HoI_3 109
holes in manifolds 368
holmium 350
homeomorphism
definition 366
Homo sapiens 36, 43
horizon 143
hormones 63
hornblende 72
hour 327
Hubble parameter 340
human
properties 344
human energy consumption 199
hummingbirds 281
hydrargyrum 351
hydrodynamics 279
hydrogen 350
properties 343
hydrogen–hydrogen cycle 201, 208
hydroxylapatite 79

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

E
Exa

tree of 32
Exa 327
exciton 87
explosions 153
exposure
radiation 194
extension sensors 40
extraterrestrial life 34
extraterrestrials 34
eye 38
eye sensitivity 38

F

F. spectabilis 43
F. suspensa 43
F. viridissima 43
faeces 52
farad 327
Faraday's constant 337
Fe
fission and 208
fusion and 208
feathers 88
femto 327
femtosecond laser 115
Fermi constant 252
Fermi coupling constant 265, 335
fermion, composite 107
fermium 349
ferromagnetism 315
ferrum 350
Feynman diagram 135
field of scalars 359
field theory, conformal 268
Fields medal 292
figure-eight 303
fine structure constant 107, 127
graphene and 98
limits number of chemical elements 133
rainbow and 138
fine structure constant, limit on 134
fine tuning 322
fine-structure constant 264, 265, 329, 335, 336
finger print 67
and radioactivity 196
fire 195
fire tornados 295
fire whirls 295
firefly 110
fireworks 195
Fischer groups 368
fish
and propellers 283
fission
nuclear 188
Sun and 200
flagella
prokaryote 286, 406
flagellum 286
flavour symmetry 225
flavours 223
flerovium 349
floor
stability of 67
flow
nodal 29
turbulent 281
flower stems 305
fluctuations
zero-point 124
fluorine 349
fly
common *Musca domestica* 18
flying systems 278
foam
as origin of life 34
food quality 192
football, hairy 375
force
entropic 73
van der Waal, at feet of geckos and spiders 90
formula of life 346
formulae 134
Forsythia europaea 43
Foucault pendulum 120
fountain effect 104
foxfire 110
fraction
brittle 88
ductile 88
fractional quantum Hall effect 107
francium 349
properties 343
Franz Aichinger 412
fraud 346
free energy 301
freedom
asymptotic 275
fruit flies 278
fruit fly 17
full width at half maximum 332
Fulling–Davies–Unruh effect 129, 146, 298
Fulling–Davies–Unruh radiation 157
fundamental group 375
fur 29
fusion
challenge of confined 213
confined 211
in stars 208
inside Sun 200
reactors 211

G

γ ray burst 152
G-parity 263
GABA 55
gadolinium 349
gait
undulatory swimming 283
galaxies as clouds 293
Galileo Galilei 140
gallium 349
gamma ray burst 152
gamma ray bursts 397
gamma-ray burst
locations of 152
gamma-ray bursts 153, 397
GaN laser 113
garlic-smelling
semiconductor 355
garnet 77
gas constant, universal 337
gauge
symmetry 317
gauge groups 268
gauge symmetry 369

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Step by step we will discover how these statements are reflected in the behaviour of living beings. But what are living beings?

Living beings are physical systems that show metabolism, information processing, information exchange, reproduction and motion. All these properties can be condensed in a single statement:

▷ A *living being* is a collection of machines that is able to self-reproduce.

By *self*-reproduction, we mean that a system uses its own metabolism to reproduce. There are examples of objects which reproduce and which nobody would call living. Can you find some examples? To avoid misunderstandings, whenever we say 'reproduction' in the following, we always mean 'self-reproduction'. Challenge 2 s

Before we explore the definition of living beings in more detail, we stress that self-reproduction is simplified if the system is miniaturized. Therefore, most living beings are extremely small machines for the tasks they perform. This is especially clear when living beings are compared to human-made machines. The smallness of living beings is often astonishing, because the design and construction of human-made machines has considerably fewer requirements.

1. Human-made machines do not need to be able to reproduce; as a result, they can be made of many parts and can include rotating macroscopic parts. This is in contrast to living beings, who are all made of a single piece of matter, and cannot use wheels, propellers, gearwheels or even screws.
2. Human made machines can make use of metals, ceramics, poisonous compounds and many other materials that living beings cannot use.
3. Human machines do not need to self-assemble and grow; in contrast, living beings always need to carry a built-in chemical factory with them.
4. Human machines can be assembled and can operate at various temperatures, in strong contrast to living beings.

Despite these extreme engineering restrictions, living beings hold many miniaturization world records for machines:

— The brain has the highest processing power per volume of any calculating device so far. Just look at the size of chess champion Gary Kasparov and the size of the computer against which he played and lost. Or look at the size of any computer that attempts to speak.
— The brain has the densest and fastest memory of any device so far. The set of compact discs (CDs) or digital versatile discs (DVDs) that compare with the brain is many thousand times larger in volume. Vol. III, page 264
— Motors in living beings are several orders of magnitude smaller than human-built ones. Just think about the muscles in the legs of an ant.
— The motion of living beings beats the acceleration of any human-built machine by orders of magnitude. No machine achieves the movement changes of a grasshopper, a fly or a tadpole.
— Living beings that fly, swim or crawl – such as fruit flies, plankton or amoebas – are still thousands of times smaller than anything comparable that is built by humans.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

In particular, already the navigation systems built by nature are far smaller than anything built by human technology.

— Living being's sensor performance, such as that of the eye or the ear, has been surpassed by human machines only recently. For the nose, this feat is still far in the future. Nevertheless, the sensor *sizes* developed by evolution – think also about the ears or eyes of a common fly – are still unbeaten.

Challenge 3 s — Can you spot more examples?

The superior miniaturization of living beings – compared to human-built machines – is due to their continuous strife for efficient construction. The efficiency has three main aspects. First of all, in the structure of living beings, *everything is connected to everything.* Each part influences many others. Indeed, the four basic processes in life, namely metabolic, mechanical, hormonal and electric, are intertwined in space and time. For example, in humans, breathing helps digestion; head movements pump liquid through the spine; a single hormone influences many chemical processes. Secondly, *all parts in living*

Challenge 4 e *systems have more than one function.* For example, bones provide structure and produce blood; fingernails are tools and shed chemical waste. Living systems use many such op-

Challenge 5 e timizations. Last but not least, living machines are *well* miniaturized because they make efficient use of quantum effects. Indeed, every single function in living beings relies on the quantum of action. And every such function is extremely well miniaturized. We explore a few important cases.

Reproduction

> "Finding a mate is life's biggest prize."
> The view of biologists.

All the astonishing complexity of life is geared towards reproduction. *Reproduction*, more precisely, *self-reproduction*, is the ability of an object to build other objects similar to itself.

Vol. IV, page 121 Quantum theory told us that it is only possible to build a *similar* object, since an *exact* copy would contradict the quantum of action. But this limitation is not a disadvantage: an imperfect copy is required for life; indeed, a similar, thus imperfect copy is essential for biological evolution, and thus for change and specialization.

Reproduction is characterized by random changes, called *mutations*, that distinguish one generation from the next. The statistics of mutations, for example Mendel's 'laws' of heredity, and the lack of intermediate states, are direct consequences of quantum theory. In other words, reproduction and heredity are quantum effects.

Reproduction requires *growth*, and growth needs metabolism. *Metabolism* is a chemical process, and thus a quantum process, to harness energy, harness materials, realize

Page 58 growth, heal injuries and realize reproduction.

Since reproduction requires an increase in mass, as shown in Figure 2, all reproducing objects show both metabolism and growth. In order that growth can lead to an object similar to the original, a construction *plan* is necessary. This plan must be similar to the plan used by the previous generation. Organizing growth with a construction plan is only possible if nature is made of smallest entities which can be assembled following that plan.

We thus deduce that reproduction and growth implies that matter is made of smallest entities. If matter were not made of smallest entities, there would be no way to realize

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

D

Dirac

Dirac equation 253
  and Sokolov–Ternov effect 147
Dirac equation and chemistry 58
disclinations 86, 88
dislocation loop 298
dislocations 86, 88, 299
distribution
  Gaussian 332
  normal 332
division algebra 360
DNA
  and genes 53
  illustrations of 64
  images of 65
DNA 62, 63
DNA molecules 307
DNS 62
dolphins 41, 282
donate
  to this book 10
dopamine 55
dose
  radioactive 193
down quark 223, 263
down quark mass 335
Drosophila bifurca 286
Drosophila melanogaster 43, 278, 286
duality 273–274
  electromagnetic 273
duality of coupling constants 268
dubnium 349
Duckburg 24
DVD 17
dyadosphere 153
DyI_3 109
dynamical Casimir effect 129
dyons 275
dysprosium 349

E

E. coli 344
ear 38
Earth
  age 338
  age of 184
  average density 338
  equatorial radius 338
  flattening 338
  gravitational length 338
  mass 338
  normal gravity 338
  radius 338
  rotation, and superfluidity 120
  snowball 391
earthquakes 83
echo 128
eddies 280
edge dislocations 299
effective width 299
egg
  picture of 23
Eiffel tower 88
eigengrau 53
eigenvalue 359
eigenvector 359
einsteinium 349
electric field, critical 133
electrical conductance 133
electricity
  solar storms and 208
electrification 137
electromagnetic unit system 330
electrometer 172
electron 242, 262
  filming a single 117
  g-factor 337
  mass 335
electron holes 87
electron magnetic moment 337
electron neutrino 242
electron radius 264
electron volt
  value 338
electron, weak charge 246
electrons 84
electronvolt 330
electroscope 172
electrostatic unit system 330
electroweak coupling 252
electroweak interaction
  does not exist 252
electroweak mixing 252
electroweak unification
  lack of 252
element, adjoint 360
elementary particle
  properties 262
  table 262
elementary particles, electric polarizability 344
elements 344, 345
embryo 22
emission
  spontaneous 125
emotions
  inspired by quantum field theory 320
Encarsia 282
energy
  Planck 329
energy of the universe 145
energy width 263
engineering 262
entity
  wobbly 309, 310
entropy
  Planck 329
entropy, state of highest 154
enzymes 349
erbium 349
error
  in measurements 332
  random 332
  relative 333
  systematic 333
  total 333
Erta Ale 185
Escherichia coli 40, 286
etanercept 67
ethene 36, 56
Ethiopia 185
Euler characteristic 366
Euphasia superba 36
europium 349
evaporation 155
Evarcha arcuata 90
eversion 292
evolution 46
  biological 29
  three principles of 29

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

C

CONES

cones 38
Conférence Générale des Poids et Mesures 325
confinement of quarks 224, 231
conformal field theory 268
conformal symmetry 225, 273
Conférence Générale des Poids et Mesures 326
connected manifold 365
consciousness 50–51
  definition 50
constants
  table of astronomical 338
  table of basic physical 264, 334
  table of cosmological 340
  table of derived physical 336
constituent quark mass 233
continuity 364
Convention du Mètre 325
Conway groups 368
Cooper pairs 87, 103
copernicium 348
copper 80, 349
copper single crystal 80
copycat 30
core 58
cork 88
corona 202, 208
  photograph of solar 205
  temperature of 208
corrected Planck units 330
corundum 76
cosmic radiation 174
  neutrinos 256
cosmic rays 153, 174
  composition 175, 177
  cosmonauts and 178
  danger for cosmonauts 178
  discovery 172
  evolution and 179
  extragalactic origin 178
  lightning 178
  types of 175
cosmological constant 340
cosmological constant Λ
  as millennium issue 317
cosmonaut 119
  and body rotation 289
  and cosmic rays 178
  eye flashes 179
  lifetime of 178
coulomb 327
Coulomb explosion 137
counter 42
coupling constant unification 270
cows, ruminating 259
CP violation 248
CPT invariance 250
creation
  none in nature 322
creation of light 113
cromosome, human Y 343
crystal
  formation of 72
  maximum density 73
  maximum entropy 73
  virus 377
crystal database 82
crystal shapes 82
crystallization dating 184
crystals 71–82
crytsal
  face formation 74
Cu 80
cube
  Bronshtein 8
  physics 8
  the physics 318
cumulonimbus 293
cuprum 349
curie (unit) 194
curium 349
current
  Planck 329
current quark mass 233
curve
  closed time-like 159
cyclotron frequency 337

D

daemons 312
dangers of MRI 193
dark energy 317
darmstadtium 349
dating, radiocarbon 184
dating, radiometric 182–184
day
  length measurement by plants 56
  sidereal 338
  time unit 327
de Broglie wavelength 326
death 56, 86
deca 327
decay 47, 48
  as nuclear motion 188
decay time
  definition 180
decay, alpha *see α* decay
decay, beta *see β* decay
deci 327
degenerate matter 186
degree
  angle unit 327
degree Celsius 327
delusion
  about unification 320
Demodex brevis 33
density
  Planck 329
deoxyribonucleic acid 62
Desmodium gyrans 43
Desoxyribonukleinsäure 62
deuterium 211
deviation
  standard, illustration 333
devils 312
dextrose 66
diamond 79, 269
  from moss 100
  harder than 100
diamonds 93
Dicomorpha 282
diffeomorphism
  definition 367
difference
  man and chimpanzee 31
differential manifold 365
diffusion 287
digital versatile discs, or DVD 17
dimension 361
dimensionless 336

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 3 A quantum machine (© Elmar Bartel).

reproduction. The observation of reproduction thus implies the existence of atoms and the necessity of quantum theory! Indeed, without the quantum of action there would be no DNA molecules and there would be no way to inherit our own properties – our own construction plan – to children.

Passing on a plan from generation to generation requires that living beings have ways to store information. Living beings must have some built-in memory storage. We know already that a system with memory must be made of *many* particles: there is no other way to store information and secure its stability over time. The large number of particles is necessary to protect the information from the influences of the outside world.

Vol. I, page 402

Our own construction plan is stored in DNA molecules in the nucleus and the mitochondria of each of the millions of cells inside our body. We will explore some details below. The plan is thus indeed stored and secured with the help of *many* particles. Therefore, reproduction is first of all a transfer of parent's DNA to the next generation. The transfer is an example of motion. It turns out that this and all other examples of motion in our bodies occur in the same way, namely with the help of molecular machines.

Page 62

Quantum machines

Living beings move. In order to reproduce, living beings must be able to move in self-directed ways.

▷ A system able to perform self-directed motion is called a *machine*.

All self-reproducing beings, such as the one of Figure 3, are thus machines. Even machines that do not grow still need fuel, and thus need a metabolism. All machines, living or not, are based on quantum effects.

How do living machines work? From a fundamental physics point of view, we need only a few sections of our walk so far to describe them: we need QED and sometimes universal gravity. Simply stated, life is an electromagnetic process taking place in weak gravity.* But the details of this statement are tricky and interesting.

* In fact, also the nuclear interactions play some role for life: cosmic radiation is one source for random

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 1 Motion and molecular machines found in living beings.

Motion type	Examples	Involved motors
Growth	collective molecular processes in cell growth, cell shape change, cell motility	linear molecular motors, ion pumps
	gene turn-on and turn-off	linear molecular motors
	ageing	linear molecular motors
Construction	material transport (polysaccharides, lipids, proteins, nucleic acids, others)	muscles, linear molecular motors
	forces and interactions between biomolecules and cells	pumps in cell membranes
Functioning	metabolism (respiration, digestion)	muscles, ATP synthase, ion pumps
	muscle working	linear molecular motors, ion pumps
	thermodynamics of whole living system and of its parts	muscles
	nerve signalling	ion motion, ion pumps
	brain working, thinking	ion motion, ion pumps
	memory: long-term potentiation	chemical pumps
	memory: synapse growth	linear molecular motors
	hormone production	chemical pumps
	illnesses	cell motility, chemical pumps
	viral infection of a cell	rotational molecular motors for RNA transport
Defence	the immune system	cell motility, linear molecular motors
	blood clotting	chemical pumps
	bronchial cleaning	cilial motors
Sensing	eye	chemical pumps, ion pumps
	ear	hair motion sensors, ion pumps, rotary molecular motors
	smell	ion pumps
	touch	ion pumps
Reproduction	information storage and retrieval	linear and rotational molecular motors inside nuclei
	cell division, organelle motion	linear molecular motors, polymerase
	sperm motion	linear molecular motors
	courting, using brain and muscles	linear molecular motors, ion pumps

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

B

BROMINE

bromine 347
Bronshtein cube 8
Brownian motors 24
bubble chamber 167
bulb
  light, scams 114–115
bumblebee 279
Bureau International des Poids et Mesures 325
Burgers vector 299
butterfly 278

C

C violation 248
C*-algebra 360
Cabibbo angle 251
Cabibbo–Kobayashi–Maskawa mixing matrix 254
cadmium 348
caesium 348
caesium and parity non-conservation 247
calcium 348
californium 348
candela
  definition 326
candle 109
candy floss 169
capsaicin 39, 332
carbon 348
  properties 343
cardiopulmonary resuscitation 36
Cartan metric tensor 362
Casimir effect 124, 314
cat
  cloned 30
  falling 287
  square 289
Cathartes aura 281
cats 38
cell 344
  first biological 34
cell motility 22
centi 327
centre 361
Cepheids 217
ceramics 76
cerium 348
CERN 174, 242, 256, 273, 331
chain reaction 189
  in everyday life 195
  in fission 189
  in nuclear devices 191
chalkogens 346
challenge
  classification 9
change
  quantum of, precise value 264, 334
charge
  elementary *e*, physics and 8
  positron or electron, value of 264, 334
charge conjugation violation 248
charged weak current interaction 254
charm quark 223, 263
charm quark mass 335
chemistry 262
Chernobyl disaster 194
Chew-Frautschi plots 230, 231
chiral symmetry 225
chirality in nature 307
chirality of knots in nature 307
Chlamydomonas 286
Chlamys 285
chlorine 348
chloroplasts 25
cholera 22
chromium 348
chromosome 31, 343
chrysoberyl 78
Chrysopelea paradisii 309
cilia 286
cilia, nodal 29
citrine 75
CKM matrix 251
clasp 305
classical 362
classical electron radius 337
classifications
  in biology 32
Clay Mathematics Institute 375
cloak of invisibility 86
clock
  biological 42–44
  does not exist 44
  living 42–44
clock in brain 44
clock oscillator 46
clocks 44, 52
clone
  human 30
clothes
  see through 390
clothes, seeing through 91
cloud chamber 167
clouds 293, 357
cluster emission 181
CNO cycle 208, 209
cobalt 348
CODATA 410
CODATA 401
coefficient of local self-induction 295
coherent 114
cold working 80
Coleman–Mandula theorem 272
colour 263
  as source of the strong interaction 227
  strong charge 223
  unknown origin of 323
colour, evidence for three 228
Commission Internationale des Poids et Mesures 325
commutative 361
commutator 361
compact discs 17
compactness 370
completeness 360
complex Lie group 369
complex numbers 360
Compton Gamma Ray Observatory 152
Compton wavelength 314, 337
conductance 133
conductance quantum 337
conduction electrons 87
conductivity, electrical 315

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

A

ATOMIC

atomic number 345
atomic radius 357
atoms
  and elementary particles 262
  history of 213
atoms and reproduction 19
atoms and swimming 282
atoms are rare 179
atoms, matter is not made of 179
ATP 23, 25, 343
ATP consumption of molecular motors 22
ATP synthase 22
  structure of 26
ATP synthase 26
atto 327
aurora australis 179
aurora borealis 179
aurora, artificial 197
aurum 350
autoradiography 196
Avogadro's number 336
awe 323

B

β decay 240
bacteria 33, 45
  gliding 285
  number of 33
bacterium
  lifetime 31
  swimming 284
badminton 88
balsa wood 88
Banach–Tarski paradox or theorem 134
bananas, knotted 305
barium 347
baryon
  diagram 221
  observed number of 317
baryon number
  definition 189
baryon number density 341
baryon table 345
baryons 222, 223
base units 325
basis 361
bath, vacuum as 131
bats 41
battery
  using the weak interaction 256
BCS theory 392
beauty 264
beauty quark 223
becquerel 327
becquerel (SI unit) 193
beech, fighting 36
beer 114
being, living 15
Bekenstein–Hawking temperature 149
beliefs 322
BeppoSAX satellite 152
berkelium 347
beryllium 347
beta decay *see* β decay
  definition 180
beta particle *see* electron
beta rays *see* β rays
Bethe-Weizsäcker cycle 208, 209
Bikini atoll 217
biology 262
biomass
  of species 36
biotite 72
BIPM 325, 326, 328
bird
  navel 31
birds 206
birth
  video of 164
bismuth 347, 410
  properties 343
$Bi_2Sr_2CaCu_2O_x$ 97
bitartrate 75
bits to entropy conversion 338
black body radiation constant 150
black hole 69, 146
  illustration of 145
black hole observations 151
black hole radiation 147
black holes 322
black holes are born 151
black holes die 151
black-hole temperature 149
blood 193
BN 97
body
  human, asymmetry of 27
Bohr atom, gravitational 143
Bohr magneton 337
Bohr radius 337
bohrium 347
Boltzmann constant 264, 334
Boltzmann constant *k*
  physics and 8
bomb
  Hiroshima 194
bomb, nuclear 191
bombs 153
  in nature 217
Bombus terrestris 279
bond
  angle of 62
  chemical, illustration of 61, 62
  chemical, measurement of 63
bonds, chemical 59
bones
  seeing own 197
books 99
boron 347
Bos taurus 36
Bose–Einsein condensation 315
Bose–Einstein condensate 105, 108
bosonization 405
bottom quark 223, 263
bottom quark mass 335
bottomness 264
box tightness 90
braid 305
brain 41
  and molecular motors 25
  size, in whales 41
brain's interval timer 44
brain, clock in 44
branching ratios 229
Bridgmanite 71

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

We can say that *living beings are systems that move against their environment faster than molecules do.* Observation shows that living systems move faster the bigger they are. Observation also shows that living beings achieve this speed by making use of a huge number of tiny machines, often made of one or only a few molecules, that work together. These machines realize the numerous processes that are part of life.

Ref. 2

An overview of processes taking place in living beings is given in Table 1. Above all, the table shows that the processes are due to *molecular machines*.

▷ A living being is a collection of a huge number of specialized molecular machines.

Molecular machines are among the most fascinating devices found in nature. Table 1 also shows that nature only needs a few such devices to realize all the motion types used by humans and by all other living beings: *molecular pumps* and *molecular motors*. Given the long time that living systems have been around, these devices are extremely efficient. They are found in every cell, including those of Figure 5. The specialized molecular machines in living beings are ion pumps, chemical pumps and rotational and linear molecular motors. Ion and chemical pumps are found *in* membranes and transport matter *across* membranes. Rotational and linear motors move structures *against* membranes. Even though there is still a lot to be learned about molecular machines, the little that is known is already spectacular enough.

Ref. 3

How do we move? – Molecular motors

How do our muscles work? What is the underlying motor? One of the beautiful results of modern biology is the elucidation of this issue.

▷ *Muscles* work because they contain molecules which change shape when supplied with energy.

This shape change is *repeatable*. A clever combination and repetition of these molecular shape changes is then used to generate macroscopic motion.

▷ Each shape-changing molecule is a molecular motor.

There are three basic classes of molecular motors in nature: linear motors, rotational motors and pumps.

mutations, which are so important in evolution. Plant growers often use radioactive sources to increase mutation rates. Radioactivity can also terminate life or be of use in medicine.

Ref. 1

The nuclear interactions are also implicitly involved in life in several other ways. The nuclear interactions were necessary to form the atoms – carbon, oxygen, etc. – required for life. Nuclear interactions are behind the main mechanism for the burning of the Sun, which provides the energy for plants, for humans and for all other living beings (except a few bacteria in inaccessible places).

Summing up, the nuclear interactions occasionally play a role in the appearance and in the destruction of life; but they usually play no role for the actions or functioning of particular living beings.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

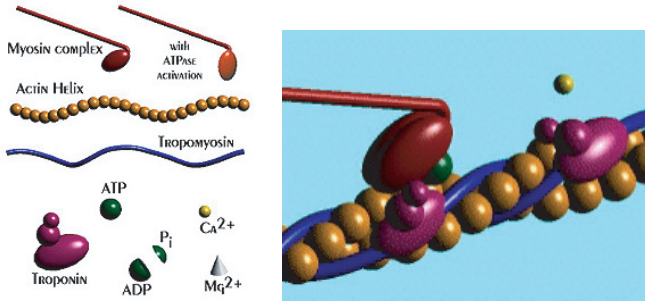


FIGURE 4 Left: myosin and actin are the two protein molecules that realize the most important linear molecular motor in living beings, including the motion in muscles. Right: the resulting motion step is 5.5 nm long; it has been slowed down by about a factor of ten (image and QuickTime film © San Diego State University, Jeff Sale and Roger Sabbadini).

1. *Linear molecular motors* are at the basis of muscle motion; an example is given in Figure 4. Other linear motors separate genes during cell division. Linear motors also move organelles inside cells and displace cells through the body during embryo growth, when wounds heal, and in all other cases of cell motility. Also assembler molecules, for example those that replicate DNA, can be seen as linear motors.

A typical molecular motor consumes around 100 to 1000 ATP molecules per second, thus about 10 to 100 aW. The numbers are small; there are more astonishing if we take
Challenge 6 s into account that the power due to the white noise of the surrounding water is 10 nW. In other words, in every molecular motor, the power of the environmental noise is eight to nine orders of magnitude higher than the power consumed by the motor! The ratio shows what a fantastic piece of machinery such a molecular motor is. At our scale, this would correspond to a car that drives, all the time, through an ongoing storm and earthquake.

Vol. I, page 92 2. We encountered *rotational motors* already earlier on; nature uses them to rotate
Ref. 4 the cilia of many bacteria as well as sperm tails. Researchers have also discovered that evolution produced molecular motors which turn around DNA helices like a motorized bolt would turn around a screw. Such motors are attached at the end of some viruses and insert the DNA into virus bodies when they are being built by infected cells, or extract
Ref. 5 the DNA from the virus after it has infected a cell. The most important rotational motor,
Page 25 and the smallest known so far – 10 nm across and 8 nm high – is ATP synthase, a protein that synthesizes most ATP in cells.

3. *Molecular pumps* are equally essential to life. They pump chemicals, such as ions or specific molecules, into every cell or out of it, using energy. They do so even if the concentration gradient tries to do the opposite. Molecular pumps are thus essential in ensuring that life is a process *far* from equilibrium. Malfunctioning molecular pumps are responsible for many health problems, for example for the water loss in cholera infection.

In the following, we explore a few specific molecular motors found in cells. How mo-
Ref. 6 lecules produce movement in linear motors was uncovered during the 1980s. The results

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

SUBJECT INDEX

Symbols
*-algebra 359
MRI, dangers of 193
α decay 180
α particle 180
α particles 172
β decay 180
β particle 180
γ decay 181
γ particle 181

A
α-ray dating 184
acceleration
  Planck 329
accelerator mass spectroscopy 184
accuracy 332
  limits to 334
aces 219
Acetabularia 43
acne 33
actin 23
actinium 346
actinoids 346
action
  Planck 329
action, quantum of, ħ
  physics and 8
Adansonia grandidieri 160
adenosine triphosphate 23, 25
adjoint representation 362
aerodynamics 280
aerogels 99
aeroplane
  why does it fly? 280
aeroplane, model 279
agate 75
age determination 182–184
ageing 42
aging 35
aircraft
  why does it fly? 280
alexandrite 78
AlGaAs laser 113
algebra 358, 359
algebra, linear 359
alkali metals 59, 346
alkaline earth metals 346
Allen belt, van 197
alpha decay *see* α decay
  definition 180
alpha particle *see* α particle
alpha rays *see* α rays
alumina 76
aluminium 346
aluminium amalgam 66
Alzheimer patients 67
Alzheimer's disease 67
amalgam 351
americium 346
amethyst 75
amoeba 287
amount of radioactive material 193
ampere
  definition 325
amphiboles 72
Anagrus 282
anapole moment 403
angels 312
angler fish 110
angular momentum 314
anti-atoms 344
antihydrogen
  properties 343
antiknot 303
antimony 347
antiscreening 233
antisymmetry 361
apes 210
aphelion 339
apogee 339
apple 344
APS 414
Arabidopsis 43
Archilochus colubris 281
argon 185, 347
Armillaria mellea 110
arsenic 347
artefact
  for measurement units 326
Ashby chart 88, 89
associative algebra 359
astatine 347
astronaut *see* cosmonaut
astronomical unit 340
astronomy 262
asymmetry
  right-left of human body 27
asymptotic freedom 232, 233
atmosphere
  pressure 338
atom
  discovery of its structure 169
  falling 140
atom interferometers 143
atomic 331
atomic mass unit 263, 336

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

V

VAROQUAUX

Varoquaux, Eric 119, 120, 415
Veevaert, John 414
Veltman, Martin 242
Verneuil, Auguste
life 76, 93
Verstegen, Mark 36
Vesselovsky, Andrey 414
Villain, J. 390
Visser, Matt 397
Vitale, L. 387
Vogel, S. 405
Volin, Leo 412
Volovik, G.E. 392
Voltaire 311
Voronin, A.Yu. 395, 396
Voss, Gustav-Adolf 237
Voss, Herbert 413
Vreeland, R.H. 387
Vuorinen, R.T. 409

W

Wald, R.M. 159, 396, 398
Wald, Robert 148, 149
Walker, Gabriele 387
Walton 238
Wang, Z.J. 405
Warkentin, John 413
Wearden, John 388
Weber, J. 386
Weber, Joachim 26, 413
Weber, T. 398
Weekes, T.C. 399
Weeks, J. 407
Weijmar Schultz, W.C.M. 399
Weijmar Schultz, Willibrord
164, 399, 416
Weill, Frederic 416
Weinberg, Steven 255, 398
Weinkamer, R. 391
Weiss, Martha 412
Weisskopf, V.F. 391, 400
Weisskopf, Victor
life 41
Weisskopf, Victor F. 401
Weiszäcker, Carl Friedrich
von 200
Weitz, M. 395, 410
Wernecke, M.E. 387
Werner, S.A. 396
Werner, Samuel 142
Wess, Julius 404
Wesson, John 400
Westphal, A. 395, 396
Wheeler, John 159
Wieman, Carl 105
Wiemann Lehrmittel 169, 415
Wiemann, C.E. 403
Wiens, R. 399
Wierda, Gerben 412
Wierzbicka, Anna 412
Wieser, M. 387
Wijk, Mike van 412
Wijngarden, R.J. 391
Wikimedia 70, 102, 413–415
Wilczek, F. 402, 406
Wilczek, Frank 232–234, 289
Wilde, Oscar 37
Wiley VCH 65, 413
Wilkinson, S.R. 389
Willberg, Hans Peter 388
Willerslev, E. 387
Williams, H.H. 403
Wilson, Charles 167
Wilson, J.R. 397
Wineland, D.J. 389
Wineland, David 50
Wisdom, J. 406
Wisdom, Jack 291
Wise, N.W. 410
Witten, Edward 307
Wodsworth, B. 400
Wohl, C.G. 411
Wohlleben, Peter 36
Wolfgang Rueckner 176
Wolfsried, Stephan 76, 79, 414
Wood, C.S. 403
World High Diving
Federation 288, 416
Worlock, J.M. 391, 394
Wright, Joseph 413
Wright, K. 388
Wrinkle, N.C. 407
Wu Chien-Shiung 247
life 245
Wyder, P. 392

X

Xue, S.-S. 397

Y

Yai, N. 390
Yamamoto, H. 393
Yang Chen Ning 245
Ynduráin, Felix J. 401
Young, Andrew 412
Yu, Kristina 23, 413
Yukawa Hidei 127
Yukawa Hideki
life 219

Z

Zaccone, Rick 413
Zaitsev, A. 402
Zalm, Peer 412
Zedler, Michael 412
Zee, A. 406
Zee, Anthony 289
Zeilinger, A. 409
Zeitler, U. 392
Zel'dovich, Ya.B. 403
Zeno of Elea 48, 49, 52
Zetsche, Frank 398
Zhang, Y. 392
Zhou, H. 407
Zimmerman, E.J. 389
Zlinsky, A. 387
Zuckerman, G. 411
Zwaxh, W. 391
Zweig, G. 401
Zweig, George
life 219

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 5 A sea urchin egg surrounded by sperm, or molecular motors in action: molecular motors make sperm move, make fecundation happen, and make cell division occur (photo by Kristina Yu, © Exploratorium www.exploratorium.edu).

started a wave of research on all other molecular motors found in nature. The research showed that molecular motors differ from most everyday motors: molecular motors do *not* involve temperature gradients, as car engines do, they do *not* involve electrical currents, as electrical motors do, and they do *not* rely on concentration gradients, as chemically induced motion, such as the rising of a cake, does.

LINEAR MOLECULAR MOTORS

The central element of the most important linear molecular motor is a combination of two protein molecules, namely myosin and actin. Myosin changes between two shapes and literally *walks* along actin. It moves in regular small steps, as shown in Figure 4. The motion step size has been measured, with the help of some beautiful experiments, to always be an integer multiple of 5.5 nm. A step, usually forward, but sometimes backwards, results whenever an ATP (adenosine triphosphate) molecule, the standard biological fuel, hydrolyses to ADP (adenosine diphosphate) and releases the energy contained in the chemical bond. The force generated is about 3 to 4 pN; the steps can be repeated several times a second. Muscle motion is the result of thousand of millions of such elementary steps taking place in concert. Ref. 6

Why does this molecular motor work? The molecular motor is so small that the noise due to the Brownian motion of the molecules of the liquid around it is extremely intense. Indeed, the transformation of disordered molecular motion into ordered macroscopic

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

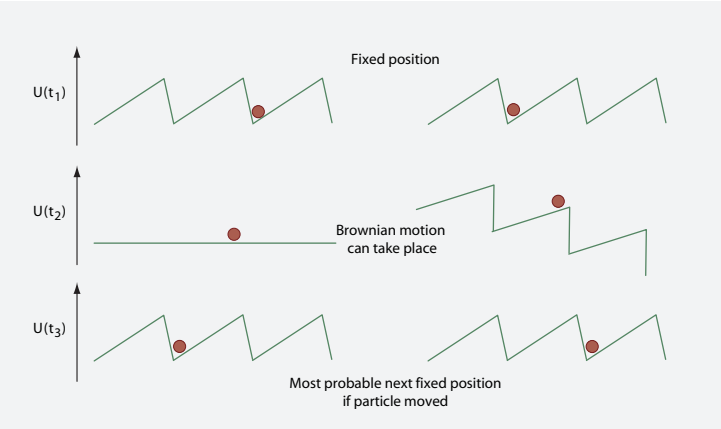


FIGURE 6 Two types of Brownian motors: switching potential (left) and tilting potential (right).

motion is one of the great wonders of nature.

Evolution is smart: with three tricks it takes advantage of Brownian motion and transforms it into macroscopic motion. (Molecular motors are therefore also called *Brownian motors*.) The first trick of evolution is the use of an asymmetric, but periodic potential, a so-called *ratchet*.* The second trick of evolution is a temporal variation of the potential of the ratchet, together with an energy input to make it happen. The two most important realizations are shown in Figure 6. Molecular motors thus work away from thermal equilibrium. The third trick is to take a large number of these molecular motors and to add their effects.

Ref. 7

The periodic potential variation in a molecular motor ensures that for a short, recurring time interval the free Brownian motion of the moving molecule – typically 1 µm/s – affects its position. Subsequently, the molecule is fixed again. In most of the short time intervals of free Brownian motion, the position will not change. But if the position does change, the intrinsic asymmetry of the ratchet shape ensures that with high probability the molecule advances in the preferred direction. (The animation of Figure 4 lacks this irregularity.) Then the molecule is fixed again, waiting for the next potential change. On average, the myosin molecule will thus move in one direction. Nowadays the motion of single molecules can be followed in special experimental set-ups. These experiments confirm that muscles use such a ratchet mechanism. The ATP molecule adds energy to the system and triggers the potential variation through the shape change it induces in the myosin molecule. Nature then takes millions of these ratchets together: that is how our muscles work.

Engineering and evolution took different choices. A moped contains one motor. An expensive car contains about 100 motors. A human contains at least 10^{16} motors.

Challenge 7 e

* It was named after Ratchet Gearloose, the famous inventor from Duckburg.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

S

Sills

Sills, K.R. 400
Simon, Julia 412
Simpson, A.A. 386
Singhal, R.P. 404
Singleton, D. 396
Singleton, Douglas 412
Sirlin, A. 403
Skrbek, L. 392
Slabber, André 412
Sloterdijk, Peter 200
Smale, S. 406
Smale, Stephen 292
Smith, D.E. 408
Smith, Eric 35
Smolin, L. 408
Snyder, Bill 214, 415
Socha, J.J. 408
Socha, Jake 309, 413
Soddy 180
Sokolov, Arsenji 147
Solomatin, Vitaliy 412
Solomon, R. 411
Sossinsky, Alexei 408
Sparenberg, Anja 392
Sparnaay, M.J. 393
Sparnaay, Marcus 124
Spencer, R. 388
Spicer, G. 406
Spies, C. 398
Sriramkumar 131
Sriramkumar, L. 394
Srygley, R.B. 405
Srygley, Robert 279, 416
Stasiak, A. 407, 408
Steinhardt, P.J. 390
Steinhardt, Paul 414
Stewart, I. 407
Stix, M. 400
Stoeferle, Th. 395
Stoehlker, Th. 394
Stone, Michael 405
Stormer, H.L. 392
Story, Don 413
Stosch, Heinz-Günther 399
Stowe, Timothy 390
Strassmann, Fritz 188
Strauch, S. 402
Strelkov, A.V. 395
Strippoli, P. 387
Strohm, C. 392
Stutz, Phil 388
Stückelberg, Ernst 189
Su, B. 392
Sudarshan, George 50, 219, 254
Sudbury Neutrino Observatory 257
Sugamoto, A. 406
Sullivan, J.M. 407
Sullivan, John 292, 293, 416
Sundaram, B. 389
Surdin, Vladimir 412
Svoboda, Robert 202
Svozil, K. 394
Swiecki, Rafal 390

T

Tafreshi, Babak 117, 415
Tait, Peter 309
Tajima, T. 396
Takamoto, M. 409
Takita, A. 393
Tamm, Igor 212
Tanaka, Y. 386
Tantalos 352
Tanton, James 411
tapperboy 99, 414
Tarko, Vlad 412
Tassani, S. 387
Taylor 219
Taylor, B.N. 409
Taylor, J.H. 409
Taylor, John R. 409
Taylor, R.E. 401
Taylor, W.R. 407
Taylor, William 307
Tegelaar, Paul 412
Teichgräber, U. 398
Teller, Edward 191
Tennekes, Henk 405
Terence, in full Publius Terentius Afer 15
Terentius Afer, Publius life 15
Ternov, Igor 147
Terpiłowski, K. 392
Thaler, Jon 412
Thiele, U. 408
Thies, Ingo 412
Thistlethwaite, M. 407
Thomas, A.L.R. 405
Thomas, Adrian 279, 416
Thomson-Kelvin, William 309
Thor 356
Thorne, Kip S. 397
Thurston, William 368
Thurston, William P. 293
Tiggelen, Bart van 392
Tipler, Frank J. 408
Tomonaga Shin'ichiro 220
life 127
Townsend, Paul 412, 413
Tozaki, K.-I. 391
Tozer, Jason 15, 413
Traser 241, 415
Treille, D. 404
Treimer, W. 396
Tretter, Felix 389
Trevorrow, Andrew 413
Trotec Laser 120
Tschichold, Jan 388
Tschira, Klaus 413
Tsubota, M. 392
Tsui, D.C. 392
Tuppen, Lawrence 412
Turing, Alan 50

U

Udem, T. 410
Uguzzoni, Arnaldo 412
Unknown 195
Unruh, W.G. 396, 397
Unruh, William 146, 148, 149, 151
Upright, Craig 412
Uranus 356
Urban, M. 395, 399

V

Valentin, Karl 67
life 44
Van, J. Tran Thanh 403
Vanadis 356
Vanier, J. 409
Vannoni, Paul 412
Varoquaux, E. 394

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

P

Pupko

Pupko, T. 387
Purcell, E. 405
Purves, William 412
Putterman, E. 406
Puttonen, E. 387
Puttonen, Eetu 36, 37
PVATePla 414
Pyykkö, P. 389

R
Röntgen, Conrad 165
Raby, S. 404
Rademacher, G. 398
Radzikowski, M. 159, 398
Rahtz, Sebastian 413
Raizen, M.G. 389
Raizen, Mark 50
Rajaraman, R. 405
Randi, James 408
Rankl, Wolfgang 412
Rao, S.M. 389
Rauch, H. 396
Rauch, Helmut 142, 415
Rawdon, E. 407
Raymer, D.M. 408
Raz, O. 406
Rector, J.H. 391
Redondi, Pietro 412
Regge, Tullio 229
Řeháček, J. 389
Reichert, J. 410
Reinhardt, Joseph 176, 415
Renselle, Doug 412
Reppisch, Michael 412
Reus, Ferdinand 16, 413
Revzen, M. 394
Richardson, Robert C. 104
Rikken, G.L.J.A. 392
Rikken, Geert 96, 392
Rimini, A. 398
Ritchie, R. 391
Rith, Klaus 398
Rivas, Martin 412
Roberts, M. 394
Robertson, Will 413
Roentgen, Conrad 354
Roman, T.A. 159, 398
Roos, B.O. 390
Rosenzweig, W.D. 387
Rosu, H. 396
Roukes, M.L. 391, 394
Rowland, Sherwood 67
Roy 124
Roy, A. 393
Royal Philips Electronics 163, 415
Royal Society 169, 415
Rubbia, Carlo 243
Ruben, Gary 412
Rudolph, Peter 412
Rueckner, Wolfgang 413
Ruess, F. 395
Ruess, F.J. 395
Ruffini 153
Ruffini, R. 397
Rummel, J.D. 387
Rushall, Brent 306
Russell, Mike 35
Rutherford 180
Rutherford, Ernest 169, 354
  life 167
Rušin, Vojtech 205, 415
Rüffer, U. 406

S
S.R. Madhu Rao 412
Sabbadini, Roger 22, 413
Sade, Donatien de
  life 278
Saghian, Damoon 412
Saitou, T. 391
Sakharov, Andrei 212
Salam, Abdus 269
  life 256
Sale, Jeff 22, 413
Sally, P. 411
Salmonson, J.D. 397
Samarski, Wassily 354
Saminadayar, L. 392
San Diego State University 22, 413
Sandage, Allan 218
Sander, C. 404
Sanger, Frederick 103
Sarazin, X. 399
Satake Ichiro 368
Scharein, Robert 302, 306, 416
Scharnhorst, K. 394
Schedin, F. 392
Schiller, Britta 412, 413
Schiller, C. 396
Schiller, Christoph 416
Schiller, Isabella 412
Schiller, P. 407
Schiller, Peter 412
Schiller, Stephan 412
Schirotzek, Andre 105, 414
Schmidt, M. 397
Scholz, Christoph 398
Schrieffer, J. Robert 103
Schrieffer, J.R. 392
Schrödinger, Erwin 62
Schunck, N. 399
Schuster, S.C. 406
Schwab, K. 391, 394
Schwarzschild, Bertram 394
Schwinger 127
Schwinger, Julian 127
Schäfer, Andreas 401
Schützhold, R. 397
Scott, Jonathan 412
Seaborg, Glenn 354
Seeger, A. 407
Seidelmann, P. Kenneth 410
Seidl, Benedikt 101, 414
Seidl, Erwin 142, 415
Seidl, T. 391
Send, W. 405
Send, Wolfgang 405
Sender, R. 387
Senior, A.E. 386
Sepp, Siim 70, 413
Shaevitz, J.W. 406
Shakespeare, William 100
Shapere, A. 406
Shapere, Alfred 289
Shapiro, Arnold 292
Sheldon, Eric 412
Sherrill, B.M. 410
Shihorocho Agricultural Cooperative Isotope Irradiation Center 198
Shockley, William 103
Siart, Uwe 413
Siegenthaler, U. 391
Sierra, Bert 412
Silchenko, Artem 288, 416

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 7 A classical ratchet, here of the piezoelectric kind, moves like a linear molecular motor (© PiezoMotor).

Another well-studied linear molecular motor is the kinesin–microtubule system that carries organelles from one place to the other within a cell. Like in the previous example, also in this case chemical energy is converted into unidirectional motion. Researchers were able to attach small silica beads to single molecules and to follow their motion. Using laser beams, they could even apply forces to these single molecules. Kinesin was found to move with around 800 nm/s, in steps lengths which are multiples of 8 nm, using one ATP molecule at a time, and exerting a force of about 6 pN.

Quantum ratchet motors do not exist only in living systems; they also exist as human-built systems. Examples are electrical ratchets that move single electrons and optical ratchets that drive small particles. These applications are pursued in various experimental research programmes.

Also *classical* ratchets exist. One example is found in every mechanical clock; also many ballpoint pens contain one. Another example of ratchet with asymmetric of mechanical steps uses the Leidenfrost effect to rapidly move liquid droplets, as shown in the video www.thisiscolossal.com/2014/03/water-maze. A further example is shown in Figure 7; indeed, many piezoelectric actuators work as ratchets and the internet is full of videos that show how they work. Piezoelectric ratchets, also called *ultrasound motors*, are found in precision stages for probe motion and inside certain automatic zoom objectives in expensive photographic cameras. Also many atomic force microscopes and scanning electron microscopes use ratchet actuators.

Vol. I, page 375

Molecular motors are essential for the growth and the working of nerves and the brain. A nerve contains large numbers of dozens of molecular motors types from all three main families: dynein, myosin and kinesin. These motors transport chemicals, called 'cargos', along axons and all have loading and unloading mechanisms at their ends. They are necessary to realize the growth of nerves, for example from the spine to the tip of the toes. Other motors control the growth of synapses, and thus ensure that we have long-term memory. Malfunctioning molecular motors are responsible for Alzheimer disease, Huntington disease, multiple sclerosis, certain cancers and many other diseases due either to genetic defects or to environmental poisons.

Ref. 8

In short, without molecular motors, we could neither move nor think.

A rotational molecular motor: ATP synthase

In cells, the usual fuel for most chemical reactions is adenosine triphosphate, or ATP. In plants, most ATP is produced on the membranes of cell organelles called *chloroplasts*, and in animal cells, in the so-called *mitochondria*. These are the power plants in most cells. ATP also powers most bacteria. It turns out that ATP is synthesized by a protein

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

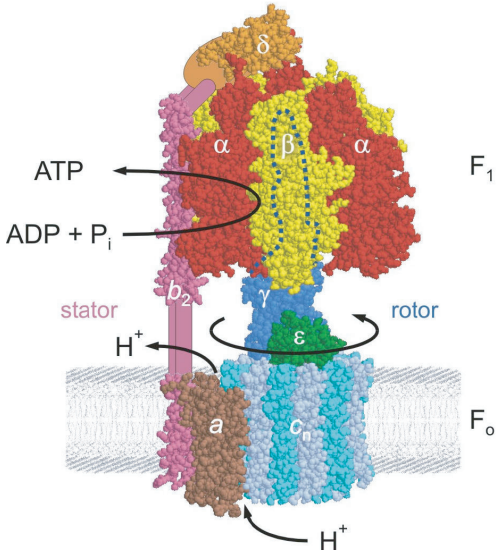


FIGURE 8 The structure of ATP synthase (© Joachim Weber).

located in membranes. The protein is itself powered by protons, H^+, which form the basic fuel of the human body, whereas ATP is the high-level fuel. For example, most other molecular motors are powered by ATP. ATP releases its energy by being changed into to adenosine diphosphate, or ADP. The importance of ATP is simple to illustrate: every human synthesizes, during a typical day, an amount of ATP that is roughly equal to his or her body mass.

The protein that synthesizes ATP is simply called *ATP synthase*. In fact, ATP synthase differs slightly from organism to organism; however, the differences are so small that they can be neglected in most cases. (An important variation are those pumps where Na^+ ions replace protons.) Even though ATP synthase is a highly complex protein, its function it easy to describe: it works like a *paddle wheel* that is powered by a proton gradient across the membrane. Figure 8 gives an illustration of the structure and the process. The research that led to these discoveries was rewarded with the 1997 Nobel Prize in Chemistry.

Ref. 9

In fact, ATP synthase also works in the reverse: if there is a large ATP gradient, it pumps protons out of the cell. In short, ATP synthase is a rotational motor and molecular pump at the same time. It resembles the electric starting motor, powered by the battery, found in the older cars; in those cars, during driving, the electric motor worked as a dynamo charging the battery. (The internet also contains animations of the rotation of ATP syn-

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

N

NABARRO

N
Nabarro, Frank R.N. 407
Nair, R.R. 392
Nakahara, Mikio 411
Nakazato, H. 389
Nambu, Y. 403
Nambu, Yoichiro 253
Namiki, M. 389
Namouni, Fathi 412
Narison, Stephan 401
NASA 206, 214, 415
National Academy of Sciences 98
Nauenberg, M. 400
Neddermeyer, Seth 172
Nelson, Bradley 279
Nesvizhevsky, V.V. 395, 396
Neto, A.C. 392
Neumaier, Heinrich 412
Neve, Erik de 293
Newell, D.B. 409
Niepraschk, Rolf 413
Nieuwpoort, Frans van 412
NIH 55, 413
Niobe 352
Niot, I. 387
Nishida, N. 393
Niu, Q. 389
Niwa, S. 386
NOAA 16
Nobel Foundation 249, 416
Nobel, Alfred 352
nobodythere 281, 416
Noecker, M.C. 403
Nogueira, Zé 294, 416
Nojiri, S. 406
Nollert, H.-P. 397
Norrby, L.J. 389
Northrop Grumman 414
Nouvian, Claire 35
Novikov, Igor 397
Novoselov, K.S. 392
Nutsch, W. 406

O
O'Dempsey, T. 408
Oberdiek, Heiko 413
Oberquell, Brian 412
Oerlemans, H. 391
Österlöf, Aksel 82, 414
Offner, Carl 412
Okada, Y. 386
Olive, David 273
Olovnikov, Alexei 42
Oostrum, Piet van 412
Ortlepp, Christine 306, 416
Osheroff, Douglas D. 104
Oskay, W.H. 389
Ott, V.R. 387
Overhauser, A.W. 396
Ovidius, in full Publius Ovidius Naro 48

P
Pacific Institute of Theoretical Physics 104, 414
Packard, R.E. 394
Page, Don 155, 156, 412
Page, Don N. 397, 398
Pagliarin, A. 400
Pahaut, Serge 412
Pahnke, Jens 67
Pais, Abraham 189
Palmer, John D. 388
Parks, David 412
Pascazio, S. 389
Pascazio, Saverio 50, 389, 412
Pasi, Enrico 412
Passilly-Degrace, P. 387
Pati 269
Patris, B. 387
Paul, Wolfgang 171
Pauli, Wolfgang 224, 241
Pauling, Linus 388
Peeters, Bert 412
Peirce, Benjamin 358
Pelleri, M.C. 387
Pennsylvania Game Commission 281, 416
Pepper, M. 392
Perelman, Grigori 376
Peres, N.M. 392
Perez-Amodio, S. 387
Perini, Romano 412
Perkins, Donald H. 401
Perros, Georges 42
Pešić, P.D. 389
Peters, A. 396
Petit, J.-P. 407
Petit, J.R. 391
Petoukhov, A.K. 395
Petrov, G.A. 395
Petukhov, A.K. 395, 396
Pfeifer, N. 387
Pfennigbauer, M. 387
Pfenning, M.J. 159, 398
Phillips, A. 407
Phillips, M.J. 387
Physik Journal 92
Piatek, M. 407
Picciotto, R. de 392
Pieranski, P. 407
Pieranski, Piotr 304, 416
PiezoMotor 25
Pimpinelli, A. 390
Pines, David 104
Pinto, Fabrizio 125
Piovesan, A. 387
Pitnick, S. 406
Piva, F. 387
Plato 388
Plouin, F. 399
PNAS 306, 416
Polder, D. 393
Politzer, David 232
Pontecorvo, Bruno 257
Popov, V.S. 403
Pouillet, Claude 200
Povh, Bogdan 398
Powell, Cecil 172
Powell, R. 387
Powers, D.W. 387
Powers, T.R. 405
Preparata, G. 397
Prescott, James W. 389
Press, Hans J. 387
Prevedelli, M. 410
Price, Richard H. 397
Prichard, Uriah 414
Prigogine, Ilya 42
Pritchard, Carol 412
Proença, Nuno 412
Prometheus 353
Protasov, K.V. 395, 396
Prout, William 170
Pruppacher, H.R. 408
Przybyl, S. 407

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

L

Laughlin

Laughlin, Robert 107
Lavinsky, Rob 75–78, 80, 82, 414
Lawrence, Ernest 350
Lawson, J.D. 400
Lawson, John 212
Le, A. 395
Leblanc, J. 410
Ledingham, K.W.D. 404
Ledingham, Ken 259
Lee Tsung-Dao 245
Lee, David M. 104
Lee, J.Y. 406
Lee, K.K.M. 390
Leibfried, G. 407
Leiderer, P. 390
Leifi Physik 102
Leinaas 147
Leppmaier, Max 390
Lestienne, R. 399
Leucippus 240, 267, 324
Leutwyler, H. 401
Levine, Peter A. 387
Levy, S. 407
Li, M. 390
Liang, Y. 391
Libby, Willard 184
Lie, Sophus 361
  life 369
Lie groups, non-linear 370
Lifshitz, E.M. 124, 393
Light, Michael 400
Linde, Johan 413
Lintel, Harald van 412
Lipps, Binie Ver 64
Livermore, Carol 89, 414
Lombardi, Luciano 412
Longo, M. 404
Lothe, J. 407
Lu, P.J. 390
Lucovac, L. 395
Lämmerzahl, C. 396
Läuger, Peter 386
Lüthi, D. 391
Lüthi, Dieter 95, 414

M

MacDonald, Douglas A. 397
Macmillan 283, 284, 416
Madison, K.W. 389
Magill, Joseph 399
Mahadevan, L. 283, 284, 405, 416
Mahoney, Alan 412
Maiman, Theodore 113
Maluszynski, M. 386
Mandlburger, G. 387
Mandula, J. 405
Mann, A. 394
Mann, A.K. 403
Mann, J.C. 392
Mansfield, Peter 193
Mao, Y. 384
Marciano, W.J. 403
Marcillac, P. de 410
Marey, Etienne-Jules 288, 416
Maris, H. 393
Maris, Humphrey 117, 118, 413
Mark, M.B. van der 395
Mark, Martin van der 412
Markow, T.A. 406
Marques, F. 410
Martikainen, J.E. 409
Martin, A. 391
Martišek, Karel 205, 415
Martos, Antonio 412
Mason, W.P. 407
Masterson, B.P. 403
Max Planck Gesellschaft 90, 94, 414
Max Planck Institute for Gravitational Physics 209, 415
Maxwell, D. 407
Maxwell, James Clerk 320, 408
Mayer, A.R. 389
Mayné, Fernand 412
Mayr, Peter 412
McCammon, C. 390
McCrone, J. 388
McInerney, J.O. 387
McKenna, P. 404
McQuarry, George 412
Meekhof, D.M. 403
Meer, Simon van der 245
Meitner, Lise 188, 351
Mendeleyev, Dmitriy Ivanovich 351
Merrit, John 412
Metrolab 97, 414
Meyer, C.A. 402
Michaelson, P.F. 410
Michels, Barry 388
Miescher, Friedrich
  life 62
Mikiewicz, M. 399
Millerd, Tiffany 414
Milo, R. 387
Milonni, P.W. 394
Mineral, Trinity 78
Misawa, H. 393
Misra, Baidyanath 50
Mitalas, R. 400
Mitchell, Edgar 119
Młyńczak, J. 394
Moalic, J.-P. 410
Mohideen 124
Mohideen, U. 393
Mohr, P.J. 409
Molina, Mario 67
Monnin, E. 391
Montgomery, R. 406
Montie, E.A. 394, 395
Montmayeur, J.P. 387
Montonen, Claus 273
Moortel, Dirk Van de 412
Morin, B. 406, 407
Morin, Bernard 292
Morion Company 77, 414
Morozov, S.V. 392
Morrison, D. 387
Morrow, P.R. 389
Morré, D.J 388
Moser, Lukas Fabian 412
Mosna, R.A. 406
Mottelson, Ben 104
Mozart 41
Mukharsky, Yu. 394
Mullarkey, M. 387
Munzner, T. 407
Murdock, Ron 412
Murillo, Nadia 412
Mutka, Miles 412
Muynck, Wim de 412
Myers, R.C. 398
Müller, D. 395

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

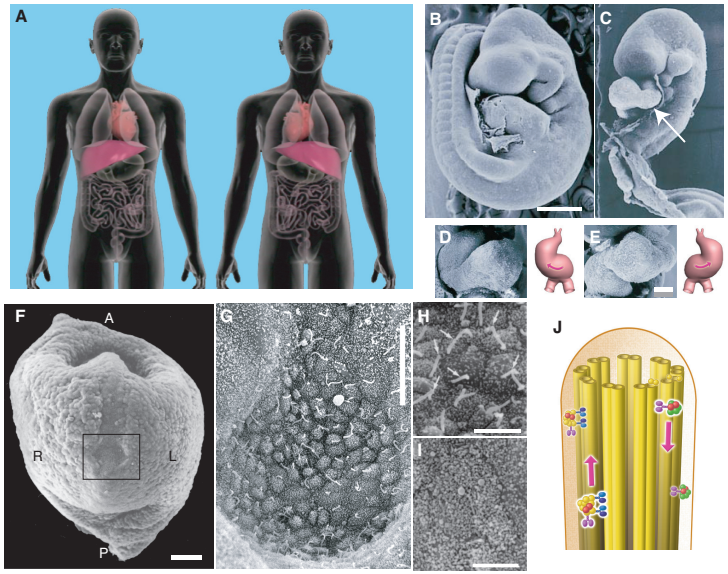


FIGURE 9 A: The asymmetric arrangement of internal organs in the human body: Normal arrangement, situs solitus, as common in most humans, and the mirrored arrangement, situs inversus. Images B to E are scanning electron micrographs of mouse embryos. B: Healthy embryos at this stage already show a right-sided tail. C: In contrast, mutant embryos with defective cilial motors remain unturned, and the heart loop is inverted, as shown by the arrow. D: Higher-magnification images and schematic representations of a normal heart loop. E: Similar image showing an inverted loop in a mutant embryo. Images F to I are scanning electron micrographs of a mouse node. F: A low-magnification view of a 7.5 day-old mouse embryo observed from the ventral side, with the black rectangle indicating the node. The orientation is indicated with the letters A for anterior, P for posterior, L for left and R for right; the scale bar is 100 µm. G: A higher-magnification image of the mouse node; the scale bar is 20 µm. H: A still higher-magnification view of healthy nodal cilia, indicated by arrows, and of the nodal pit cells; the scale bar is 5 µm. I: The nodal pit cells of mutant embryos lacking cilia. J: Illustration of the molecular transport inside a healthy flagellum (© Hirokawa Nobutaka).

thase.) ATP synthase has been studied in great detail. For example, it is known that it produces three ATP molecules per rotation, that it produces a torque of around $20kT/2\pi$, where kT is the kinetic energy of a molecule at temperature T. There are at least 10^{16} such motors in an adult body. The ATP synthase paddle wheel is one of the central building blocks of life.

Rotational motors and parity breaking

Why is our heart on the left side and our liver on the right side? The answer of this old question is known only since a few years. The left-right asymmetry, or chirality, of human

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

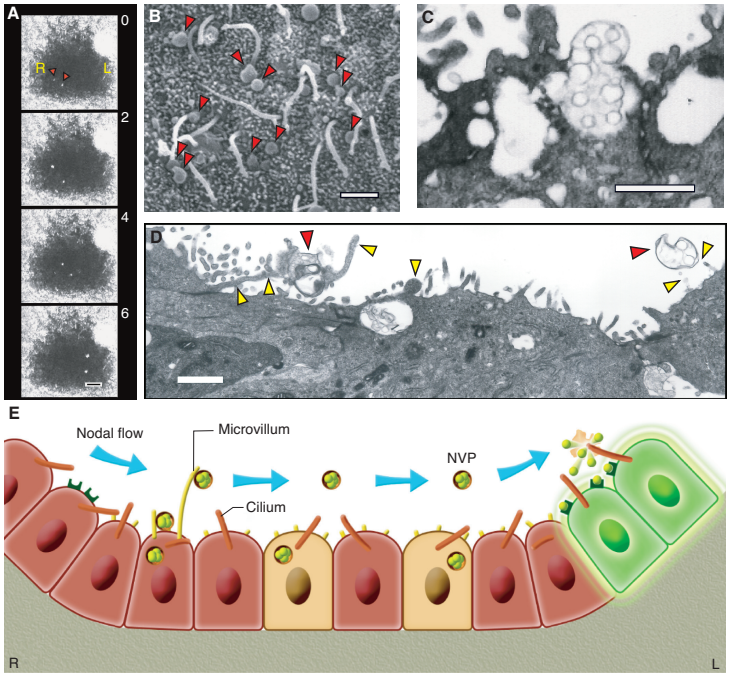


FIGURE 10 A: Optical microscope images of flowing nodal vesicular parcels (NVPs). L and R indicate the orientation. The NVPs, indicated by arrowheads, are transported to the left side by the nodal flow. The scale bar is 10 µm. B: A scanning electron micrograph of the ventral surface of nodal pit cells. The red arrowheads indicate NVP precursors. The scale bar is 2 µm. C and D: Transmission electron micrographs of nodal pit cells. The scale bar is 1 µm. E: A schematic illustration of NVP flow induced by the cilia. The NVPs are released from dynamic microvilli, are transported to the left side by the nodal flow due to the cilia, and finally are fragmented with the aid of cilia at the left periphery of the node. The green halos indicate high calcium concentration – a sign of cell activation that subsequently starts organ formation (© Hirokawa Nobutaka).

bodies must be connected to the chirality of the molecules that make up life. In all living beings, sugars, proteins and DNS/DNA are chiral molecules, and in all living beings, only one of the two molecular mirror types is actually used. But how does nature translate the chirality of molecules into the chirality of a body? The answer was deduced only recently by Hirokawa Nobutaka and his team; and surprisingly, rotational molecular motors are the key to the puzzle. Ref. 10

The position of the internal organs is fixed during the early development of the embryo. At an early stage, a central part of the embryo, the so-called *node*, is covered with

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

H

HOYLE

Hoyle, Fred 210, 218
Hradil, Z. 389
Hsich, T. 391
Huang, Kerson 401
Huber, A. 410
Huber, Daniel 412
Huiberts, J.N. 391
Hulet, Rand 105
Hungarian Academy of Sciences 415
Hänggi, P. 386
Hänsch, T.W. 395

I
IBM 63
Ikeda Kikunae 40
Inaba Hideaki 91
Inaba, H. 391
Indermühle, A. 391
Itano, W.M. 389
Ivanov, Igor 412
Ivry, R.B. 388

J
Jackson, John David 409
Jacobson, T. 407
Jacobson, Ted 298
Jaffe, R.L. 402
Jalink, Kim 412
Jamil, M. 412
Janek, Jürgen 412
Janka, H.T. 401
Janka, Thomas 415
Jarlskog, C. 403
Jarlskog, Cecilia 251
Jarvis, Dave 68, 413
Jefferson Lab 93, 414
Jensen, D. 408
Jeon, H. 404
Jiang, D. 392
Jiang, Z. 392
Jin, Deborah 105
Jin, Y. 392
Johansson, Mikael 412
Johnson, George 401
Joliot, Frédéric 192
Joliot-Curie, Irène 192
Jona–Lasinio, G. 403
Jones, Quentin David 412
Jones, Tony 409
Jones, Vaughan 303
Jong, Marc de 412
Joos, E. 398
Jordan, P. 404
Jordan, Pascual 259
Jouzel, J. 391
Joyce, James 219
Jüstel, T. 393

K
Köppe, Thomas 412
Kalache, K.D. 398
Kamerlingh Onnes, Heike 103
Kanno, S. 398
Kapitsa, Pyotr 103
Kara-Ivanov, M. 406
Kardar, M. 394
Kasparian, J. 393
Kasparov, Gary 17
Katori, H. 409
Katrin collaboration 241, 415
Kauffman, Lou 305
Kauffman, Louis H. 407
Kawamura, M. 406
Kay, B.S. 159, 398
Kells, W. 404
Kelu, Jonatan 412
Kendall 219
Kendall, H.W. 401
Kenneth, O. 393
Kenny, T. 391
Kepler, Johannes 73
Kesel, A.B. 391
Ketterle, Wolfgang 105, 414
Khan, S. 406
Khokhlov, Alexei R. 407
Khotkevich, V.V. 392
Kibble, T.W.B. 403, 404
Killing, Wilhelm 362
Kim, P. 392
Kippenhahn, R. 400
Kiss, Joseph 412
Klapdor, H.V. 403
Klaus Tschira Foundation 413
Klempt, E. 402
Kleppner, D. 390
Klett, J.D. 408
Klich, I. 394
Klitzing, K. von 392
Klitzing, Klaus von 107
Klocok, Ľubomír 205, 415
Klose, S. 397
Knight, R. 387
Kobayashi, H. 389
Kockel, B. 394
Koeman, N.J. 391
Kohshima, S. 389
Kolberg, Ulrich 298, 416
Kontorowa, T. 407
Koolen, Anna 412
Kopczyński, K. 394
Kopnin, N.B. 392
Kosack, Joe 281, 416
Kraus, Ute 145, 415
Kreimer, Dirk 137, 395
Krenn, G. 389
Krijn, Marcel 412
Kronig, R. de Laer 404
Krusius, M. 392
Królikowski, Jarosław 412
Kubala, Adrian 412
Kubicki, J. 394
Kuchiev, M.Yu. 398
Kuchiev, Michael 157
Kuroda, Paul 196
Kusner, R. 407
Kusner, R.B. 408
Kuzin, Pavel 412
Küster, Johannes 413

L
LaBarbera, M. 408
Laer Kronig, Ralph de 259
Lafrance, R. 398
Lamb, Willis life 125
Lambrecht, A. 393
Lamoreaux 124
Lamoreaux, S.K. 393
Langacker, P. 403
Larraza, A. 393
Laser Zentrum Hannover 109, 415
Lauber, C.L. 387
Lauga, E. 405
Laugerette, F. 387
Laughlin, R.B. 392

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

G
Gamow

Gamow, George 181, 213
Garanderie, A. de la 388
Garner, Wightman 56
Garwin, R.L. 400
Gauß, Carl-Friedrich 307
Gazzola, M. 405
Gearloose, Ratchet 24
Geiger, Hans 167
Geim, A.K. 392
Geim, Andre 98, 107, 392, 414
Gell-Mann, M. 401
Gell-Mann, Murray
life 219
Geluck, Philippe 364
Gennes, P.-G. de 407
Gennes, Pierre-Gilles de 407
Georgi, H. 404
Georgi, Renate 412
Geroch, Robert 148
Ghirardi, G.C. 50, 398
Giacosa, F. 402
Giessibl, F. 390
Giovannini, G. 400
Glashow, Sheldon 255
Glassey, Olivier 412
Glattli, D.C. 392
Gmelin 410
God, A. 399
Goldman, V.J. 392
Golestanian, R. 394
Golota, Ivan 96, 414
González, Antonio 412
Gooch, Van 43
Gordon, J.I. 387
Goriely, S. 401
Goss Levi, Barbara 386
Gossard, A.C. 392
Gottfried, Kurt 401
Gould, Stephen J. 410
Gour 131
Gour, G. 394
Graham, Geoff 387
Grahn, Alexander 413
Graur, D. 387
Gray, Theodore 61, 413
Greenland, P.T. 410
Gregorio, Enrico 413
Greiner, J. 397
Greiner, Jochen 152, 412
Greiner, Walter 401
Grevesse, N. 400
Griessen, R. 391
Griessen, Ronald 85, 414
Griffin, Scott 414
Groot, D.G. de 391
Grosberg, Alexander Yu. 407
Gross, B. 410
Gross, David 232
Grotz, K. 403
Grumman, Northrop 78
Grünberg, H.-H. von 390
GT Advanced 77, 414
Gu, T. 390
Guinea, F. 392
Guo, W. 393
Guo, Wei 117
Gupta, R. 402
Guralnik, G.S. 403
Gutiérrez-Medina, B. 389
Guéron, E. 406
Gácsi, Zoltán 412
Güttler, F. 398

H

Haan, Patrick Voss-de 390
Haber, John 412
Hadron Collider, Large 273
Hagen, C.R. 403
Hahn, Otto 188
Haken, Hermann 113
Hakonen, P.J. 409
Halberg, F. 388
Hales, Tom 73, 390
Haley, Stephen 412
Hall, Edwin
life 95
Halliday, A.N. 399
Hamady, M. 387
Hansma, P. 391
Hardcastle, Martin 412
Harrington, D.L. 389
Hartmann, D. 397
HAS 182
Hashimoto, H. 407
Hausch, T.W. 410
Hausherr, Tilman 412
Hawking, Stephen 147
Hayasaki, Y. 393
Hayashi, H. 391
Hayes, Allan 412
Heß, Viktor
life 172
Hebsgaard, M.B. 387
Heinzen, D.J. 389
Heisenberg, W. 394
Heisenberg, Werner 170
Hellinger, Bert 388
Helmond, Tom 412
Hemley, R. 391
Henderson, Paula 412
Henley, E.M. 402
Henrich, W. 398
Henriksen, E.A. 391, 394
Hertzlinger, Joseph 413
Herzog, W. 386
Heumann, John 412
Hicks, K. 403
Higashi, R. 409
Higgs, P.W. 403
Higgs, Peter 253, 258
Hilgevoord, Jan 389
Hillman, Chris 412
Hinkson, L. 398
Hirokawa Nobutaka 27, 28, 413
Hirokawa, N. 386
Hirshfeld, A.C. 408
Hirth, J.P. 407
Hite, Kevin 413
Hobbes, Thomas 41
Hoffman, Richard 412
Hogan, C.J. 408
Holdin, P. 408
Holst, Gilles 103
Hołysz, L. 392
Hong, F.-L. 409
't Hooft, Gerard 146, 232, 242, 269
Hooft, G.W. 't 395
Horgan, John 400
Hornak, Joseph 415
Hornak, Joseph P. 164
HortNET 282, 416
Hoste, J. 407
Houtermans, Friedrich (Fritz) 200, 208
Hoyle, F. 400

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

rotational cilia, i.e., rotating little hairs. They are shown in Figure 9. In fact, all vertebrates have a node at some stage of embryo development. The nodal cilia are powered by a molecular motor; they all rotate in the *same* (clockwise) direction about ten times per second. The rotation direction is a consequence of the chirality of the molecules that are contained in the motors. However, since the cilia are inclined with respect to the surface – towards the tail end of the embryo – the rotating cilia effectively move the fluid above the node towards the left body side of the embryo. The fluid of this newly discovered *nodal flow* contains substances – nodal vesicular parcels – that accumulate on the left side of the node and subsequently trigger processes that determine the position of the heart. If the cilia do not rotate due to a genetic defect, or if the flow is reversed by external means, the heart and other organs get misplaced. This connection also explains all the other consequences of such genetic defects or interventions.

In other words, through the rotation of the cilia and the mentioned mechanism, the chirality of molecules is mapped to the chirality of the whole vertebrate organism. It might even be that similar processes occur also elsewhere in nature, for example in the development of the brain asymmetry. This is still a field of intense research. In summary, molecular motors are truly central to our well-being and life.

Curiosities and fun challenges about biology

> Una pelliccia è una pelle che ha cambiato bestia.*
>
> Girolamo Borgogelli Avveduti

With modern microscopic methods it is possible to film, in all three dimensions, the evolution of the eye of a fruit fly until it walks away as a larva. Such a film allows to follow every single cell that occurs during the 20 hours: the film shows how cells move around during development and show every single cell division. Watch this amazing film, taken at the EMBL in Heidelberg, at youtu.be/MefTPoeVQ3w.

* *

Biological evolution can be summarized in three principles:

1. All living beings are different – also in a species.
2. All living beings have a tough life – due to competition.
3. Living beings with an advantage will survive and reproduce.

The last principle is often called the 'survival of the fittest'. As a result of these three principles, with each generation, *species and living beings can change*. The result of accumulated generational change is called *biological evolution*. In particular, these three principles explain the change from unicellular to multicellular life, from fish to land animals, and from animals to people.

Quantum effects are fundamental in all three principles of evolution. Of course, life and metabolism are quantum effects. The differences mentioned in the first principle are due to quantum physics: perfect copies of macroscopic systems are impossible. The second principle mentions competition; that is a kind of measurement, which, as we saw,

Vol. IV, page 121

* 'A *fur* is a skin that has changed beast.'

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Vol. IV, page 20 is only possible due to the existence of a quantum of action. The third principle mentions reproduction: that is again a quantum effect, based on the copying of genes, which are Page 18 quantum structures. In short, biological evolution is a process due to the quantum of action.

* *

Challenge 8 d How would you determine which of two identical twins is the father of a baby?

* *

Can you give at least five arguments to show that a human clone, if there will ever be one, Challenge 9 s is a completely different person than the original?

It is well known that the first ever cloned cat, *copycat*, born in 2002, looked completely different from the 'original' (in fact, its mother). The fur colour and its patch pattern were completely different from that of the mother. Analogously, identical human twins have different finger prints, iris scans, blood vessel networks and intrauterine experiences, among others.

Many properties of a mammal are not determined by genes, but by the environment of the pregnancy, in particular by the womb and the birth experience. Womb influences include fur patches, skin fold shapes, but also character traits. The influence of the birth experience on the character is well-known and has been studied by many psychologists.

* *

Discuss the following argument: If nature were classical instead of quantum, there would not be just *two* sexes – nor any other *discrete* number of them, as in some lower animals – but there would be a *continuous range* of them. In a sense, there would be an infinite Challenge 10 s number of sexes. True?

* *

Here is a well-known unanswered question on evolution: how did the first *kefir grains* form? Kefir grains produce the kefir drink when covered with milk for about 8 to 12 hours. The grains consist of a balanced mixture of about 40 types of bacteria and yeasts. All kefir grains in the world are related. But how did the first ones form, about 1000 years Challenge 11 r ago?

* *

Molecular motors are quite capable. The molecular motors in the sooty shearwater (*Puffinus griseus*), a 45 cm long bird, allow it to fly 74 000 km in a year, with a measured record of 1094 km a day.

* *

When the ciliary motors that clear the nose are overwhelmed and cannot work any more, they send a distress signal. When enough such signals are sent, the human body triggers the sneezing reaction. The sneeze is a reaction to blocked molecular motors.

* *

The growth of human embryos is one of the wonders of the world. The website embryo.

Motor Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motormountain.net

D

Derbyshire

Derbyshire, Sam 234
Derjaguin, B.W. 124, 393
Desari, R.R. 393
DESY 236, 415
Diamatrix 414
Diamatrix Ltd. 80
Diamond Materials GmbH 80, 414
Diener Electronics 99, 414
Dierking, Ingo 95, 392
Dietze, H. 407
Dietzel, Martin 205, 415
Diez, C. Alvarez 395
Diez, Ulrich 413
DiFilippo, Frank 412
Digital Globe 190
Dirac 144
Dirac, P. 404
Dirac, P.A.M. 394
Dirac, Paul 132, 394
Dirr, Ulrich 413
Divkovic, G. 395
Dixon, Bernard 406
Dmitriyev, V.P. 407
Dobra, Ciprian 412
Doe, Peter 82, 414
Dolto, Françoise 388
Dombrowski, H.J. 387
Dombrowski, Heinz 31
Dombrwoski, H.J. 387
Dorda, G. 392
Dragon, Norbert 412
Druckmüller, Miloslav 205, 415
Drury, L.O'C. 395
Dudek, J. 399
Dudenhausen, J.W. 398
Dumont, Jean-Paul 408
Durkin, L.S. 403
Dusenbery, David 406
Dyson, Freeman 127, 412
Dürr, S. 401

E

ed g2s 138, 415
EFDA-JET 211, 415
Efron, R. 389
Egedal, J. 395
Ehrlich, G. 390
Einstein, Albert 58, 113, 349, 388
Els, Danie 413
Elswijk, Herman B. 412
Eltsov, V.B. 392
Emelin, Sergei 412
Englert, F. 403
Enhag, Per 411
EOS 116, 415
Epicurus 57
ESA 214, 415
Escher, C. 390
Eshelby, J. 407
ESO 117, 415
Espiritu, Zach Joseph 412
Etheridge, D.M. 391
Etienne, B. 392
Euler, H. 394
Euler, M. 378
Everitt, C.W. 410
Exploratorium 23, 413
Eyring, Henry 90

F

Facchi, P. 389
Facchi, Paolo 389
Facchin, F. 387
Fairbanks, J.D. 410
Farinati, Claudio 412
Fearing, R. 391
Febbraio, M. 387
Fermani, Antonio 412
Fermi, Enrico 188, 349
Feynman 127
Feynman, Richard 127, 219
Field, M.S. 393
Fierer, N. 387
Fink, H.-W. 390
Fink, Hans-Werner 65, 73, 74, 413, 414
Fink, T. 384
Finkenzeller, Klaus 412
Finne, A.P. 392
Firestone, R.B. 410
Fisahn, Gert 414
Fischer, M.C. 389
Fischer, Ulrike 412
Fisher, Helen 56, 389
Fitch, Val 248
Flambaum, V.V. 398
Flato, M. 411
Fletcher, D.A. 406
Fleury, P. 399
Fonda, L. 50
Foong, S.K. 398
Ford, L.H. 159, 398
Forssman, Friedrich 388
Fowler, W. 400
Fox, D.W. 397
Frabetti, F. 387
Francis, G.K. 406
Francis, George 406
Frank, F.C. 407
Fratzl, P. 391
Fratzl, Peter 92, 414
Fray, S. 395
Frederick, Ann 387
Frenkel, J. 407
Freud, Sigmund 57
Freund, Peter G.O. 404
Friedman 219
Friedman, J.I. 401
Fritsch, H. 401
Fritzsch, Harald 401
Fu, J.H.G. 407
Fuchs, Manfred 77, 414
Fuchs, S. 387
Full, R.J. 391
Full, Robert 90
Fulle, Marco 185, 415
Fulling, S.A. 396
Fulling, Stephen 146
Furrie, Pat 412
Furukawa Yoshinori 74, 414
Furukawa, Y. 390
Fürstenau, H. 404

G

Gabrielse, G. 404
Gadolin, Johan 349
Gagarski, A.M. 395
Gagarsky, A.M. 395
Gagliardi, L. 390
Gagnon, Bernard 160, 415
Galileo Galilei 140
Galli, M. 400
Galy, Jean 399
Gamow, G. 400

Motor Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motormountain.net

B

BOEBINGER

Boebinger, G.S. 392
Boer, W. de 271, 404, 416
Boer, Wim de 404
Boerner, H.G. 395
Boersma, S.L. 393
Boersma, Sipko 122, 125
Bohr, Aage 104
Bohr, Niels 58, 347
Bollinger, J.J. 389
Bombelli, Luca 412
Bonner, John T. 386
Bonse, U. 396
Boone, Roggie 412
Booth, T. 392
Bordé, Ch.J. 396
Borgogelli Avveduti, Girolamo 29
Borin, A.C. 390
Born, M. 393
Borucki, M.K. 386
Bouchiat 246
Bouchiat, C.C. 403
Bouchiat, M.A. 403
Bousso 146
Bousso, R. 146, 396
Boyer, T.H. 393
Boyer, Timothy 125
Brackenbury, John 405
Brandelik, R. 402
Brandes, John 412
Brattain, Walter 103
Brebner, Douglas 412
Briese, C. 387
Bringhurst, Robert 388
Britten, R.J. 377
Britten, Roy 377
Bronshtein, Matvei 8
Brookhaven National Laboratory 249, 416
Brout, R. 403
Brown, S.L. 281, 416
Bruce, Tom 412
Bruckner, N. 394
Bruker 193, 415
Brunetti, M. 400
Bryant, D.A. 395
Buchmann, A.J. 402
Buchmann, Alfons 412
Buck, Linda 40
Budney, Ryan 412
Buehler, M.J. 391
Burbidge, G. 400
Burbidge, M. 400
Burke, D.L. 394
Burton 116
Burton Inc. 415
Busch, Wilhelm 386
Bémont, Gustave 165
Böhm, A. 403
Böhncke, Klaus 412
Bührer, C. 398

C

Cabibbo, Nicola 251
Canaider, S. 387
Cano, R.J. 386
Cantarella, J. 407
Cantarella, Jason 305, 416
Caplan, S.R. 406
Carlip, S. 396
Carlip, Steve 412
Carr, Jim 412
Casadei, R. 387
Casimir, H.B.G. 393
Casimir, Hendrik 124
Cecchini, S. 400
Ceramtec 79, 414
CERN 168, 221, 243–245, 276, 415, 416
CERN Courier 177
Chan, W.P. 391
Chandler, D.L. 395
Chang, J. 410
Chantell, M. 399
Charpak, G. 400
Chen, P. 396
Chibowski, L 392
Childs, J.J. 393
Chmela, Harald 173, 415
Christophe Afonso 138, 415
Chu, S. 396
Chung, K.Y. 396
Clark, R. 400
Clarke, T. 384
Clausius, Rudolph 145
Clery, D. 390
Close, F. 402
Cockcroft 238
Colazingari, Elena 412
Colella, R. 396
Coleman, S. 405
Colwell, Dave 285, 416
Conti, Andrea 412
Cooper, L.N. 392
Cooper, Leon N. 103
Cornell, Eric 105
Coron, N. 410
Corovic, Dejan 412
Cosman, E.C. 394, 395
Costello, E.K. 387
Cranswick, Lachlan 82, 414
Crede, V. 402
Cremer, M. 398
Crespi, Roberto 412
Creutz, Michael 402
Crockett, Allen 413
Cronin, James 248
Crutzen, Paul 67
Curie, Marie 103, 165, 349
Curie, Pierre 165, 349
Curtis, Jan 178, 415

D

Dahlman, John 412
Dalì, Salvador 47
Dalrymple, G.B. 399
Dalton, John 170
Dambier, G. 410
Damour 153
Damour, T. 397
Danecek, Petr 412
Darley, Vincent 413
Darre, Daniel 412
Darwin, Charles 388
Daughton, W. 395
Davies, P. 396
Davies, Paul 146
Deaver, B.S. 410
Deerfield, David 64, 413
Degasperis, A. 50
Dehmelt, H. 404
Dehmelt, Hans 404
Dehn, Max 303
Dekker, J.P. 391
Democritus 40, 240, 267, 323, 324
Denardo, B. 393

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

soad.umich.edu provides extensive data, photos, animations and magnetic resonance images on the growth process.

* *

Challenge 12 s Do birds have a navel?

* *

All animals with the possibility of regenerating themselves from a small piece, such as *Planaria*, reproduce asexually, by dividing. All animals that reproduce sexually are unable to regenerating the whole animal from a small part.

* *

Challenge 13 s All animals that move with limbs are left-right symmetric. Why?

* *

Many molecules found in living beings, such as sugar, have mirror molecules. However, in all living beings only one of the two sorts is found. Life is intrinsically asymmetric.

Challenge 14 s How can this be?

* *

How is it possible that the genetic difference between man and chimpanzee is regularly given as about 1 %, whereas the difference between man and woman is one chromosome

Challenge 15 s in 46, in other words, about 2.2 %?

* *

What is the longest time a single bacterium has survived? It is more than the 5000 years of the bacteria found in Egyptian mummies. For many years, the survival time was estimated to lie at over 25 million years, a value claimed for the bacteria spores resurrected

Ref. 11 from the intestines in insects enclosed in amber. Then it was claimed to lie at over 250 million years, the time estimated that certain bacteria discovered in the 1960s by Heinz Dombrowski in (low-radioactivity) salt deposits in Fulda, in Germany, have hibernated there before being brought back to life in the laboratory. A similar result has been recently claimed by the discovery of another bacterium in a North-American salt deposit

Ref. 12 in the Salado formation.

However, these values are now disputed, as DNA sequencing has shown that these bacteria were probably due to sample contamination in the laboratory, and were not part

Ref. 13 of the original sample. So the question of the longest survival time of bacteria is still open.

* *

In 1967, a TV camera was deposited on the Moon. Unknown to everybody, it contained a small patch of *Streptococcus mitis*. Three years later, the camera was brought back to Earth. The bacteria were still alive. They had survived for three years without food, water or air. Life can be resilient indeed. This widely quoted story is so unbelievable that it

Ref. 15 was checked again in 2011. The conclusion: the story is false; the bacteria were added by mistake in the laboratory after the return of the camera.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 2 Approximate numbers of living species.

Life group	Described species	Estimated species min.	Estimated species max.
Viruses	$4 \cdot 10^3$	$50 \cdot 10^3$	$1 \cdot 10^6$
Prokaryotes ('bacteria')	$4 \cdot 10^3$	$50 \cdot 10^3$	$3 \cdot 10^6$
Fungi	$72 \cdot 10^3$	$200 \cdot 10^3$	$2.7 \cdot 10^6$
Protozoa	$40 \cdot 10^3$	$60 \cdot 10^3$	$200 \cdot 10^3$
Algae	$40 \cdot 10^3$	$150 \cdot 10^3$	$1 \cdot 10^6$
Plants	$270 \cdot 10^3$	$300 \cdot 10^3$	$500 \cdot 10^3$
Nematodes	$25 \cdot 10^3$	$100 \cdot 10^3$	$1 \cdot 10^6$
Crustaceans	$40 \cdot 10^3$	$75 \cdot 10^3$	$200 \cdot 10^3$
Arachnids	$75 \cdot 10^3$	$300 \cdot 10^3$	$1 \cdot 10^6$
Insects	$950 \cdot 10^3$	$2 \cdot 10^6$	$100 \cdot 10^6$
Molluscs	$70 \cdot 10^3$	$100 \cdot 10^3$	$200 \cdot 10^3$
Vertebrates	$45 \cdot 10^3$	$50 \cdot 10^3$	$55 \cdot 10^3$
Others	$115 \cdot 10^3$	$200 \cdot 10^3$	$800 \cdot 10^3$
Total	$\mathbf{1.75 \cdot 10^6}$	$\mathbf{3.6 \cdot 10^6}$	$\mathbf{112 \cdot 10^6}$

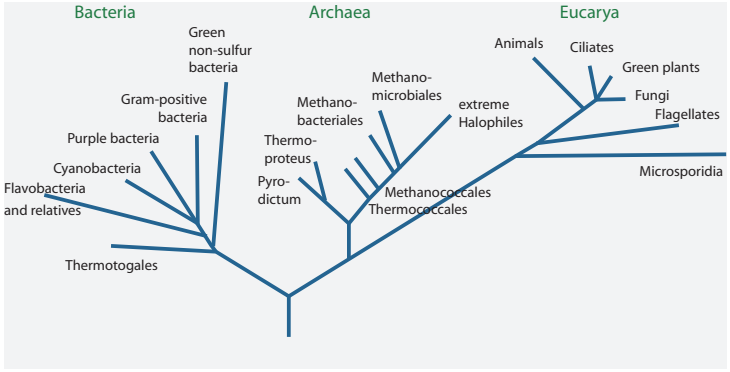


FIGURE 11 A modern version of the evolutionary tree.

* *

In biology, classifications are extremely useful. (This is similar to the situation in astrophysics, but in full contrast to the situation in physics.) Table 2 gives an overview of the magnitude of the task. This wealth of material can be summarized in one graph, shown in Figure 11. Newer research seems to suggest some slight changes to the picture. So far however, there still is only a single root to the tree.

Ref. 16

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

NAME INDEX

A
Abe

A
Abe, F. 402
Abele, H. 395, 396
Abele, Hartmut 141
Abrikosova, I.I. 124, 393
Adams, Douglas 323
Ahlgren, A. 388
Ahloowalia, B.S. 386
Aichinger, Franz 116, 415
Akhmedov, E.T. 396
Akhmedov, Emil 412
Albertus Magnus 268
Albus, Margot 389
Alcock, Nathaniel W. 411
Aleksandrov, D.V. 410
Allard, Harry 56
Allton, J.H. 387
Alpher, R.A. 400
Alt-Haddou, R. 386
Amaldi, U. 403, 404
Amenomori, M. 399
Amsler, C. 401
An, K. 393
Anders, E. 400
Anderson, Carl 172
Anderson, P.W. 403
Anderson, Philip 253
Aniol, Peter 205, 415
Anthony, P.L. 403
APS 74
Araki, T. 392
Argentina, M. 405
Argyres, P.C. 405
Aristotle 324, 408
Aronson, Jeff K. 409, 412
Arseneau, Donald 412
Arzt, Eduard 91
Ashby, Michael 89
Ashcroft, Frances 389
Ashton, T. 407
Asimov, I. 408
Astumian, R.D. 386
Ata Masafumi 412
Audoin, C. 409
Augel, Barbara 412
Augel, Edgar 412
Autumn, K. 391
Avenel, O. 394
Axel, Richard 40

B
Babinet, Jacques
  life 326
Baessler, S. 395, 396
Baez, John 412
Bagger, Jonathan 404
Bagnoli, Franco 412
Ball, P. 393
Bamberg, C. 164, 398, 415
Baranova, T.A. 395
Barberi Gnecco, Bruno 412
Bardeen, J. 392
Bardeen, John
  life 103
Barrow, John D. 408
Bartel, Elmar 19, 412, 413
Barton, G. 394
Bartussek, R. 386
Batchelor, George K. 407
Bauswein, A. 401
Bautista, Ferdinand 412
Beaty, William 412
Bechinger, C. 390
Becquerel, Henri
  life 165
Beeksma, Herman 412
Beenakker, C.W.J. 395
Bekenstein, J.D. 396
Bekenstein, Jacob 145, 147
Belfort, François 412
Belic, D. 409, 410
Bell 147
Benjah-bmm27 62, 413
Bennet, S.C. 403
Beraudi, A. 387
Berg, H.C. 406
Bergquist, J. 409
Bernard, C. 401
Berry, Michael 289
Bertulani, C.A. 410
Besnard, P. 387
Bessel, Friedrich 388
Bethe, H. 400
Bethe, Hans 200
  life 191
Bethke, S. 402
Bethke, Siegfried 232, 415
Beyer, Lothar 412
Bharucha, C.F. 389
Bianco, C.L. 397
Bianconi, E. 387
Bierce, Ambrose 46
Biggar, Mark 412
Bindi, L. 390
Bindi, Luca 80, 82, 414
Bird, D.J. 409
Blaauwgeers, R. 392
Blackett, Patrick 169, 415
Block, S.M. 386
blog.ioactive.com 101, 414
Blumensath, Achim 412

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

tesy of the Brookhaven National Laboratory; the measurement result is copyright and courtesy of the Nobel Foundation. The photograph of the Sudbury Neutrino Observatory on page 257 is courtesy and copyright SNO, and found on their website at www.sno.phy.queensu.ca/sno/images. The unification graph on page 271 is courtesy and copyright of W. de Boer and taken from his home page at www-ekp.physik.uni-karlsruhe.de/~deboer. The graph on unification on page 276 is courtesy and copyright of CERN. The picture of the butterfly in a wind tunnel on page 279 is courtesy and copyright of Robert Srygley and Adrian Thomas. On page 281, the picture of the vulture is courtesy and copyright of S.L. Brown from the website SLBrownPhoto.com; the picture of the hummingbird is courtesy and copyright of the Pennsylvania Game Commission and Joe Kosack and taken from the website www.pgc.state.pa.us; the picture of the dragonfly is courtesy and copyright of nobodythere and found on his website xavier.favre2.free.fr/coppermine. The pictures of feathers insects on page 282 are material used with kind permission of HortNET, a product of The Horticulture and Food Research Institute of New Zealand. The figures on page 283 and page 284 are copyright of L. Mahadevan and courtesy of Macmillan. The picture of the scallop on page 285 is courtesy and copyright of Dave Colwell. The historical cat photographs on page 288 are by Etienne-Jules Marey and have no copyright. The picture of cliff diver Artem Silchenko on page 288 is copyright of the World High Diving Federation, found at the web site www.whdf.com, and courtesy of Frederic Weill. The picture of the eversion of the sphere on page 292 is courtesy and copyright of John Sullivan and found on his *Optiverse* website on new.math.uiuc.edu/optiverse. The photograph of a waterspout on page 294 is copyright and courtesy of Zé Nogueira and found on his website at www.flickr.com/photos/zenog. The drawing of a mixed dislocation on page 298 has been produced especially for this text and is copyright and courtesy of Ulrich Kolberg. The knot and link diagrams on pages 302 and 306 are courtesy and copyright of Robert Scharein and taken from his website on www.knotplot.com. The images of the tight knots on page 304 are copyright and courtesy of Piotr Pieranski. The clasp images on page 305 is courtesy and copyright of Jason Cantarella. The photograph of a hagfish on page 306 is courtesy and copyright of Christine Ortlepp; it is also found on the web page www.lemonodor.com/scruz-2003-01-24/17m.shtml. The disordered knot images on page 306 are courtesy and copyright of PNAS. The MRI image on page 399 of a married couple is courtesy and copyright of Willibrord Weijmar Schultz. The photograph on the back cover, of a basilisk running over water, is courtesy and copyright by the Belgian group TERRA vzw and found on their website www.terravzw.org. All drawings are copyright by Christoph Schiller. If you suspect that your copyright is not correctly given or obtained, this has not been done on purpose; please contact me in this case.



Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

* *

Muscles produce motion through electrical stimulation. Can technical systems do the same? Candidate are appearing: so-called *electroactive polymers* change shape when they are activated with electrical current or with chemicals. They are lightweight, quiet and simple to manufacture. However, the first arm wrestling contest between human and artificial muscles, held in 2005, was won by a teenage girl. The race to do better is ongoing.

* *

Life is not a clearly defined concept. The definition used above, the ability to self-reproduce, has its limits. Can it be applied to old animals, to a hand cut off by mistake, to sperm, to ovules or to the first embryonal stages of a mammal? The definition of life also gives problems when trying to apply it to single cells. Can you find a better definition? Is
Challenge 16 e the definition of living beings as 'what is made of cells' useful?

* *

Every example of growth is a type of motion. Some examples are extremely complex. Take the growth of acne. It requires a lack of zinc, a weak immune system, several bacteria, as well as the help of *Demodex brevis*, a mite (a small insect) that lives in skin pores. With a size of 0.3 mm, somewhat smaller than the full stop at the end of this sentence, this and other animals living on the human face can be observed with the help of a strong magnifying glass.

* *

Humans have many living beings on board. For example, humans need bacteria to live. It is estimated that 90 % of the bacteria in the human mouth alone are not known yet; only about 1000 species have been isolated so far.

Ref. 17 Bacteria are essential for our life: they help us to digest and they defend us against illnesses due to dangerous bacteria. In fact, the number of bacteria in a human body is estimated to be $3.8(2.0) * 10^{13}$, more than 99 % of which are in the gut. The number of cells in a adult, average human body is estimated to be $3.0(0.3) * 10^{13}$ – of which 70 to 85 % are red blood cells. In short, a human body contains more bacteria than own cells! Nevertheless, the combined mass of all bacteria in a human body is estimated to be only around 0.2 kg, because gut bacteria are much smaller than human cells.

Of the around 100 groups of bacteria in nature, the human body mainly contains species from four of them: actinobacteria, bacteroidetes, firmicutes and proteobacteria. They play a role in obesity, malnutrition, heart disease, diabetes, multiple sclerosis, autism and many other conditions. These connections are an important domain of present research.

* *

How do trees grow? When a tree – biologically speaking, a *monopodal phanerophyte* – grows and produces leaves, between 40 % and 60 % of the mass it consists of, namely the water and the minerals, has to be lifted upwards from the ground. (The rest of the mass comes from the CO_2 in the air.) How does this happen? The materials are pulled upwards by the water columns inside the tree; the pull is due to the negative pressure that is created when the top of the column evaporates. This is called the *transpiration-cohesion-tension*

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

model. (This summary is the result of many experiments.) In other words, no energy is needed for the tree to pump its materials upwards.

Trees do not need energy to transport water. As a consequence, a tree grows purely by adding material to its surface. This implies that when a tree grows, a branch that is formed at a given height is also found at that *same* height during the rest of the life of that tree. Just check this observation with the trees in your garden.

Challenge 17 e

* *

Mammals have a narrow operating temperature. In contrast to machines, humans function only if the internal temperature is within a narrow range. Why? And does this requirement also apply to extraterrestrials – provided they exist?

Challenge 18 d

* *

How did the first cell arise? This important question is still open. As a possible step towards the answer, researchers have found several substances that spontaneously form closed membranes in water. Such substances also form foams. It might well be that life formed in foam. Other options discussed are that life formed underwater, at the places where magma rises into the ocean. Elucidating the origins of cells is one of the great open riddles of biology – though the answer will not be of much use.

Challenge 19 r

* *

Could life have arrived to Earth from outer space?

Challenge 20 s

* *

Is there life elsewhere in the universe? The answer is clear. First of all, there *might* be life elsewhere, though the probability is extremely small, due to the long times involved and the requirements for a stable stellar system, a stable planetary system, and a stable geological system. In addition, so far, all statements that claim to have detected an example were *lies*. Not mistakes, but actual lies. The fantasy of extraterrestrial life poses an interesting challenge to everybody: Why would an extraterrestrial being be of interest to you? If you can answer, realize the motivation in some other way, *now*, without waiting. If you cannot answer, do something else.

Challenge 21 e

* *

What could *holistic medicine* mean to a scientist, i.e., avoiding nonsense and false beliefs? Holistic medicine means treating illness with view on the whole person. That translates to four domains:

— *physical* support, to aid mechanical or thermal healing processes in the body;
— *chemical* support, with nutrients or vitamins;
— *signalling* support, with electrical or chemical means, to support the signalling system of the body;
— *psychological* support, to help all above processes.

When all theses aspects are taken care of, healing is as rapid and complete as possible. However, one main rule remains: *medicus curat, natura sanat*.*

* 'The physician helps, but nature heals.'

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

and found on their research website at cua.mit.edu/ketterle_group. The photograph of a laser delay line on page 109 is courtesy and copyright of the Laser Zentrum Hannover. The photograph of the violin on page 116 is copyright Franz Aichinger and courtesy of EOS. The figure of the floating display is copyright and courtesy of Burton Inc. and found on www.burton-jp.com. The photograph of the guide star laser on page 117 is courtesy and copyright of ESO and Babak Tafreshi. The photograph of the helium gyroscope on page 119 is courtesy and copyright of Eric Varoquaux. The pictures of rainbows on page 138 are courtesy and copyright of ed g2s, found on Wikimedia, and of Christophe Afonso, found on his beautiful site www.flickr.com/photos/chrisafonso21. The picture of neutron interferometers on page 142 is courtesy and copyright of Helmut Rauch and Erwin Seidl, and found on the website of the Atominstitut in Vienna at www.ati.ac.at. The simulated view of a black hole on page 145 is copyright and courtesy of Ute Kraus and can be found on her splendid website www.tempolimit-lichtgeschwindigkeit.de. The map with the γ ray bursts on page 152 is courtesy of NASA and taken from the BATSE website at www.batse.msfc.nasa.gov/batse. The baobab photograph on page 160 is copyright and courtesy of Bernard Gagnon and found on Wikimedia. The photograph of the MRI machine on page 163 is courtesy and copyright of Royal Philips Electronics. The MRI images of the head and the spine on page 163 are courtesy and copyright of Joseph Hornak and taken from his website www.cis.rit.edu/htbooks/mri. The image of the birth on page 164is courtesy and copyright of C. Bamberg. The photograph of the Big European Bubble Chamber on page 168 is courtesy and copyright of CERN. On page 169, the photograph of the Wilson cloud chamber is courtesy and copyright of Wiemann Lehrmittel; the picture of α rays taken by Patrick Blackett is courtesy and copyright of the Royal Society. The electroscope photograph on page 173 is courtesy and copyright of Harald Chmela and taken from his website www.hcrs.at. The photograph of Vicor Hess on page 174 has no known copyright. The photograph of the Geigerpod on page 176 is courtesy and copyright of Joseph Reinhardt, and found on his website flickr.com/photos/javamoose. The photograph of the Moon shadow on page 177 is courtesy and copyright of CERN and found on cerncourier.com/cws/article/cern/28658. The photograph of an aurora on page 178 is courtesy and copyright of Jan Curtis and taken from his website climate.gi.alaska.edu/Curtis/curtis.html. The photograph of the spectrometer on page 182 is courtesy and copyright of the Hungarian Academy of Sciences and found at www.atomki.hu/hekal/muszaki_hatter/ams_en.html. The figure of the Erta Ale volcano on page 185 is courtesy and copyright of Marco Fulle and part of the wonderful photograph collection at www.stromboli.net. The photograph of the NMR machine on page 193 is courtesy and copyright of Bruker and found on their website www.bruker.com. The stunning photographs of the solar corona on page 205 are copyright of Miloslav Druckmüller and his team, including Peter Aniol, Vojtech Rušin, Ľubomír Klocok, Karel Martišek and Martin Dietzel. The images are part of the fascinating site www.zam.fme.vutbr.cz/~druck/Eclipse/Index.htm and used here with the permission of Miloslav Druckmüller. The drawing on nucleic binding energies on page 209is courtesy and copyright of the Max Planck Institute for Gravitational Physics. The drawing of the JET reactor on page 211 is courtesy and copyright of EFDA-JET. On page 214, the photograph of the Crab nebula is courtesy NASA and ESA; the photograph of the Dumbbell nebula is courtesy and copyright Bill Snyder and was featured on apod.nasa.gov/apod/ap111227.html The graph of the nuclide abundances on page 216 is courtesy and copyright of Thomas Janka. The photograph of the Proton Synchroton on page 221 is copyright and courtesy of CERN. The drawing of the strong coupling constant on page page 232 is courtesy and copyright of Siegfried Bethke. The photograph of the quark jet on page 236 is courtesy and copyright of DESY. On page 241, the photograph of the watch is courtesy and copyright of Traser and found at www.traser.com; the spectrum is courtesy of the Katrin collaboration. The photographs of the neutrino collision on page 243 and of the W and Z boson experiments on page 244 and page 245 are courtesy and copyright ofCERN. On page 249, the photograph of the experimental set-up is copyright and cour-

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

site www.sandatlas.org. The photograph of the marble is a detail of the Rape of Proserpina by Gian Lorenzo Bernini and is courtesy of Wikimedia; the marble can be admired in the Galleria Borghese in Rome. The rhenium photographs on page 74 are courtesy of Hans-Werner Fink and copyright and courtesy of the American Physical Society; they are found at journals.aps.org/prl/abstract/10.1103/PhysRevLett.52.1532. The pictures of snow flakes on page 74 are courtesy and copyright of Furukawa Yoshinori; his website is www.lowtem.hokudai.ac.jp/~frkw/index_e.html. The mineral photographs on page 75 onwards are copyright and courtesy of Rob Lavinsky at irocks.com, and taken from his large and beautiful collection there and at www.mindat.org/photo-49529.html. The photograph of natural corundum on page 76, the malachite photograph on page 172 and the magnetite photograph on page page 174 are copyright and courtesy of Stephan Wolfsried and taken from his beautiful collection of microcrystals at www.mindat.org/user-1664.html. The photograph of synthetic corundum on page 77 is copyright of the Morion Company at www.motioncompany.com and courtesy of Uriah Prichard. The photograph of Paraiba tourmalines on page page 77 is copyright and courtesy of Manfred Fuchs and found on his website at www.tourmalinavitalis.de. The photograph of the large corundum single crystal, usually falsely called 'sapphire', is cortesy and copyright of GT Advanced and found on www.gtat.com. The synthetic crystals photographs on page 78 and later are copyright of Northrop Grumman and courtesy of Scott Griffin. The alexandrite photographs on page 78 are copyright and courtesy of John Veevaert and Trinity Mineral Co., trinityminerals.com. The photograph of PZT – lead zirconium titanate – products on page 79 is copyright and courtesy of Ceramtec. The photograph of synthetic diamond on page 80 is copyright and courtesy of Diamond Materials GmbH. The photograph of a diamond knife on page 80 is copyright and courtesy of Diamatrix. The photographs of the silicon crystal growing machines and of the resulting silicon crystals on page 81 are copyright of PVATePla at www.PVATePla.com, and are used by kind permission of Gert Fisahn. The photograph of hydroxylapatite on page 82 is copyright and courtesy of Aksel Österlöf. The shark teeth photograph on page 82 is courtesy and copyright of Peter Doe and found at www.flickr.com/photos/peteredin. The photograph of a copper single crystal on page 82 is courtesy and copyright of Lachlan Cranswick. The photographs of the natural quasicrystal and its propeties on page 82 are copyright and courtesy of Luca Bindi and Paul Steinhardt. The photograph and drawings of a switchable mirror on page 85 are courtesy and copyright Ronald Griessen and found on his website www.nat.vu.nl/~griessen. The drawing of an Ashby chart on page 89 is courtesy and copyright of Carol Livermore; it is found in the MIT OpenCourseWare course materials for 6.777J / 2.372J *Design and Fabrication*. The insect leg images on page 90 are copyright and courtesy of the Max Planck Gesellschaft and found in the cited article. The photographs of bone structure on page 92 is courtesy of Peter Fratzl and copyright of him and Physik Journal. The photograph of a bystander with light and terahertz waves on page 93 are courtesy of the Jefferson Lab. The climate graph on page 95 is copyright and courtesy of Dieter Lüthi. The images of crystal growth techniques on page 96 are copyright of the Ivan Golota and used with his permission and that of Andrey Vesselovsky. The photograph of a Hall probe on page 97 is courtesy and copyright Metrolab, and found on their website at www.metrolab.com. The collection of images of single atom sheets on page 98 is taken from Ref. 73, copyright of the National Academy of Sciences, and are courtesy of the authors and of Tiffany Millerd. The graphene photograph on page 98 is copyright and courtesy of Andre Geim. The photographs on page 99 are copyright and courtesy of tapperboy and Diener Electronics. The photograph of a piece of aerogel on page 100 is courtesy of NASA. The photograph of transistors on page 101 is copyright and courtesy of Benedikt Seidl and found on Wikimedia; the chip image is copyright and courtesy of the Ioactive blog at blog.ioactive.com. The photograph of the fountain effect on page 104 is courtesy and copyright of the Pacific Institute of Theoretical Physics. The photograph of a vortex lattice on page 105 is copyright of Andre Schirotzek, courtesy of Wolfgang Ketterle,

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

* *

Life is, above all, beautiful. For example, the book by Claire Nouvian, *The Deep: The Extraordinary Creatures of the Abyss*, presented at www.press.uchicago.edu/books/nouvian/index.html allows one to savour the beauty of life deep in the ocean.

* *

What are the effects of *environmental pollution* on life? Answering this question is an intense field of modern research. Here are some famous stories.

Page 195

— Herbicides and many genetically altered organisms kill bees. For this reason, bees are dying (since 2007) in the United States; as a result, many crops – such as almonds and oranges – are endangered there. In countries where the worst herbicides and genetically modified crops have been banned, bees have no problems. An example is France, where the lack of bees posed a threat to the wine industry.
— Chemical pollution leads to malformed babies. In mainland China, one out of 16 children is malformed for this reason (in 2007). In Japan, malformations have been much reduced – though not completely – since strict anti-pollution laws have been passed.
— Radioactive pollution kills. In Russia, the famous Lake Karachay had to be partly filled with concrete because its high radioactivity killed anybody that walked along it for an hour.
— Smoking kills – though slowly. Countries that have lower smoking rates or that have curbed smoking have reduced rates for cancer and several other illnesses.
— Eating tuna is dangerous for your health, because of the heavy metals it contains.
— Cork trees are disappearing. The wine industry has started large research programs to cope with this problem.
— Even arctic and antarctic animals have livers full of human-produced chemical poisons.
— Burning fossil fuels raises the CO_2 level of the atmosphere. This leads to many effects for the Earth's climate, including a slow rise of average temperature and sea level.

Ecological research is uncovering many additional connections. Let us hope that the awareness for these issues increases across the world.

* *

Some researchers prefer to define living beings as *self-reproducing* systems, others prefer to define them as *metabolic* systems. Among the latter, Mike Russell and Eric Smith propose the following definition of life: '*The purpose of life is to hydrogenate carbon dioxide.*' In other terms, the aim of life is to realize the reaction

$$CO_2 + 4\,H_2 \rightarrow CH_4 + 2\,H_2O\,. \qquad (1)$$

This beautifully dry description is worth pondering – and numerous researchers are indeed exploring the consequences of this view.

* *

Not only is death a quantum process, also aging is one. Research in the details of this vast

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

field is ongoing. A beautiful example is the loss of leaves in autumn. The loss is triggered by ethene, a simple gas. You can trigger leave loss yourself, for example by putting cut apples – a strong source of ethene – together with a rose branch in a plastic bag: the roses will lose their leaves.

* *

The reanimation of somebody whose heart and breathing stopped is an useful movement sequence, called *cardiopulmonary resuscitation*. Do learn it.

* *

New research has shown that motion is important to staying healthy. In particular, it is important to do sports, but it is even more important to reduce the time of being seated. People who sit many hours per day have increased risk to get diabetes, breast cancer, white mass reduction in the brain, dementia, and various other diseases. Research into the dangerous effects of sitting is still in its infancy. For example, research has shown that sitting in front of a tv, in front of a PC or in a car for many hours a day *cannot* be compensated by doing sport.

* *

To stay fit and to ensure that you feel fit, enjoy life and enjoy the books by Mark Verstegen.

* *

Which species of living being is the most successful, if we measure success as the species' biomass? This simple question has no known answer. Among animals, cattle (*Bos taurus*), humans (*Homo sapiens*) and Antarctic krill (*Euphasia superba*) have similar biomass values, but it is not clear whether these are the highest values. No good data seem to exist for plants – except for crops. It is almost sure that several species of bacteria, such as from the marine genus *Prochlorococcus* or some other bacteria species found in soil, and several species of fungi achieve much higher biomass values. But no reliable overview is available.

* *

Trees move in many interesting ways. For example, trees fight with their neighbours over space and access to light and nutrients. This occurs with most vehemence if the neighbour is of another species. Most trees do not like to be touched by other trees – but there are exceptions, such as beeches. For example, when beeches fight with oaks, after a few years, the oak is left with little space and light, and the beech has taken over most of it. But trees also help neighbours, for example in case of sickness, by providing nutrients and water. Many more fascinating stories about trees – including the way the communicate via aiborne chemical signals such as ethylene (ethene) – are told by Peter Wohlleben, *Das geheime Leben der Bäume: Was sie fühlen, wie sie kommunizieren – die Entdeckung einer verborgenen Welt*, Ludwig Verlag, 2015.

* *

Trees sleep at night and get up in the morning. The observation is known since centuries; a beautiful measurement of the effect, using a laser scanner, was performed by Eetu

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

right, Herbert Voss, Andrew Trevorrow, Danie Els, Heiko Oberdiek, Sebastian Rahtz, Don Story, Vincent Darley, Johan Linde, Joseph Hertzlinger, Rick Zaccone, John Warkentin, Ulrich Diez, Uwe Siart, Will Robertson, Joseph Wright, Enrico Gregorio, Rolf Niepraschk, Alexander Grahn and Paul Townsend.

The typesetting and book design is due to the professional consulting of Ulrich Dirr. The typography was much improved with the help of Johannes Küster and his Minion Math font. The design of the book and its website also owe much to the suggestions and support of my wife Britta.

I also thank the lawmakers and the taxpayers in Germany, who, in contrast to most other countries in the world, allow residents to use the local university libraries.

From 2007 to 2011, the electronic edition and distribution of the Motion Mountain text was generously supported by the Klaus Tschira Foundation.

Film credits

The animation of the actin–myosin system on page 22 is copyright and courtesy by San Diego State University, Jeff Sale and Roger Sabbadini. It can be found on the website www.sci.sdsu.edu/movies/actin_myosin.html. The film on page 118, showing single electrons moving through liquid helium, is copyright and courtesy of Humphrey Maris; it can be found on his website physics.brown.edu/physics/researchpages/cme/bubble. The film of the spark chamber showing the cosmic rays on page 176 is courtesy and copyright of Wolfgang Rueckner and Allen Crockett and found on isites.harvard.edu/icb. The film of the solar flare on page 206 was taken by NASA's TRACE satellite, whose website is trace.lmsal.com. The film of a flying snake on page 309 is copyright and courtesy by Jake Socha. It can be found on his website www.flyingsnake.org.

Image credits

The photograph of the east side of the Langtang Lirung peak in the Nepalese Himalayas, shown on the front cover, is courtesy and copyright by Kevin Hite and found on his blog thegettingthere.com. The photograph of a soap bubble on page 14 is courtesy and copyright of Jason Tozer for Creative Review/Sony; its making is described on creativereview.co.uk/crblog. The whale photograph on page 16 is courtesy by the NOAA in the USA. The photograph of a baobab with elephant is courtesy and copyright by Ferdinand Reus. The picture of the orchid on page 19 is courtesy and copyright of Elmar Bartel. The sea urchin photograph on page 23 was taken by Kristina Yu, and is copyright and courtesy of the Exploratorium, found at www.exploratorium.edu. The photograph of the piezoelectric motor on page 25 is courtesy and copyright of Piezomotor AB and is found on their website www.piezomotor.se. The beautiful illustration of ATP synthase on page 26 is courtesy and copyright of Joachim Weber and is found on his website www.depts.ttu.edu/chemistry/Faculty/weber. The images of embronic nodes on page 27 are courtesy and copyright by Hirokawa Nobutaka and found in the cited paper. The illustration of the pleasure system in the human brain on page 55 is courtesy of the NIH and can be found, e.g., on the website irp.drugabuse.gov/NRB/technical/RFCMRI.php. The wonderful table of the elements on page 61 is courtesy and copyright of Theodore Gray and is for sale at www.theodoregray.com. The image of the water molecule on page 62 is copyright of Benjah-bmm27 and is found on Wikimedia. The illustrations of DNA on page 64 are copyright and courtesy by David Deerfield and dedicated to his memory. They are taken from his website www.psc.edu/~deerfiel/Nucleic_Acid-SciVis.html. The images of DNA molecules on page 65 are copyright and courtesy by Hans-Werner Fink and used with permission of Wiley VCH. The beautiful illustration of star sizes on page 68 is courtesy and copyright of Dave Jarvis and found on Wikimedia. The photographs of rocks on page 70 are copyright and courtesy of Siim Sepp; they can be found on his wonderful web-

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

CREDITS

Acknowledgements

Many people who have kept their gift of curiosity alive have helped to make this project come true. Most of all, Peter Rudolph and Saverio Pascazio have been – present or not – a constant reference for this project. Fernand Mayné, Anna Koolen, Ata Masafumi, Roberto Crespi, Serge Pahaut, Luca Bombelli, Herman Elswijk, Marcel Krijn, Marc de Jong, Martin van der Mark, Kim Jalink, my parents Peter and Isabella Schiller, Mike van Wijk, Renate Georgi, Paul Tegelaar, Barbara and Edgar Augel, M. Jamil, Ron Murdock, Carol Pritchard, Richard Hoffman, Stephan Schiller, Franz Aichinger and, most of all, my wife Britta have all provided valuable advice and encouragement.

Many people have helped with the project and the collection of material. Most useful was the help of Mikael Johansson, Bruno Barberi Gnecco, Lothar Beyer, the numerous improvements by Bert Sierra, the detailed suggestions by Claudio Farinati, the many improvements by Eric Sheldon, the detailed suggestions by Andrew Young, the continuous help and advice of Jonatan Kelu, the corrections of Elmar Bartel, and in particular the extensive, passionate and conscientious help of Adrian Kubala.

Important material was provided by Bert Peeters, Anna Wierzbicka, William Beaty, Jim Carr, John Merrit, John Baez, Frank DiFilippo, Jonathan Scott, Jon Thaler, Luca Bombelli, Douglas Singleton, George McQuarry, Tilman Hausherr, Brian Oberquell, Peer Zalm, Martin van der Mark, Vladimir Surdin, Julia Simon, Antonio Fermani, Don Page, Stephen Haley, Peter Mayr, Allan Hayes, Norbert Dragon, Igor Ivanov, Doug Renselle, Wim de Muynck, Steve Carlip, Tom Bruce, Ryan Budney, Gary Ruben, Chris Hillman, Olivier Glassey, Jochen Greiner, squark, Martin Hardcastle, Mark Biggar, Pavel Kuzin, Douglas Brebner, Luciano Lombardi, Franco Bagnoli, Lukas Fabian Moser, Dejan Corovic, Paul Vannoni, John Haber, Saverio Pascazio, Klaus Finkenzeller, Leo Volin, Jeff Aronson, Roggie Boone, Lawrence Tuppen, Quentin David Jones, Arnaldo Uguzzoni, Frans van Nieuwpoort, Alan Mahoney, Britta Schiller, Petr Danecek, Ingo Thies, Vitaliy Solomatin, Carl Offner, Nuno Proença, Elena Colazingari, Paula Henderson, Daniel Darre, Wolfgang Rankl, John Heumann, Joseph Kiss, Martha Weiss, Antonio González, Antonio Martos, André Slabber, Ferdinand Bautista, Zoltán Gácsi, Pat Furrie, Michael Reppisch, Enrico Pasi, Thomas Köppe, Martin Rivas, Herman Beeksma, Tom Helmond, John Brandes, Vlad Tarko, Nadia Murillo, Ciprian Dobra, Romano Perini, Harald van Lintel, Andrea Conti, François Belfort, Dirk Van de Moortel, Heinrich Neumaier, Jarosław Królikowski, John Dahlman, Fathi Namouni, Paul Townsend, Sergei Emelin, Freeman Dyson, S.R. Madhu Rao, David Parks, Jürgen Janek, Daniel Huber, Alfons Buchmann, William Purves, Pietro Redondi, Douglas Singleton, Emil Akhmedov Damoon Saghian, Zach Joseph Espiritu, Miles Mutka, plus a number of people who wanted to remain unnamed.

The software tools were refined with extensive help on fonts and typesetting by Michael Zedler and Achim Blumensath and with the repeated and valuable support of Donald Arseneau; help came also from Ulrike Fischer, Piet van Oostrum, Gerben Wierda, Klaus Böhncke, Craig Up-

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

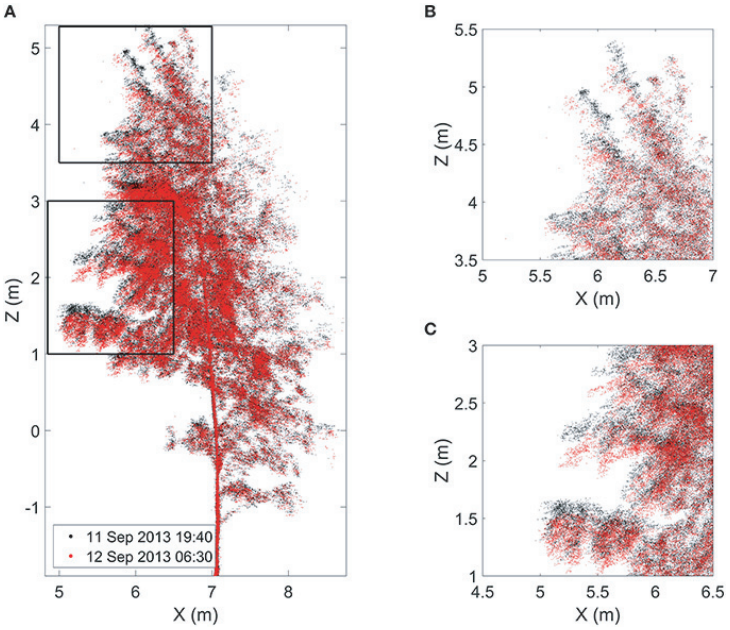


FIGURE 12 Branch and leaf position of a birch at the end of the day (black) and in the early morning (red), with magnified sections shown on the right (© Eetu Puttonen et al.).

Ref. 18 Puttonen and his group. Their results, shown in Figure 12, show that the height of a typical birch branch and its leaves in the early morning is up to 10 cm lower than during the day. The measurements also show that the trees move most in the early morning, when they wake up. The origin of these effects seems to be the difference of water intake during day and night.

THE PHYSICS OF PLEASURE

> What is mind but motion in the intellectual sphere?
>
> Oscar Wilde, *The Critic as Artist.*

Pleasure is a quantum effect. The reason is simple. Pleasure comes from the senses. All senses measure. And all measurements rely on quantum theory.

The human body, like an expensive car, is full of sensors. Evolution has built these sensors in such a way that they trigger pleasure sensations whenever we do with our

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

body what we are made for. Of course, no researcher will admit that he studies pleasure. Therefore the researcher will say that he or she studies the senses, and that he or she is doing *perception research*. But pleasure and all human sensors exist to let life continue. Pleasure is highest when life is made to continue. In the distant past, the appearance of new sensors in living systems has always had important effects of evolution, for example during the Cambrian explosion.

Research into pleasure and biological sensors is a fascinating field that is still evolving; here we can only have a quick tour of the present knowledge.

The *ear* is so sensitive and at the same time so robust against large signals that the experts are still studying how it works. No known sound sensor can cover an energy range of 10^{13}; indeed, the detected sound intensities range from $1\,\mathrm{pW/m^2}$ (some say $50\,\mathrm{pW/m^2}$) to $10\,\mathrm{W/m^2}$, the corresponding air pressures vary from $20\,\mu\mathrm{Pa}$ to 60 Pa. The lowest intensity that can be heard is that of a 20 W sound source heard at a distance of 10 000 km, if no sound is lost in between. Audible sound wavelengths span from 17 m (for 20 Hz) to 17 mm (for 20 kHz). In this range, the ear, with its 16 000 to 20 000 hair cells and 30 000 cochlear neurons, is able to distinguish at least 1500 pitches. But the ear is also able to distinguish nearby frequencies, such as 400 and 401 Hz, using a special pitch sharpening mechanism.

The *eye* is a position dependent photon detector. Each eye contains around 126 million separate detectors on the retina. Their spatial density is the highest possible that makes sense, given the diameter of the lens of the eye. They give the eye a resolving power of $1'$, or 0.29 mrad, and the capacity to consciously detect down to 60 *incident* photons in 0.15 s, or 4 *absorbed* photons in the same time interval.

Each eye contains 120 million highly sensitive general light intensity detectors, the *rods*. They are responsible for the mentioned high sensitivity. Rods cannot distinguish colours. Before the late twentieth century, human built light sensors with the same sensitivity as rods had to be helium cooled, because technology was not able to build sensors at room temperature that were as sensitive as the human eye.

Vol. III, page 196

The human eye contains about 6 million not so sensitive colour detectors, the *cones*, whose distribution we have seen earlier on. The different chemicals in the three cone types (red, green, blue) lead to different sensor speeds; this can be checked with the simple test shown in Figure 13. The sensitivity difference between the colour-detecting cones and the colour-blind rods is the reason that at night all cats are grey.

Ref. 19

The images of the eye are only sharp if the eye constantly moves in small random motions. If this motion is stopped, for example with chemicals, the images produced by the eye become unsharp.

The eye also contains about 1 million retinal ganglion cells. All signals from the eye are transmitted through 1 million optical nerve fibres to a brain region, the virtual cortex, that contains over 500 million cells.

Human *touch sensors* are distributed over the skin, with a surface density which varies from one region to the other. The density is lowest on the back and highest in the face and on the tongue. The hand has about 17 000 tactile receptors, most of them at the finger tips. There are separate sensors for light touch (Meissner's corpuscles) and pressure (Merkel cells), for deformation (Ruffini corpuscles), for vibration (Pacinian corpuscles), and for tickling (unmyelinated fibers); there are additional separate sensors for heat, for

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

element. On the same topic, an incredibly expensive book with an equally bad layout is Per Enhag, *Encyclopedia of the Elements*, Wiley–VCH, 2004. Cited on page 346.

298 The atomic masses, as given by IUPAC, can be found in Pure and Applied Chemistry 73, pp. 667–683, 2001, or on the www.iupac.org website. For an isotope mass list, see the csnwww.in2p3.fr website. Cited on pages 346, 356, and 357.

299 The metallic, covalent and Van der Waals radii are from Nathaniel W. Alcock, *Bonding and Structure*, Ellis Horwood, 1999. This text also explains in detail how the radii are defined and measured. Cited on page 357.

300 M. Flato, P. Sally & G. Zuckerman (editors), *Applications of Group Theory in Physics and Mathematical Physics*, Lectures in applied mathematics, volume 21, American Mathematical Society, 1985. This interesting and excellent book is well worth reading. Cited on page 363.

301 For more puzzles, see the excellent book James Tanton, *Solve This – Math Activities for Studends and Clubs*, Mathematical Association of America, 2001. Cited on page 363.

302 For an introduction to topology, see for example Mikio Nakahara, *Geometry, Topology and Physics*, IOP Publishing, 1990. Cited on page 364.

303 An introduction to the classification theorem is R. Solomon, *On finite simple groups and their classification*, Notices of the AMS 42, pp. 231–239, 1995, also available on the web as www.ams.org/notices/199502/solomon.ps Cited on page 368.

304 A pedagogical explanation is given by C. G. Wohl, *Scientist as detective: Luis Alvarez and the pyramid burial chambers, the JFK assassination, and the end of the dinosaurs*, American Journal of Physics 75, pp. 968–977, 2007. Cited on page 378.



Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

constants resulting from an international adjustment and recommended for international use by the Committee on Data for Science and Technology (CODATA), a body in the International Council of Scientific Unions, which brings together the International Union of Pure and Applied Physics (IUPAP), the International Union of Pure and Applied Chemistry (IUPAC) and other organizations. The website of IUPAC is www.iupac.org. Cited on pages 334 and 401.

287 Some of the stories can be found in the text by N. W. Wise, *The Values of Precision*, Princeton University Press, 1994. The field of high-precision measurements, from which the results on these pages stem, is a world on its own. A beautiful introduction to it is J. D. Fairbanks, B. S. Deaver, C. W. Everitt & P. F. Michaelson, eds., *Near Zero: Frontiers of Physics*, Freeman, 1988. Cited on page 334.

288 For details see the well-known astronomical reference, P. Kenneth Seidelmann, *Explanatory Supplement to the Astronomical Almanac*, 1992. Cited on page 340.

289 See the corresponding reference in the first volume. Cited on page 341.

290 The proton charge radius was determined by measuring the frequency of light emitted by hydrogen atoms to high precision by T. Udem, A. Huber, B. Gross, J. Reichert, M. Prevedelli, M. Weitz & T. W. Hausch, *Phase-coherent measurement of the hydrogen 1S–2S transition frequency with an optical frequency interval divider chain*, Physical Review Letters **79**, pp. 2646–2649, 1997. Cited on page 342.

291 For a full list of isotopes, see R. B. Firestone, *Table of Isotopes, Eighth Edition, 1999 Update*, with CD-ROM, John Wiley & Sons, 1999. For a list of isotopes on the web, see the Corean website by J. Chang, atom.kaeri.re.kr. For a list of precise isotope masses, see the csnwww.in2p3.fr website. Cited on pages 343, 346, and 357.

292 The ground state of bismuth 209 was thought to be stable until early 2003. It was then discovered that it was radioactive, though with a record lifetime, as reported by P. de Marcillac, N. Coron, G. Dambier, J. Leblanc & J.-P. Moalic, *Experimental detection of α-particles from the radioactive decay of natural bismuth*, Nature **422**, pp. 876–878, 2003. By coincidence, the excited state 83 MeV above the ground state of the same bismuth 209 nucleus is the shortest known radioactive nuclear state. Cited on page 343.

293 For information on the long life of tantalum 180, see D. Belic & al., *Photoactivation of* $^{180}\mathrm{Ta}^{m}$ *and its implications for the nucleosynthesis of nature's rarest naturally occurring isotope*, Physical Review Letters **83**, pp. 5242–5245, 20 December 1999. Cited on page 343.

294 Stephen J. Gould, *The Panda's Thumb*, W.W. Norton & Co., 1980. This is one of several interesting and informative books on evolutionary biology by the best writer in the field. Cited on page 344.

295 F. Marques & al., *Detection of neutron clusters*, Physical Review C **65**, p. 044006, 2002. Opposite results have been obtained by B. M. Sherrill & C. A. Bertulani, *Proton-tetraneutron elastic scattering*, Physical Review C **69**, p. 027601, 2004, and D.V. Aleksandrov & al., *Search for resonances in the three- and four-neutron systems in the 7Li(7Li, 11C)3n and 7Li(7Li, 10C)4n reactions*, JETP Letters **81**, p. 43, 2005. No citations.

296 For a good review, see the article by P. T. Greenland, *Antimatter*, Contemporary Physics **38**, pp. 181–203, 1997. Cited on page 344.

297 Almost everything known about each element and its chemistry can be found in the encyclopaedic Gmelin, *Handbuch der anorganischen Chemie*, published from 1817 onwards. There are over 500 volumes, now all published in English under the title *Handbook of Inorganic and Organometallic Chemistry*, with at least one volume dedicated to each chemical

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 13 The different speed of the eye's colour sensors, the cones, lead to a strange effect when this picture (in colour version) is shaken right to left in *weak* light.

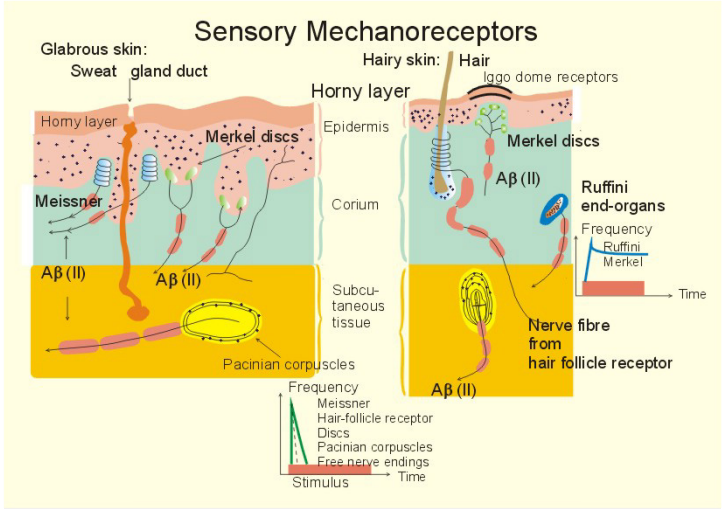


FIGURE 14 The five sensors of touch in humans, from the most to the least common ones: Meissner's corpuscles, Merkel cells, Ruffini corpuscles, Pacinian corpuscles and hair receptors.

coldness,* and for pain. Some of the sensors, whose general appearance is shown in Fig-

* There are *four* sensors for heat; one is triggered above 27°C, one above 31°C, one above 42°C, and one above 52°C. The sensor for temperatures above 42°C, TRPV1, is also triggered by capsaicin, the sharp chemical in chilli peppers.

There seems to be only *one* sensor for coldness, the ion channel TRPM8, triggered between 8 and 26°C. It is also triggered by menthol, a chemical contained in mojito and mint. Coldness neurons, i.e., neurons with TRPM8 at their tips, can be seen with special techniques using fluorescence and are known to arrive into the teeth; they provide the sensation you get at the dentist when he applies his compressed air test.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

ure 14, react proportionally to the stimulus intensity, some differentially, giving signals only when the stimulus changes. Many of these sensors are also found inside the body – for example on the tongue. The sensors are triggered when external pressure deforms them; this leads to release of Na^+ and K^+ ions through their membranes, which then leads to an electric signal that is sent via nerves to the brain.

The human body also contains *orientation sensors* in the ear, *extension sensors* in each muscle, and *pain sensors* distributed with varying density over the skin and inside the body.

The *taste sensor* mechanisms of tongue are only partially known. The tongue is known to produce six taste signals* – sweet, salty, bitter, sour, proteic and fatty – and the mechanisms are just being unravelled. The sense for proteic, also called *umami*, has been discovered in 1907, by Ikeda Kikunae; the sense for 'fat' has been discovered only in 2005. The tongue, palate and cheeks have about 10 000 taste buds, 90 % of which are on the tongue. Each taste bud has between 50 and 150 receptors; their diameter is around 10 µm.

Ref. 20

In ancient Greece, Democritus imagined that taste depends on the shape of atoms. Today it is known that sweet taste is connected with certain shape of molecules. Modern research is still unravelling the various taste receptors in the tongue. At least three different sweetness receptors, dozens of bitterness receptors, and one proteic and one fattiness receptor are known. In contrast, the sour and salty taste sensation are known to be due to ion channels. Despite all this knowledge, no sensor with a distinguishing ability of the same degree as the tongue has yet been built by humans. A good taste sensor would have great commercial value for the food industry. Research is also ongoing to find substances to block taste receptors; one aim is to reduce the bitterness of medicines or of food.

The *nose* has about 350 different smell receptors and a total of about 40 million receptor cells. (Dogs have 25 times more.) Through the possible combinations it is estimated that the nose can detect about 10 000 different smells.** Together with the six signals that the sense of taste can produce, the nose also produces a vast range of taste sensations. It protects against chemical poisons, such as smoke, and against biological poisons, such as faecal matter. In contrast, artificial gas sensors exist only for a small range of gases. Good artificial taste and smell sensors would allow checking wine or cheese during their production, thus making their inventor extremely rich. At the moment, humans, with all their technology at their disposal, are not even capable of producing sensors as good as those of a bacterium; it is known that *Escherichia coli* can sense at least 30 substances in its environment.

Challenge 23 ny

Other animals feature additional types of sensors. Sharks can *feel electrical fields*. Many snakes have *sensors for infrared light*, such as the pit viper or vampire bats. These sensors are used to locate prey or food sources. Some beetles, such as *Melanophila acuminata*, can also detect infrared; they use this sense to locate the wildfires they need to make their eggs hatch. Also other insects have such organs. Pigeons, trout and sharks can *feel*

Vol. III, page 32

* Taste sensitivity is *not* separated on the tongue into distinct regions; this is an incorrect idea that has been copied from book to book for over a hundred years. You can perform a falsification by yourself, using sugar or salt grains.

Challenge 22 s

** Linda Buck and Richard Axel received the 2004 Nobel Prize in Physiology or Medicine for their unravelling of the working of the sense of smell.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

British equivalent, www.npl.co.uk/npl/reference, is much better; it provides many details as well as the English-language version of the SI unit definitions. Cited on page 325.

274 The bible in the field of time measurement is the two-volume work by J. Vanier & C. Audoin, *The Quantum Physics of Atomic Frequency Standards*, Adam Hilge, 1989. A popular account is Tony Jones, *Splitting the Second*, Institute of Physics Publishing, 2000.

The site opdafl.obspm.fr/www/lexique.html gives a glossary of terms used in the field. For precision *length* measurements, the tools of choice are special lasers, such as mode-locked lasers and frequency combs. There is a huge literature on these topics. Equally large is the literature on precision *electric current* measurements; there is a race going on for the best way to do this: counting charges or measuring magnetic forces. The issue is still open. On *mass* and atomic mass measurements, see page 71 in volume II. On high-precision *temperature* measurements, see page 543 in volume I. Cited on page 326.

275 The unofficial SI prefixes were first proposed in the 1990s by Jeff K. Aronson of the University of Oxford, and might come into general usage in the future. See New Scientist **144**, p. 81, 3 December 1994. Other, less serious proposals also exist. Cited on page 327.

276 For more details on electromagnetic unit systems, see the standard text by John David Jackson, *Classical Electrodynamics*, 3rd edition, Wiley, 1998. Cited on page 330.

277 D.J. Bird & al., *Evidence for correlated changes in the spectrum and composition of cosmic rays at extremely high energies*, Physical Review Letters **71**, pp. 3401–3404, 1993. Cited on page 331.

278 P. J. Hakonen, R. T. Vuorinen & J. E. Martikainen, *Nuclear antiferromagnetism in rhodium metal at positive and negative nanokelvin temperatures*, Physical Review Letters **70**, pp. 2818–2821, 1993. See also his article in Scientific American, January 1994. Cited on page 331.

279 A. Zeilinger, *The Planck stroll*, American Journal of Physics **58**, p. 103, 1990. Can you find another similar example? Cited on page 331.

Challenge 211 e

280 An overview of this fascinating work is given by J. H. Taylor, *Pulsar timing and relativistic gravity*, Philosophical Transactions of the Royal Society, London A **341**, pp. 117–134, 1992. Cited on page 331.

281 The most precise clock built in 2004, a caesium fountain clock, had a precision of one part in 10^{15}. Higher precision has been predicted to be possible soon, among others by M. Takamoto, F.-L. Hong, R. Higashi & H. Katori, *An optical lattice clock*, Nature **435**, pp. 321–324, 2005. Cited on page 331.

282 J. Bergquist, ed., *Proceedings of the Fifth Symposium on Frequency Standards and Metrology*, World Scientific, 1997. Cited on page 331.

283 See the information on $D_s^{\pm}$ mesons from the particle data group at pdg.web.cern.ch/pdg. Cited on page 332.

284 About the long life of tantalum 180, see D. Belic & al., *Photoactivation of* ^{180}Ta^m *and its implications for the nucleosynthesis of nature's rarest naturally occurring isotope*, Physical Review Letters **83**, pp. 5242–5245, 20 December 1999. Cited on page 332.

285 The various concepts are even the topic of a separate international standard, ISO 5725, with the title *Accuracy and precision of measurement methods and results*. A good introduction is John R. Taylor, *An Introduction to Error Analysis: the Study of Uncertainties in Physical Measurements*, 2nd edition, University Science Books, Sausalito, 1997. Cited on page 333.

286 P. J. Mohr, B. N. Taylor & D. B. Newell, *CODATA recommended values of the fundamental physical constants: 2010*, preprint at arxiv.org/abs/1203.5425. This is the set of

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

262 Alexei Sossinsky, *Nœuds – histoire d'une théorie mathématique*, Editions du Seuil, 1999. D. Jensen, *Le poisson noué*, Pour la science, dossier hors série, pp. 14–15, April 1997. Cited on page 306.

263 D. M. Raymer & D. E. Smith, *Spontaneous knotting of an agitated string*, Proceedings of the National Academy of Sciences (USA) **104**, pp. 16432–16437, 2007, or www.pnas.org/cgi/doi/10.1073/pnas.0611320104. This work won the humorous Ignobel Prize in Physics in 2008; seeimprobable.com/ig. Cited on page 307.

264 A. C. Hirshfeld, *Knots and physics: Old wine in new bottles*, American Journal of Physics **66**, pp. 1060–1066, 1998. Cited on page 307.

265 For some modern knot research, see P. Holdin, R. B. Kusner & A. Stasiak, *Quantization of energy and writhe in self-repelling knots*, New Journal of Physics **4**, pp. 20.1–20.11, 2002. Cited on page 308.

266 H. R. Pruppacher & J. D. Klett, *Microphysics of Clouds and Precipitation*, Reidel, 1978, pp. 316–319. Falling drops are flattened and look like a pill, due to the interplay between surface tension and air flow. See also U. Thiele, *Weine nicht, wenn der Regen zerfällt*, Physik Journal **8**, pp. 16–17, 2009. Cited on page 308.

267 J. J. Socha, *Becoming airborne without legs: the kinematics of take-off in a flying snake, Chrysopelea paradisi*, Journal of Experimental Biology **209**, pp. 3358–3369, 2006, J. J. Socha, T. O'Dempsey & M. LaBarbera, *A three-dimensional kinematic analysis of gliding in a flying snake, Chrysopelea paradisi*, Journal of Experimental Biology **208**, pp. 1817–1833, 2005, J. J. Socha & M. LaBarbera, *Effects of size and behavior on aerial performance of two species of flying snakes (Chrysopelea)*, Journal of Experimental Biology **208**, pp. 1835–1847, 2005. A full literature list on flying snakes can be found on the website www.flyingsnake.org. Cited on page 309.

268 An informative account of the world of psychokinesis and the paranormal is given by the famous professional magician James Randi, *Flim-flam!*, Prometheus Books, Buffalo 1987, as well as in several of his other books. See also the www.randi.org website. No citations.

269 James Clerk Maxwell, *Scientific Papers*, **2**, p. 244, October 1871. Cited on page 320.

270 A good introduction is C. J. Hogan, *Why the universe is just so*, Reviews of Modern Physics **72**, pp. 1149–1161, 2000. Most of the material of Table 27 is from the mighty book by John D. Barrow & Frank J. Tipler, *The Anthropic Cosmological Principle*, Oxford University Press, 1986. Discarding unrealistic options is also an interesting pastime. See for example the reasons why life can only be carbon-based, as explained in the essay by I. Asimov, *The one and only*, in his book *The Tragedy of the Moon*, Doubleday, Garden City, New York, 1973. Cited on pages 320 and 383.

271 L. Smolin, *The fate of black hole singularities and the parameters of the standard models of particle physics and cosmology*, arxiv.org/abs/gr-qc/9404011. Cited on page 322.

272 Aristotle, *Treaty of the heaven*, III, II, 300 b 8. See Jean-Paul Dumont, *Les écoles présocratiques*, Folio Essais, Gallimard, p. 392, 1991. Cited on page 324.

273 *Le Système International d'Unités*, Bureau International des Poids et Mesures, Pavillon de Breteuil, Parc de Saint Cloud, 92310 Sèvres, France. All new developments concerning SI units are published in the journal *Metrologia*, edited by the same body. Showing the slow pace of an old institution, the BIPM launched a website only in 1998; it is now reachable at www.bipm.fr. See also the www.utc.fr/~tthomass/Themes/Unites/index.html website; this includes the biographies of people who gave their names to various units. The site of its

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

magnetic fields, and use this sense for navigation. Many birds and certain insects can *see UV light*. Bats and dolphins are able to *hear ultrasound* up to 100 kHz and more. Whales and elephants can detect and localize *infrasound* signals.

Vol. I, page 324

In summary, the sensors with which nature provides us are state of the art; their sensitivity and ease of use is the highest possible. Since all sensors trigger pleasure or help to avoid pain, nature obviously wants us to enjoy life with the most intense pleasure possible. Studying physics is one way to do this.

Ref. 21

> "There are two things that make life worth living: Mozart and quantum mechanics."
> Victor Weisskopf*

The nerves and the brain

> "There is no such thing as perpetual tranquillity of mind while we live here; because life itself is but motion, and can never be without desire, nor without fear, no more than without sense."
> Thomas Hobbes, *Leviathan*.

The main unit processing all the signals arriving from the sensors, the brain, is essential for all feelings of pleasure. The human brain has the highest complexity of all brains known.** In addition, the processing power and speed of the human brain is still larger than any device build by man.

We saw already earlier on how electrical signals from the sensors are transported into the brain. In the brain itself, the arriving signals are *classified* and *stored*, sometimes for a short time, sometimes for a long time. Most storage mechanisms take place in the structure and the connection strength between brain cells, the *synapses*, as we have seen. The process remaining to understand is the classification, a process we usually call *thinking*. For certain low level classifications, such as geometrical shapes for the eye or sound harmonies for the ear, the mechanisms are known. But for high-level classifications, such as the ones used in conceptual thinking, the aim is not yet achieved. It is not yet known how to describe the processes of reading or understanding in terms of signal motions. Research is still in full swing and will probably remain so for a large part of the twenty-first century.

Vol. I, page 314

Vol. III, page 261

In the following we look at a few abilities of our brain, of our body and of other bodies that are important for the types of pleasure that we experience when we study motion.

* Victor Friedrich Weisskopf (b. 1908 Vienna, d. 2002 Cambridge), acclaimed theoretical physicist who worked with Einstein, Born, Bohr, Schrödinger and Pauli. He catalysed the development of quantum electrodynamics and nuclear physics. He worked on the Manhattan project but later in life intensely campaigned against the use of nuclear weapons. During the cold war he accepted the membership in the Soviet Academy of Sciences. He was professor at MIT and for many years director of CERN, in Geneva. He wrote several successful physics textbooks. The author heard him making the above statement in 1982, during one of his lectures.

** This is not in contrast with the fact that a few *whale* species have brains with a larger mass. The larger mass is due to the protection these brains require against the high pressures which appear when whales dive (some dive to depths of 1 km). The number of neurons in whale brains is considerably smaller than in human brains.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Living clocks

> L'horologe fait de la réclame pour le temps.*
> Georges Perros

Vol. I, page 44 We have given an overview of living clocks already at the beginning of our adventure. They are common in bacteria, plants and animals. And as Table 3 shows, without biological clocks, neither life nor pleasure would exist.

When we sing a musical note that we just heard we are able to reproduce the original frequency with high accuracy. We also know from everyday experience that humans are Ref. 22 able to keep the beat to within a few per cent for a long time. When doing sport or when dancing, we are able to keep the timing to high accuracy. (For shorter or longer times, the internal clocks are not so precise.) All these clocks are located in the brain.

Brains process information. Also computers do this, and like computers, all brains need a clock to work well. Every clock is made up of the same components. It needs an *oscillator* determining the rhythm and a mechanism to feed the oscillator with energy. In addition, every clock needs an oscillation *counter*, i.e., a mechanism that reads out the clock signal, and a means of *signal distribution* throughout the system is required, synchronizing the processes attached to it. Finally, a clock needs a *reset mechanism*. If the clock has to cover many time scales, it needs several oscillators with different oscillation frequencies and a way to reset their relative phases.

Even though physicists know fairly well how to build good clocks, we still do not know many aspects of biological clocks. Most biological oscillators are chemical systems; some, Ref. 23 like the heart muscle or the timers in the brain, are electrical systems. The general elucidation of chemical oscillators is due to Ilya Prigogine; it has earned him a Nobel Prize for chemistry in 1977. But not all the chemical oscillators in the human body are known yet, not to speak of the counter mechanisms. For example, a 24-minute cycle inside each human cell has been discovered only in 2003, and the oscillation mechanism is not yet fully clear. (It is known that a cell fed with heavy water ticks with 27–minute instead of Ref. 24 24–minute rhythm.) It might be that the daily rhythm, the circadian clock, is made up of or reset by 60 of these 24–minute cycles, triggered by some master cells in the human body. The clock reset mechanism for the circadian clock is also known to be triggered by daylight; the cells in the eye who perform this resetting action have been pinpointed only in 2002. The light signal from these cells is processed by the superchiasmatic nuclei, two dedicated structures in the brain's hypothalamus. The various cells in the human body act differently depending on the phase of this clock.

The clocks with the longest cycle in the human body control *ageing*. One of the more famous ageing clock limits the number of divisions that a cell can undergo. Indeed, the number of cell divisions is finite for most cell types of the human body and typically lies between 50 and 200. (An exception are reproductory cells – we would not exist if they would not be able to divide endlessly.) The cell division counter has been identified; it is embodied in the *telomeres*, special structures of DNA and proteins found at both ends of each chromosome. These structures are reduced by a small amount during each cell division. When the structures are too short, cell division stops. The purely theoretical prediction of this mechanism by Alexei Olovnikov in 1971 was later proven by a number

* 'Clocks are ads for time.'

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

248 B. Morin & J.-P. Petit, *Le retournement de la sphere*, Pour la Science **15**, pp. 34–41, 1979. See also the clear article by A. Phillips, *Turning a surface inside out*, Scientific American pp. 112–120, May 1966. Cited on page 292.

249 S. Levy, D. Maxwell & T. Munzner, *Making Waves – a Guide to the Ideas Behind Outside In*, Peters, 1995. Cited on page 293.

250 George K. Batchelor, *An Introduction to Fluid Mechanics*, Cambridge University Press, 1967, and H. Hashimoto, *A soliton on a vortex filament*, Journal of Fluid Mechanics **51**, pp. 477–485, 1972. A summary is found in H. Zhou, *On the motion of slender vortex filaments*, Physics of Fluids **9**, p. 970-981, 1997. Cited on page 295.

251 V. P. Dmitriyev, *Helical waves on a vortex filament*, American Journal of Physics **73**, pp. 563–565, 2005, and V. P. Dmitriyev, *Mechanical analogy for the wave-particle: helix on a vortex filament*, arxiv.org/abs/quant-ph/0012008. Cited on page 296.

252 T. Jacobson, *Thermodynamics of spacetime: the Einstein equation of state*, Physical Review Letters **75**, pp. 1260–1263, 1995, or arxiv.org/abs/gr-qc/9504004. Cited on page 298.

253 J. Frenkel & T. Kontorowa, *Über die Theorie der plastischen Verformung*, Physikalische Zeitschrift der Sowietunion **13**, pp. 1–10, 1938. F. C. Frank, *On the equations of motion of crystal dislocations*, Proceedings of the Physical Society A **62**, pp. 131–134, 1949, J. Eshelby, *Uniformly moving dislocations*, Proceedings of the Physical Society A **62**, pp. 307–314, 1949. See also G. Leibfried & H. Dietze, Zeitschrift für Physik **126**, p. 790, 1949. A general introduction can be found in A. Seeger & P. Schiller, *Kinks in dislocations lines and their effects in internal friction in crystals*, Physical Acoustics **3A**, W. P. Mason, ed., Academic Press, 1966. See also the textbooks by Frank R. N. Nabarro, *Theory of Crystal Dislocations*, Oxford University Press, 1967, or J. P. Hirth & J. Lothe, *Theory of Dislocations*, McGraw Hills Book Company, 1968. Cited on page 299.

254 Enthusiastic introductions into the theoretical aspects of polymers are the books by Alexander Yu. Grosberg & Alexei R. Khokhlov, *Statistical Physics of Macromolecules*, AIP, 1994, and Pierre-Gilles de Gennes, *Scaling Concepts in Polymer Physics*, Cornell University Press, 1979. See also the review by P.-G. de Gennes, *Soft matter*, Reviews of Modern Physics **63**, p. 645, 1992. Cited on page 300.

255 The master of combining research and enjoyment in mathematics is Louis Kauffman. An example is his art is the beautiful text Louis H. Kauffman, *Knots and Physics*, World Scientific, third edition, 2001. It gives a clear introduction to the mathematics of knots and their applications. Cited on page 302.

256 A good introduction to knot tabulation is the paper by J. Hoste, M. Thistlethwaite & J. Weeks, *The first 1,701,936 knots*, The Mathematical Intelligencer **20**, pp. 33–47, 1998. Cited on page 303.

257 I. Stewart, *Game, Set and Math*, Penguin Books, 1989, pp. 58–67. Cited on page 303.

258 P. Pieranski, S. Przybyl & A. Stasiak, *Tight open knots*, arxiv.org/abs/physics/0103016. No citations.

259 T. Ashton, J. Cantarella, M. Piatek & E. Rawdon, *Self-contact sets for 50 tightly knotted and linked tubes*, arxiv.org/abs/math/0508248. Cited on page 304.

260 J. Cantarella, J. H. G. Fu, R. Kusner, J. M. Sullivan & N. C. Wrinkle, *Criticality for the Gehring link problem*, Geometry and Topology **10**, pp. 2055–2116, 2006, preprint at arxiv.org/abs/math/0402212. Cited on page 305.

261 W. R. Taylor, *A deeply knotted protein structure and how it might fold*, Nature **406**, pp. 916–919, 2000. Cited on page 307.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

235 Most bacteria are flattened, ellipsoidal sacks kept in shape by the membrane enclosing the cytoplasma. But there are exceptions; in salt water, quadratic and triangular bacteria have been found. More is told in the corresponding section in the interesting book by Bernard Dixon, *Power Unseen – How Microbes Rule the World*, W.H. Freeman, New York, 1994. Cited on page 286.

236 S. Pitnick, G. Spicer & T. A. Markow, *How long is a giant sperm?*, Nature **375**, p. 109, 1995. Cited on page 286.

237 M. Kawamura, A. Sugamoto & S. Nojiri, *Swimming of microorganisms viewed from string and membrane theories*, Modern Journal of Physics Letters A **9**, pp. 1159–1174, 1994. Also available as arxiv.org/abs/hep-th/9312200. Cited on page 286.

238 W. Nutsch & U. Rüffer, *Die Orientierung freibeweglicher Organismen zum Licht, dargestellt am Beispiel des Flagellaten Chlamydomonas reinhardtii*, Naturwissenschaften **81**, pp. 164–174, 1994. Cited on page 286.

239 They are also called *prokaryote flagella*. See for example S. C. Schuster & S. Khan, *The bacterial flagellar motor*, Annual Review of Biophysics and Biomolecular Structure **23**, pp. 509–539, 1994, or S. R. Caplan & M. Kara-Ivanov, *The bacterial flagellar motor*, International Review of Cytology **147**, pp. 97–164, 1993. See also the information on the topic that can be found on the website www.id.ucsb.edu:16080/fscf/library/origins/graphics-captions/flagellum.html. Cited on page 286.

240 For an overview of the construction and the motion of coli bacteria, see H. C. Berg, *Motile behavior of bacteria*, Physics Today **53**, pp. 24–29, January 2000. Cited on page 287.

241 J. W. Shaevitz, J. Y. Lee & D. A. Fletcher, *Spiroplasma swim by a processive change in body helicity*, Cell **122**, pp. 941–945, 2005. Cited on page 287.

242 This is from the book by David Dusenbery, *Life at a Small Scale*, Scientific American Library, 1996. Cited on page 287.

243 F. Wilczek & A. Zee, *Appearance of gauge structures in simple dynamical systems*, Physical Review Letters **52**, pp. 2111–2114, 1984, A. Shapere & F. Wilczek, *Self-propulsion at low Reynold number*, Physical Review Letters **58**, pp. 2051–2054, 1987, A. Shapere & F. Wilczek, *Gauge kinematics of deformable bodies*, American Journal of Physics **57**, pp. 514–518, 1989, A. Shapere & F. Wilczek, *Geometry of self-propulsion at low Reynolds number*, Journal of Fluid Mechanics **198**, pp. 557–585, 1989, A. Shapere & F. Wilczek, *Efficiencies of self-propulsion at low Reynolds number*, Journal of Fluid Mechanics **198**, pp. 587–599, 1989. See also R. Montgomery, *Gauge theory of the falling cat*, Field Institute Communications **1**, pp. 75–111, 1993. Cited on page 289.

244 E. Putterman & O. Raz, *The square cat*, American Journal of Physics **76**, pp. 1040–1045, 2008. Cited on page 289.

245 J. Wisdom, *Swimming in spacetime: motion by cyclic changes in body shape*, Science **299**, pp. 1865–1869, 21st of March, 2003. A similar effect was discovered later on by E. Guéron & R. A. Mosna, *The relativistic glider*, Physical Review D **75**, p. 081501(R), 2007, preprint at arxiv.org/abs/gr-qc/0612131. Cited on page 291.

246 S. Smale, *A classification of immersions of the two-sphere*, Transactions of the American Mathematical Society **90**, pp. 281–290, 1958. Cited on page 292.

247 G. K. Francis & B. Morin, *Arnold Shapiro's Eversion of the Sphere*, Mathematical Intelligencer pp. 200–203, 1979. See also the unique manual for drawing manifolds by George Francis, *The Topological Picturebook*, Springer Verlag, 1987. It also contains a chapter on sphere eversion. Cited on page 292.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 3 Examples of biological rhythms and clocks.

Living being	Oscillating system	Period
Sand hopper (*Talitrus saltator*)	knows in which direction to flee from the position of the Sun or Moon	circadian
Human (*Homo sapiens*)	gamma waves in the brain	0.023 to 0.03 s
	alpha waves in the brain	0.08 to 0.13 s
	heart beat	0.3 to 1.5 s
	delta waves in the brain	0.3 to 10 s
	blood circulation	30 s
	cellular circahoral rhythms	1 to 2 ks
	rapid-eye-movement sleep period	5.4 ks
	nasal cycle	4 to 14 ks
	growth hormone cycle	11 ks
	suprachiasmatic nucleus (SCN), circadian hormone concentration, temperature, etc.; leads to jet lag	90 ks
	skin clock	circadian
	monthly period	2.4(4) Ms
	built-in aging	3.2(3) Gs
Common fly (*Musca domestica*)	wing beat	30 ms
Fruit fly (*Drosophila melanogaster*)	wing beat for courting	34 ms
Most insects (e.g. wasps, fruit flies)	winter approach detection (diapause) by length of day measurement; triggers metabolism changes	yearly
Algae (*Acetabularia*)	Adenosinetriphosphate (ATP) concentration	
Moulds (e.g. *Neurospora crassa*)	conidia formation	circadian
Many flowering plants	flower opening and closing	circadian
Tobacco plant	flower opening clock (photoperiodism); triggered by length of days, discovered in 1920 by Garner and Allard	annual
Arabidopsis	circumnutation	circadian
	growth	a few hours
Telegraph plant (*Desmodium gyrans*)	side leaf rotation	200 s
Forsythia europaea, *F. suspensa*, *F. viridissima*, *F. spectabilis*	Flower petal oscillation, discovered by Van Gooch in 2002	5.1 ks

of researchers. (Only the latter received the Nobel Prize in medicine, in 2009, for this confirmation.) Research into the mechanisms and the exceptions to this process, such as cancer and sexual cells, is ongoing.

Not all clocks in human bodies have been identified, and not all mechanisms are

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

known. For example, basis of the monthly period in women is interesting, complex, and unclear.

Other fascinating clocks are those at the basis of *conscious* time. Of these, the brain's stopwatch or *interval timer* has been most intensely studied. Only recently was its mechanism uncovered by combining data on human illnesses, human lesions, magnetic resonance studies and effects of specific drugs. The basic interval timing mechanism takes Ref. 25 place in the striatum in the basal ganglia of the brain. The striatum contains thousands of timer cells with different periods. They can be triggered by a 'start' signal. Due to their large number, for small times of the order of one second, every time interval has a different pattern across these cells. The brain can read these patterns and learn them. In this way we can time music or specific tasks to be performed, for example, one second after a signal.

Even though not all the clock mechanisms in humans are known, biological clocks share a property with all human-built and all non-living clocks: they are limited by quantum mechanics. Even the simple pendulum is limited by quantum theory. Let us explore the topic.

When do clocks exist?

> "Die Zukunft war früher auch besser.*"
>
> Karl Valentin.

When we explored general relativity we found out that purely gravitational clocks do not exist, because there is no unit of time that can be formed using the constants c and G. Vol. II, page 282 Clocks, like any measurement standard, need matter and non-gravitational interactions to work. This is the domain of quantum theory. Let us see what the situation is in this case.

First of all, in quantum theory, the time is *not* an observable. Indeed, the time operator is not Hermitean. In other words, quantum theory states that there is no physical observable whose value is proportional to time. On the other hand, clocks are quite common; for example, the Sun or Big Ben work to most people's satisfaction. Observations thus encourages us to look for an operator describing the position of the hands of a clock. However, if we look for such an operator we find a strange result. Any quantum system having a Hamiltonian bounded from below – having a lowest energy – lacks a Hermitean operator whose expectation value increases monotonically with time. This result can be Challenge 24 ny proven rigorously, as a mathematical theorem.

Take a mechanical pendulum clock. In all such clocks the weight has to stop when the chain end is reached. More generally, all clocks have to stop when the battery or the energy source is empty. In other words, in all real clocks the Hamiltonian is bounded from below. And the above theorem from quantum theory then states that such a clock cannot really work.

In short, quantum theory shows that exact *clocks do not exist in nature*. Quantum theory states that any clock can only be *approximate*. Time cannot be measured exactly; time can only be measured approximately. Obviously, this result is of importance for high

* 'Also the future used to be better in the past.' Karl Valentin (b. 1882 Munich, d. 1948 Planegg), playwright, writer and comedian.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

223 S. Coleman & J. Mandula, *All possible symmetries of the S matrix*, Physical Review **159**, pp. 1251–1256, 1967. Cited on page 272.

224 P. C. Argyres, *Dualities in supersymmetric field theories*, Nuclear Physics Proceedings Supplement **61A**, pp. 149–157, 1998, preprint available at arxiv.org/abs/hep-th/9705076. Cited on page 274.

225 Michael Stone editor, *Bosonization*, World Scientific, 1994. R. Rajaraman, *Solitons and Instantons*, North Holland, 1987. However, the hope of explaining the existence of fermions as the result of an infinite number of interacting bosons – this is what 'bosonization' means – has not been successful. Cited on page 275.

226 In 1997, the smallest human-made flying object was the helicopter built by a group of the Institut für Mikrotechnik in Mainz, in Germany. A picture is available at their web page, to be found at www.imm-mainz.de/English/billboard/f_hubi.html. The helicopter is 24 mm long, weighs 400 mg and flies (though not freely) using two built-in electric motors driving two rotors, running at between 40 000 and 100 000 revolutions per minute. See also the helicopter from Stanford University at www-rpl.stanford.edu/RPL/htmls/mesoscopic/mesicopter/mesicopter.html, with an explanation of its battery problems. Cited on page 279.

227 Henk Tennekes, *De wetten van de vliegkunst – over stijgen, dalen, vliegen en zweven*, Aramith Uitgevers, 1992. This clear and interesting text is also available in English. Cited on page 279.

228 The most recent computational models of lift still describe only two-dimensional wing motion, e.g., Z. J. Wang, *Two dimensional mechanism for insect hovering*, Physical Review Letters 85 pp. 2216–2219, 2000. A first example of a mechanical bird has been constructed by Wolfgang Send; it can be studied on the www.aniprop.de website. See also W. Send, *Physik des Fliegens*, Physikalische Blätter **57**, pp. 51–58, June 2001. Cited on page 280.

229 R. B. Srygley & A. L. R. Thomas, *Unconventional lift-generating mechanisms in free-flying butterflies*, Nature **420**, pp. 660–664, 2002. Cited on page 280.

230 The book by John Brackenbury, *Insects in Flight*, 1992. is a wonderful introduction into the biomechanics of insects, combining interesting science and beautiful photographs. Cited on page 282.

231 The simulation of insect flight using enlarged wing models flapping in oil instead of air is described for example in www.dickinson.caltech.edu/research_robofly.html. The higher viscosity of oil allows achieving the same Reynolds number with larger sizes and lower frequencies than in air. See also the 2013 video of the talk on insect flight at www.ted.com/talks/michael_dickinson_how_a_fly_flies.html. Cited on page 282.

232 A summary of undulatory swimming that includes the two beautiful illustrations included in the text, Figure 157 and Figure 158, is M. Gazzola, M. Argentina & L. Mahadevan, *Scaling macroscopic aquatic locomotion*, Nature Physics **10**, pp. 758–761, 2014. Cited on pages 283 and 284.

233 E. Purcell, *Life at low Reynolds number*, American Journal of Physics **45**, p. 3, 1977. See also the review E. Lauga & T. R. Powers, *The hydrodynamics of swimming microorganisms*, Reports on Progress in Physics **72**, p. 096601, 2009, preprint at arxiv.org/abs/0812.2887. Cited on page 285.

234 A short but informative review is by S. Vogel, *Modes and scaling in aquatic locomotion*, Integrative and Comparative Biology **48**, pp. 702–712, 2008, available online at icb.oxfordjournals.org/content/48/6/702.full. Cited on page 284.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

conservations laws and massless particles, Physical Review Letters **13**, pp. 585–587, 1964, T. W. B. Kibble, *Symmetry breaking in non-Abelian gauge theories*, Physical Review **155**, pp. 1554–1561, 1967. For the ideas that inspired all these publications, see Ref. 208. Cited on pages 258 and 403.

211 D. Treille, *Particle physics from the Earth and from the sky: Part II*, Europhysics News **35**, no. 4, 2004. Cited on page 256.

212 Rumination is studied in P. Jordan & de Laer Kronig, in Nature **120**, p. 807, 1927. Cited on page 259.

213 K.W.D. Ledingham & al., *Photonuclear physics when a multiterawatt laser pulse interacts with solid targets*, Physical Review Letters **84**, pp. 899–902, 2000. K.W.D. Ledingham & al., *Laser-driven photo-transmutation of Iodine-129 – a long lived nuclear waste product*, Journal of Physics D: Applied Physics **36**, pp. L79–L82, 2003. R. P. Singhal, K. W. D. Ledingham & P. McKenna, *Nuclear physics with ultra-intense lasers – present status and future prospects*, Recent Research Developments in Nuclear Physics **1**, pp. 147–169, 2004. Cited on page 259.

214 The electron radius limit is deduced from the $g-2$ measurements, as explained in the Nobel Prize talk by Hans Dehmelt, *Experiments with an isolated subatomic particle at rest*, Reviews of Modern Physics **62**, pp. 525–530, 1990, or in Hans Dehmelt, *Is the electron a composite particle?*, Hyperfine Interactions **81**, pp. 1–3, 1993. Cited on page 264.

215 G. Gabrielse, H. Dehmelt & W. Kells, *Observation of a relativistic, bistable hysteresis in the cyclotron motion of a single electron*, Physical Review Letters **54**, pp. 537–540, 1985. Cited on page 264.

216 For the bibliographic details of the latest print version of the *Review of Particle Physics*, see Appendix B. The online version can be found at pdg.web.cern.ch. The present status on grand unification can also be found in the respective section of the overview. Cited on pages 268, 269, and 270.

217 Slides of a very personal review talk by H. Georgi, *The future of grand unification*, can be found at www2.yukawa.kyoto-u.ac.jp/~yt100sym/files/yt100sym_georgi.pdf. A modern research approach is S. Raby, *Grand unified theories*, arxiv.org/abs/hep-ph/0608183. Cited on page 269.

218 H. Jeon & M. Longo, *Search for magnetic monopoles trapped in matter*, Physical Review Letters **75**, pp. 1443–1447, 1995. Cited on page 269.

219 The quantization of charge as a consequence of the existence of magnetic monopoles is due to P. Dirac, *Quantised singularities in the electromagnetic Field*, Proceedings of the Royal Society (London) A **133**, pp. 60–72, 1931. Cited on page 269.

220 On proton decay rates, see the latest data of the Particle Data Group, at pdg.web.cern.ch. Cited on page 270.

221 U. Amaldi, de Boer & H. Fürstenau, *Comparison of grand unified theories with electroweak and strong coupling constants measured at LEP*, Physics Letters **260**, pp. 447–455, 1991. This widely cited paper is the standard reference for this issue. An update is found in de Boer & C. Sander, *Global electroweak fits and gauge coupling unification*, Physics Letters B 585 pp. 276–286, 2004, or preprint at arxiv.org/abs/hep-ph/0307049. The figure is taken with permission from the home page of Wim de Boer www-ekp.physik.uni-karlsruhe.de/~deboer/html/Forschung/forschung.html. Cited on page 270.

222 Peter G. O. Freund, *Introduction to Supersymmetry*, Cambridge 1988. Julius Wess & Jonathan Bagger, *Supersymmetry and Supergravity*, Princeton University Press, 1992. This widely cited book contains a lot of mathematics but little physics. Cited on page 271.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

precision clocks. What happens if we try to increase the precision of a clock as much as possible?

High precision implies high sensitivity to fluctuations. Now, all clocks have an oscillator inside, e.g., a motor, that makes them work. A high precision clock thus needs a high precision oscillator. In all clocks, the position of this oscillator is read out and shown on the dial. Now, the quantum of action implies that even the most precise clock oscillator has a position indeterminacy. The precision of any clock is thus limited.

Worse, like any quantum system, any clock oscillator even has a small, but finite probability to stop or to run backwards for a while. You can check this conclusion yourself. Just have a look at a clock when its battery is almost empty, or when the weight driving the pendulum has almost reached the bottom position. The clock will start doing funny things, like going backwards a bit or jumping back and forward. When the clock works normally, this behaviour is strongly suppressed; however, it is still possible, though with low probability. This is true even for a sundial.

Challenge 25 e

In summary, clocks necessarily have to be *macroscopic* in order to work properly. A clock must be as large as possible, in order to average out its fluctuations. Astronomical systems are good examples. A good clock must also be *well-isolated* from the environment, such as a freely flying object whose coordinate is used as time variable. For example, this is regularly done in atomic optical clocks.

The precision of clocks

Given the limitations due to quantum theory, what is the ultimate accuracy τ of a clock? To start with, the indeterminacy relation provides the limit on the mass of a clock. The clock mass M must obey

Challenge 26 ny

$$M > \frac{\hbar}{c^2\tau} \tag{2}$$

which is obviously always fulfilled in everyday life. But we can do better. Like for a pendulum, we can relate the accuracy τ of the clock to its maximum reading time T. The idea was first published by Salecker and Wigner. They argued that

Challenge 27 e

Ref. 27

$$M > \frac{\hbar}{c^2\tau}\frac{T}{\tau} \tag{3}$$

where T is the time to be measured. You might check that this condition directly requires that any clock must be *macroscopic*.

Challenge 28 e

Let us play with the formula by Salecker and Wigner. It can be rephrased in the following way. For a clock that can measure a time t, the size l is connected to the mass m by

$$l > \sqrt{\frac{\hbar t}{m}}\,. \tag{4}$$

How close can this limit be achieved? It turns out that the smallest clocks known, as well as the clocks with most closely approach this limit, are bacteria. The smallest bacteria, the *mycoplasmas*, have a mass of about $8 \cdot 10^{-17}$ kg, and reproduce every 100 min, with a

Ref. 28

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

precision of about 1 min. The size predicted from expression (4) is between 0.09 μm and 0.009 μm. The observed size of the smallest mycoplasmas is 0.3 μm. The fact that bacteria can come so close to the clock limit shows us again what a good engineer evolution has been.

Note that the requirement by Salecker and Wigner is not in contrast with the possibility to make the *oscillator* of the clock very small; researchers have built oscillators made of a single atom. In fact, such oscillations promise to be the most precise human built clocks. But the oscillator is only one part of any clock, as explained above.

Ref. 29
Page 42

In the real world, the clock limit can be tightened even more. The whole mass M cannot be used in the above limit. For clocks made of atoms, only the binding energy between atoms can be used. This leads to the so-called *standard quantum limit for clocks*; it limits the accuracy of their frequency ν by

$$\frac{\delta\nu}{\nu} = \sqrt{\frac{\Delta E}{E_{\text{tot}}}} \tag{5}$$

where $\Delta E = \hbar/T$ is the energy indeterminacy stemming from the finite measuring time T and $E_{\text{tot}} = NE_{\text{bind}}$ is the total binding energy of the atoms in the metre bar. So far, the quantum limit has not yet been achieved for any clock, even though experiments are getting close to it.

In summary, clocks exist only in the limit of $\hbar$ being negligible. In practice, the errors made by using clocks and metre bars can be made as small as required; it suffices to make the clocks large enough. Clock built into human brains comply with this requirement. We can thus continue our investigation into the details of matter without much worry, at least for a while. Only in the last part of our mountain ascent, where the requirements for precision will be even higher and where general relativity will limit the size of physical systems, trouble will appear again: the impossibility to build precise clocks will then become a central issue.

Vol. VI, page 64

Why are predictions so difficult, especially of the future?

> Future: that period of time in which our affairs prosper, our friends are true, and our happiness is assured.
>
> Ambrose Bierce

Nature limits predictions in four ways:

1. We have seen that quantum theory, through the uncertainty relations, limits the precision of measurements, and of clocks and time measurements in particular. Thus, the quantum of action makes it hard to determine initial states to full precision – even for a single particle.
2. We have seen that high numbers of particles make it difficult to predict the future due to the often statistical nature of their initial conditions.
3. We have found in our adventure that predictions of the future are made difficult by non-linearities and by the divergence from nearby initial conditions.
4. We have seen that a non-trivial space-time topology can limit predictability. For ex-

Vol. I, page 238
Vol. I, page 422
Vol. II, page 110

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

200 Pentaquarks were first predicted by Maxim Polyakov, Dmitri Diakonov, and Victor Petrov in 1997. Two experimental groups in 2003 claimed to confirm their existence, with a mass of 1540 MeV; see K. Hicks, *An experimental review of the Θ^+ pentaquark*, arxiv.org/abs/hep-ex/0412048. Results from 2005 and later, however, ruled out that the 1540 MeV particle is a pentaquark. Cited on page 237.

201 See, for example, Ya. B. Zel'dovich & V. S. Popov, *Electronic structure of superheavy atoms*, Soviet Physics Uspekhi **17**, pp. 673–694, 2004 in the English translation. Cited on page 134.

202 J. Tran Thanh Van, editor, *CP violation in Particle Physics and Astrophysics*, Proc. Conf. Chateau de Bois, France, May 1989, Editions Frontières, 1990. Cited on page 245.

203 P.L. Anthony & al., *Observation of parity nonconservation in Møller scattering*, Physical Review Letters **92**, p. 181602, 2004. Cited on page 246.

204 M. A. Bouchiat & C. C. Bouchiat, *Weak neutral currents in atomic physics*, Physics Letters B **48**, pp. 111–114, 1974. U. Amaldi, A. Böhm, L. S. Durkin, P. Langacker, A. K. Mann, W. J. Marciano, A. Sirlin & H. H. Williams, *Comprehensive analysis of data pertaining to the weak neutral current and the intermediate-vector-boson masses*, Physical Review D **36**, pp. 1385–1407, 1987. Cited on page 246.

205 M. C. Noecker, B. P. Masterson & C. E. Wiemann, *Precision measurement of parity nonconservation in atomic cesium: a low-energy test of electroweak theory*, Physical Review Letters **61**, pp. 310–313, 1988. See also D.M. Meekhof & al., *High-precision measurement of parity nonconserving optical rotation in atomic lead*, Physical Review Letters **71**, pp. 3442–3445, 1993. Cited on page 247.

206 S. C. Bennet & C. E. Wiemann, *Measurement of the 6S – 7S transition polarizability in atomic cesium and an improved test of the standard model*, Physical Review Letters **82**, pp. 2484–2487, 1999. The group has also measured the spatial distribution of the weak charge, the so-called the *anapole moment*; see C.S. Wood & al., *Measurement of parity nonconservation and an anapole moment in cesium*, Science **275**, pp. 1759–1763, 1997. Cited on page 247.

207 C. Jarlskog, *Commutator of the quark mass matrices in the standard electroweak model and a measure of maximal CP nonconservation*, Physical Review Letters **55**, pp. 1039–1042, 1985. Cited on page 251.

208 The correct list of citations is a topic of intense debate. It surely includes Y. Nambu & G. Jona-Lasinio, *Dynamical model of the elementary particles based on an analogy with superconductivity - I*, Physical Review **122**, p. 345-358, 1961, P. W. Anderson, *Plasmons, gauge invariance, and mass*, Physical Review **130**, pp. 439–442, 1963, The list then continues with reference Ref. 210. Cited on pages 253 and 404.

209 K. Grotz & H. V. Klapdor, *Die schwache Wechselwirkung in Kern-, Teilchen- und Astrophysik*, Teubner Verlag, Stuttgart, 1989. Also available in English and in several other languages. Cited on page 255.

210 P. W. Higgs, *Broken symmetries, massless particles and gauge fields*, Physics Letters **12**, pp. 132–133, 1964, P. W. Higgs, *Broken symmetries and the masses of the gauge bosons*, Physics Letters **13**, pp. 508–509, 1964. He then expanded the story in P. W. Higgs, *Spontaneous symmetry breakdown without massless bosons*, Physical Review **145**, pp. 1156–1163, 1966. Higgs gives most credit to Anderson, instead of to himself; he also mentions Brout and Englert, Guralnik, Hagen, Kibble and 't Hooft. These papers are F. Englert & R. Brout, *Broken symmetry and the mass of the gauge vector mesons*, Physics Review Letters **13**, pp. 321–323, 1964, G. S. Guralnik, C. R. Hagen & T. W. B. Kibble, *Global*

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

191 R. Brandelik & al., *Evidence for planar events in e^+e^- annihilation at high energies*, Physics Letters B **86**, pp. 243–249, 1979. Cited on page 236.

192 For a pedagogical introduction to lattice QCD calculations, see R. Gupta, *Introduction to Lattice QCD*, preprint at arxiv.org/abs/hep-lat/9807028, or the clear introduction by Michael Creutz, *Quarks, Gluons and Lattices*, Cambridge University Press, 1983. Cited on page 231.

193 S. Bethke, *Experimental tests of asymptotic freedom*, Progress in Particle and Nuclear Physics **58**, pp. 351–368, 2007, preprint at arxiv.org/abs/hep-ex/0606035. Cited on page 232.

194 F. Abe & al., *Measurement of dijet angular distributions by the collider detector at Fermilab*, Physical Review Letters 77, pp. 5336–5341, 1996. Cited on page 233.

195 The approximation of QCD with zero mass quarks is described by F. Wilczek, *Getting its from bits*, Nature **397**, pp. 303–306, 1999. It is also explained in F. Wilczek, *Asymptotic freedom*, Nobel lecture 2004. The proton's mass is set by the energy scale at which the strong coupling, coming from its value at Planck energy, becomes of order unity. Cited on pages 233, 234, and 258.

196 A. J. Buchmann & E. M. Henley, *Intrinsic quadrupole moment of the nucleon*, Physical Review C **63**, p. 015202, 2000. Alfons Buchmann also predicts that the quadrupole moment of the other, strange $J = 1/2$ octet baryons is positive, and predicts a prolate structure for all of them (private communication). For the decuplet baryons, with $J = 3/2$, the quadrupole moment can often be measured spectroscopically, and is always negative. The four Δ baryons are thus predicted to have a negative intrinsic quadrupole moment and thus an oblate shape. This explained in A. J. Buchmann & E. M. Henley, *Quadrupole moments of baryons*, Physical Review D **65**, p. 073017, 2002. For recent updates, see A. J. Buchmann, *Charge form factors and nucleon shape*, pp. 110–125, in the Shape of Hadrons Workshop Conference, Athens Greece, 27-29 April 2006, AIP Conference Proceedings 904, Eds. C.N. Papanicolas, Aron Bernstein. For updates on other baryons, see A. J. Buchmann, *Structure of strange baryons*, Hyp 2006, International Conference on Hypernuclear and Strange Particle Physics, Oct.10-14, Mainz, Germany, to be published in European Physics Journal A 2007. The topic is an active field of research; for example, results on magnetic octupole moments are expected soon. Cited on page 234.

197 S. Strauch & al., *Polarization transfer in the ^4He (e,e'p) ^3H reaction up to $Q^2 = 2.6(GeV/c)^2$*, Physical Review Letters **91**, p. 052301, 2003. Cited on page 234.

198 F. Close, *Glueballs and hybrids: new states of matter*, Contemporary Physics **38**, pp. 1–12, 1997. See also the next reference. Cited on page 237.

199 A tetraquark is thought to be the best explanation for the $f_0(980)$ resonance at 980 MeV. The original proposal of this explanation is due to R. L. Jaffe, *Multiquark hadrons I: phenomenology of $Q^2\overline{Q}^2$ mesons*, Physical Review D **15**, pp. 267–280, 1977, R. L. Jaffe, *Multiquark hadrons II: methods*, Physical Review D **15**, pp. 281–289, 1977, and R. L. Jaffe, Physical Review D *$Q^2\overline{Q}^2$ resonances in the baryon-antibaryon system*,**17**, pp. 1444–1458, 1978. For a clear and detailed modern summary, see the excellent review by E. Klempt & A. Zaitsev, *Glueballs, hybrids, multiquarks: experimental facts versus QCD inspired concepts*, Physics Reports **454**, pp. 1–202, 2007, preprint at arxiv.org/abs/0708.4016. See also F. Giacosa, *Light scalars as tetraquarks*, preprint at arxiv.org/abs/0711.3126, and V. Crede & C. A. Meyer, *The experimental status of glueballs*, preprint at arxiv.org/abs/0812.0600. However, other researchers argue against this possibility; see, e.g., arxiv.org/abs/1404.5673v2. The issue is not closed. Cited on page 237.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

ample, we will discover that black hole and horizons can limit predictability due to their one-way inclusion of energy, mass and signals.

Vol. VI, page 39

5. We will find out in the last pat of our adventure that quantum gravity effects even make a precise definition of time and space impossible.

Measurements and practical predictability are thus limited. The central reason for this limitation is the quantum of action. But if the quantum of action makes perfect clocks impossible, is determinism still the correct description of nature? And does time exist after all? The answer is clear: yes and no. We learned that all the mentioned limitations of clocks can be overcome for limited time intervals; in practice, these time intervals can be made so large that the limitations do *not* play a role in everyday life. As a result,

▷ In practice, in all quantum systems both determinism and the concept of time remain applicable.

This conclusion is valid even though theory says otherwise. Our ability to enjoy the pleasures due to the flow of time remains intact.

However, when extremely large momentum flows or extremely large dimensions need to be taken into account, quantum theory cannot be applied alone; in those cases, general relativity needs to be taken into account. The fascinating effects that occur in those

Vol. VI, page 56

situations will be explored in detail later on.

Decay and the golden rule

> "I prefer most of all to remember the future."
> Salvador Dalì

All pleasure only makes sense in the face of death. And death is a form of decay. Decay is any spontaneous change. Like the wave aspect of matter, decay is a process with no classical counterpart. Of course, any decay – including the emission of light by a lamp, the triggering of a camera sensor, radioactivity or the ageing of humans – can be observed classically; however, the *origin* of decay is a pure quantum effect.

In any decay of unstable systems or particles, the decoherence of superpositions of

Vol. IV, page 142

macroscopically distinct states plays an important role. Indeed, experiments confirm that the prediction of decay for a specific system, like a scattering of a particle, is only possible on *average*, for a large number of particles or systems, and never for a single one. These observations confirm the quantum origin of decay. In every decay process, the superposition of macroscopically distinct states – in this case those of a decayed and an undecayed particle – is made to decohere rapidly by the interaction with the environment. Usually the 'environment' vacuum, with its fluctuations of the electromagnetic, weak and strong fields, is sufficient to induce decoherence. As usual, the details of the involved environment states are unknown for a single system and make any prediction for a specific system impossible.

What is the *origin* of decay? Decay is always due to *tunnelling*. With the language of quantum electrodynamics, we can say that decay is motion induced by the vacuum fluctuations. Vacuum fluctuations are random. The experiment between the plates confirms the importance of the environment fluctuations for the decay process.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Quantum theory gives a simple description of decay. For a system consisting of a large number N of decaying identical particles, any *decay* is described by

$$\dot{N} = -\frac{N}{\tau} \quad \text{where} \quad \frac{1}{\tau} = \frac{2\pi}{\hbar} \left| \langle \psi_{\text{initial}} | H_{\text{int}} | \psi_{\text{final}} \rangle \right|^2 . \tag{6}$$

This result for $\dot{N} = \mathrm{d}N/\mathrm{d}t$ was named the *golden rule* by Fermi,* because it works so well despite being an approximation whose domain of applicability is not easy to specify. The golden rule leads to

Challenge 29 e

$$N(t) = N_0 \, \mathrm{e}^{-t/\tau} . \tag{7}$$

Decay is thus predicted to follow an exponential behaviour, independently of the details of the physical process. In addition, the decay time τ depends on the interaction and on the square modulus of the transition matrix element. For almost a century, all experiments confirmed that quantum decay is *exponential*.

On the other hand, when quantum theory is used to derive the golden rule, it is found that decay is exponential only in certain special systems. A calculation that takes into account higher order terms predicts two deviations from exponential decay for completely isolated systems: for short times, the decay rate should *vanish*; for long times, the decay rate should follow an *algebraic* – not an exponential – dependence on time, in some cases even with superimposed oscillations. After an intense experimental search, deviations for short times have been observed. The observation of deviations at long times are rendered impossible by the ubiquity of thermal noise. In summary, it turns out that decay is exponential only when the environment is noisy, the system made of many weakly interacting particles, or both. Since this is usually the case, the mathematically exceptional exponential decrease becomes the (golden) rule in the description of decay.

Ref. 30

Ref. 31

Can you explain why human life, despite being a quantum effect, is not observed to follow an exponential decay?

Challenge 30 s

The present in quantum theory

> “Utere temporibus.**”
>
> Ovidius

Many sages advise to enjoy the present. As shown by perception research, what humans call ‘present’ has a duration of between 20 and 70 milliseconds. This result on the biological present leads us to ask whether the *physical* present might have a duration as well.

Ref. 32

In everyday life, we are used to imagine that shortening the time taken to measure the position of a point object as much as possible will approach the ideal of a particle fixed at a given point in space. When Zeno discussed the flight of an arrow, he assumed that this is possible. However, quantum theory changes the situation.

Can we really say that a moving system is at a given spot at a given time? In order to

* Originally, the golden rule is a statement from the christian bible, (Matthew 7,12) namely the precept ‘Do to others whatever you would like them to do to you.’

** ‘Use the occasions.’ *Tristia* 4, 3, 83

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

181 S. Goriely, A. Bauswein & H. T. Janka, *R-process nucleosynthesis in dynamically ejected matter of neutron star mergers*, Astrophysical Journal **738**, p. L38, 2011, preprint at arxiv.org/abs/1107.0899. Cited on pages 215 and 216.

182 Kendall, Friedman and Taylor received the 1990 Nobel Prize in Physics for a series of experiments they conducted in the years 1967 to 1973. The story is told in the three Nobel lectures R. E. Taylor, *Deep inelastic scattering: the early years*, Review of Modern Physics **63**, pp. 573–596, 1991, H. W. Kendall, *Deep inelastic scattering: Experiments on the proton and the observation of scaling*, Review of Modern Physics **63**, pp. 597–614, 1991, and J. I. Friedman, *Deep inelastic scattering: Comparisons with the quark model*, Review of Modern Physics **63**, pp. 615–620, 1991. Cited on page 219.

183 G. Zweig, *An SU3 model for strong interaction symmetry and its breaking II*, CERN Report No. 8419TH. 412, February 21, 1964. Cited on page 219.

184 About the strange genius of Gell-Mann, see the beautiful book by George Johnson, *Murray Gell-Mann and the Revolution in Twentieth-Century Physics*, Knopf, 1999. Cited on page 219.

185 The best introduction might be the wonderfully clear text by Donald H. Perkins, *Introduction to High Energy Physics*, Cambridge University Press, fourth edition, 2008. Also beautiful, with more emphasis on the history and more detail, is Kurt Gottfried & Victor F. Weisskopf, *Concepts of Particle Physics*, Clarendon Press, Oxford, 1984. Victor Weisskopf was one of the heroes of the field, both in theoretical research and in the management of CERN, the European organization for particle research. Cited on pages 221, 231, and 401.

186 The official reference for all particle data, worth a look for every physicist, is the massive collection of information compiled by the Particle Data Group, with the website pdg.web.cern.ch containing the most recent information. A printed review is published about every two years in one of the major journals on elementary particle physics. See for example C. Amsler & al., *The Review of Particle Physics*, Physics Letters B **667**, p. 1, 2008. For some measured properties of these particles, the official reference is the set of so-called CODATA values given in reference Ref. 286. Cited on pages 221, 232, 233, 235, 245, 251, 252, 255, and 262.

187 H. Fritsch, M. Gell-Mann & H. Leutwyler, *Advantages of the color octet picture*, Physics Letters B **47**, pp. 365–368, 1973. Cited on page 224.

188 Quantum chromodynamics can be explored in books of several levels. For the first, popular level, see the clear longseller by one of its founders, Harald Fritzsch, *Quarks – Urstoff unserer Welt*, Piper Verlag, 2006, or, in English language, *Quarks: the Stuff of Matter*, Penguin Books, 1983. At the second level, the field can be explored in texts on high energy physics, as those of Ref. 185. The third level contains books like Kerson Huang, *Quarks, Leptons and Gauge Fields*, World Scientific, 1992, or Felix J. Ynduráin, *The Theory of Quark and Gluon Interactions*, Springer Verlag, 1992, or Walter Greiner & Andreas Schäfer, *Quantum Chromodynamics*, Springer Verlag, 1995, or the modern and detailed text by Stephan Narison, *QCD as a Theory of Hadrons*, Cambridge University Press, 2004. As always, a student has to discover by himself or herself which text is most valuable. Cited on pages 224, 230, and 232.

189 S. Dürr & al., *Ab initio determination of the light hadron masses*, Science **322**, pp. 1224–1227, 2008. Cited on page 228.

190 See for example C. Bernard & al., *Light hadron spectrum with Kogut–Susskind quarks*, Nuclear Physics, Proceedings Supplement **73**, p. 198, 1999, and references therein. Cited on page 228.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

2002. Cited on page 186.

165 A good introduction is R. Clark & B. Wodsworth, *A new spin on nuclei*, Physics World pp. 25–28, July 1998. Cited on page 187.

166 John Horgan, *The End of Science – Facing the Limits of Knowledge in the Twilight of the Scientific Age*, Broadway Books, 1997, chapter 3, note 1. Cited on page 191.

167 G. Charpak & R. L. Garwin, *The DARI*, Europhysics News **33**, pp. 14–17, January/February 2002. Cited on page 193.

168 M. Brunetti, S. Cecchini, M. Galli, G. Giovannini & A. Pagliarin, *Gamma-ray bursts of atmospheric origin in the MeV energy range*, Geophysical Research Letters **27**, p. 1599, 2000. Cited on page 195.

169 For a recent image of Lake Karachay, see www.google.com/maps/@55.6810205,60.796688,3519m/data=!3m1!1e3. Cited on page 196.

170 A book with nuclear explosion photographs is Michael Light, *100 Suns*, Jonathan Cape, 2003. Cited on page 197.

171 *A conversation with Peter Mansfield*, Europhysics Letters **37**, p. 26, 2006. Cited on page 193.

172 An older but still fascinating summary of solar physics is R. Kippenhahn, *Hundert Milliarden Sonnen*, Piper, 1980. It was a famous bestseller and is available also in English translation. Cited on page 200.

173 H. Bethe, *On the formation of deuterons by proton combination*, Physical Review **54**, pp. 862–862, 1938, and H. Bethe, *Energy production in stars*, Physical Review **55**, pp. 434–456, 1939. Cited on page 200.

174 M. Nauenberg & V. F. Weisskopf, *Why does the sun shine?*, American Journal of Physics **46**, pp. 23–31, 1978. Cited on page 202.

175 The slowness of the speed of light inside the Sun is due to the frequent scattering of photons by solar matter. The most serious estimate is by R. Mitalas & K. R. Sills, *On the photon diffusion time scale for the Sun*, The Astrophysical Journal **401**, pp. 759–760, 1992. They give a photon escape time of 0.17 Ma, an average photon free mean path of 0.9 mm and an average speed of 0.97 cm/s. See also the interesting paper by M. Stix, *On the time scale of energy transport in the sun*, Solar Physics **212**, pp. 3–6, 2003, which comes to the conclusion that the speed of energy transport is 30 Ma, two orders of magnitude higher than the photon diffusion time. Cited on page 203.

176 See the freely downloadable book by John Wesson, *The Science of JET - The Achievements of the Scientists and Engineers Who Worked on the Joint European Torus 1973-1999*, JET Joint Undertaking, 2000, available at www.jet.edfa.org/documents/wesson/wesson.html. Cited on page 211.

177 J. D. Lawson, *Some criteria for a power producing thermonuclear reactor*, Proceedings of the Physical Society, London **B 70**, pp. 6–10, 1957. The paper had been kept secret for two years. However, the result was already known, before Lawson, to all Russian nuclear physicists several years earlier. Cited on page 212.

178 The classic paper is R. A. Alpher, H. Bethe & G. Gamow, *The Origin of Chemical Elements*, Physical Review **73**, pp. 803–804, 1948. Cited on page 213.

179 The famous overview of nucleosyntehis, over 100 pages long, is the so-called B^2FH paper by M. Burbidge, G. Burbidge, W. Fowler & F. Hoyle, *Synthesis of the elements in stars*, Reviews of Modern Physics **29**, pp. 547–650, 1957. Cited on page 213.

180 The standard reference is E. Anders & N. Grevesse, *Abundances of the elements – meteoritic and solar*, Geochimica et Cosmochimica Acta **53**, pp. 197–214, 1989. Cited on page 215.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

find an answer through experiment, we could use a photographic camera whose shutter time can be reduced at will. What would we find? When the shutter time approaches the oscillation period of light, the sharpness of the image would decrease; in addition, the colour of the light would be influenced by the shutter motion. We can increase the energy of the light used, but the smaller wavelengths only shift the problem, they do not solve it. Worse, at extremely small wavelengths, matter becomes transparent, and shutters cannot be realized any more. All such investigations confirm: Whenever we reduce shutter times as much as possible, observations become unsharp. The lack of sharpness is due to the quantum of action. Quantum theory thus does not confirm the naive expectation that shorter shutter times lead to sharper images. In contrast, the quantum aspects of nature show us that there is no way in principle to approach the limit that Zeno was discussing.

In summary, the indeterminacy relation and the smallest action value prevent that moving objects are at a fixed position at a given time. Zeno's discussion was based on an extrapolation of classical concepts into domains where it is not valid any more. Every observation, like every photograph, implies a *time average*:

Observations average interactions over a given time span.

For a photograph, the duration is given by the shutter time; for a measurement, the average is defined by the details of the set-up. Whatever this set-up might be, the averaging time is never zero. * There is no 'point-like' instant of time that describes the present. The observed, physical *present* is always an average over a non-vanishing interval of time. In nature, the present has a finite duration. To give a rough value that guides our thought, in most situations the length of the present will be less than a yoctosecond, so that it can usually be neglected.

Why can we observe motion?

Zeno of Elea was thus wrong in assuming that motion is a sequence of specific positions in space. Quantum theory implies that motion is *only approximately* the change of position with time.

Why then can we observe and describe motion in quantum theory? Quantum theory shows that motion is the *low energy approximation* of quantum evolution. Quantum evolution *assumes* that space and time measurements of sufficient precision can be performed. We know that for any given observation energy, we can build clocks and metre bars with much higher accuracy than required, so that in practice, quantum evolution is applicable in all cases. As long as energy and time have no limits, all problems are avoided, and *motion is a time sequence of quantum states*.

In summary, we can observe motion because for any known observation energy we can find a still higher energy and a still longer averaging time that can be used by the measurement instruments to define space and time with higher precision than for the system under observation. In the final part of our mountain ascent, we will discover that there is a maximum energy in nature, so that we will need to change our description in those situations. However, this energy value is so huge that it does not bother us at all at the present point of our exploration.

Vol. VI, page 45

Page 50

* Also the discussion of the quantum Zeno effect, below, does not change the conclusions of this section.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Rest and the quantum Zeno effect

The quantum of action implies that there is no rest in nature. Rest is thus always either an approximation or a time average. For example, if an electron is bound in an atom, not freely moving, the probability cloud, or density distribution, is stationary in time. But there is another apparent case of rest in quantum theory, the *quantum Zeno effect*. Usually, observation *changes* the state of a system. However, for certain systems, observation can have the opposite effect, and *fix* a system.

Quantum mechanics predicts that an unstable particle can be prevented from decaying if it is continuously observed. The reason is that an observation, i.e., the interaction with the observing device, yields a non-zero probability that the system does not evolve. If the frequency of observations is increased, the probability that the system does not decay at all approaches 1. Three research groups – Alan Turing by himself in 1954, the group of A. Degasperis, L. Fonda and G.C. Ghirardi in 1974, and George Sudarshan and Baidyanath Misra in 1977 – have independently predicted this effect, today called the *quantum Zeno effect*. In sloppy words, the quantum Zeno effect states: if you look at a system all the time, nothing happens.

The quantum Zeno effect is a natural consequence of quantum theory; nevertheless, its strange circumstances make it especially fascinating. After the prediction, the race for the first observation began. The effect was partially observed by David Wineland and his
Ref. 33 group in 1990, and definitively observed by Mark Raizen and his group in 2001. In the meantime, other groups have confirmed the measurements. Thus, quantum theory has been confirmed also in this surprising aspect.

The quantum Zeno effect is also connected to the deviations from exponential decay – due to the golden rule – that are predicted by quantum theory. Indeed, quantum theory predicts that every decay is exponential only for intermediate times, and quadratic for short times and polynomial for extremely long times. These issues are research topics to this day.

Ref. 34 In a fascinating twist, in 2002, Saverio Pascazio and his team have predicted that the quantum Zeno effect can be used to realize X-ray tomography of objects with the lowest radiation levels imaginable.

In summary, the quantum Zeno effect does not contradict the statement that there is no rest in nature; in situations showing the effect, there is an non-negligible interaction between the system and its environment. The details of the interaction are important: in certain cases, frequent observation can actually accelerate the decay or evolution.
Ref. 35 Quantum physics still remains a rich source of fascinating effects.

Consciousness – a result of the quantum of action

In the pleasures of life, consciousness plays an essential role.

Vol. III, page 335 ▷ *Consciousness* is our ability to observe what is going on in our mind.

This activity, like any type of change, can itself be observed and studied. Though it is hard and probably impossible to do so by introspection, we can study consciousness in others. Obviously, consciousness takes place in the brain. If it were not, there would be no way to keep it connected with a given person. Simply said, we know that each brain

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 190 The wonderful origin of human life (© W.C.M. Weijmar Schultz).

157 W.C.M. Weijmar Schultz & al., *Magnetic resonance imaging of male and female genitals during coitus and female sexual arousal*, British Medical Journal **319**, pp. 1596–1600, December 18, 1999, available online as www.bmj.com/cgi/content/full/319/7225/1596. Cited on page 164.

158 M. Chantell, T. C. Weekes, X. Sarazin & M. Urban, *Antimatter and the moon*, Nature **367**, p. 25, 1994. M. Amenomori & al., *Cosmic ray shadow by the moon observed with the Tibet air shower array*, Proceedings of the 23rd International Cosmic Ray Conference, Calgary **4**, pp. 351–354, 1993. M. Urban, P. Fleury, R. Lestienne & F. Plouin, *Can we detect antimatter from other galaxies by the use of the Earth's magnetic field and the Moon as an absorber?*, Nuclear Physics, Proceedings Supplement **14B**, pp. 223–236, 1990. Cited on page 177.

159 Joseph Magill & Jean Galy, *Radioactivity Radionuclides Radiation*, Springer, 2005. This dry but dense book contains most data about the topic, including much data on all the known nuclides. Cited on pages 181 and 198.

160 An good summary on radiometric dating is by R. Wiens, *Radiometric dating – a christian perpective*, www.asa3.org/ASA/resources/Wiens.html. The absurd title is due to the habit in many religious circles to put into question radiometric dating results. Putting apart the few religious statements in the review, the content is well explained. Cited on pages 182 and 184.

161 See for example the excellent and free lecture notes by Heinz-Günther Stosch, *Einführung in die Isotopengeochemie*, 2004, available on the internet. Cited on page 182.

162 G. B. Dalrymple, *The age of the Earth in the twentieth century: a problem (mostly) solved*, Special Publications, Geological Society of London **190**, pp. 205–221, 2001. Cited on page 184.

163 A good overview is given by A. N. Halliday, *Radioactivity, the discovery of time and the earliest history of the Earth*, Contemporary Physics **38**, pp. 103–114, 1997. Cited on page 185.

164 J. Dudek, A. God, N. Schunck & M. Mikiewicz, *Nuclear tetrahedral symmetry: possibly present throughout the periodic table*, Physical Review Letters **88**, p. 252502, 24 June

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

142 See Don N. Page, *Average entropy of a subsystem*, Physical Review Letters **71**, pp. 1291–1294, 1993. The entropy formula of this paper, used above, was proven by S. K. Foong & S. Kanno, *Proof of Page's conjecture on the average entropy of a subsystem*, Physical Review Letters **72**, pp. 1148–1151, 1994. Cited on page 156.

143 R. Lafrance & R. C. Myers, *Gravity's rainbow: limits for the applicability of the equivalence principle*, Physical Review D **51**, pp. 2584–2590, 1995, arxiv.org/abs/hep-th/9411018. Cited on page 157.

144 M. Yu. Kuchiev & V. V. Flambaum, *Scattering of scalar particles by a black hole*, arxiv.org/abs/gr-qc/0312065. See also M. Yu. Kuchiev & V. V. Flambaum, *Reflection on event horizon and escape of particles from confinement inside black holes*, arxiv.org/abs/gr-qc/0407077. Cited on page 157.

145 See the widely cited but wrong paper by G. C. Ghirardi, A. Rimini & T. Weber, *Unified dynamics for microscopic and macroscopic systems*, Physical Review D **34**, pp. 470–491, 1986. Cited on page 143.

146 I speculate that this version of the coincidences could be original; I have not found it in the literature. Cited on page 144.

147 Steven Weinberg, *Gravitation and Cosmology*, Wiley, 1972. See equation 16.4.3 on page 619 and also page 620. Cited on page 144.

148 It could be that knot theory provides a relation between a local knot invariant, related to particles, and a global one. Cited on page 144.

149 This point was made repeatedly by Steven Weinberg, namely in *Derivation of gauge invariance and the equivalence principle from Lorentz invariance of the S-matrix* , Physics Letters **9**, pp. 357–359, 1964, in *Photons and gravitons in S-matrix theory: derivation of charge conservation and equality of gravitational and inertial mass*, Physical Review B **135**, pp. 1049–1056, 1964, and in *Photons and gravitons in perturbation theory: derivation of Maxwell's and Einstein's equations*, Physical Review B **138**, pp. 988–1002, 1965. Cited on page 158.

150 E. Joos, *Why do we observe a classical space-time?*, Physics Letters A **116**, pp. 6–8, 1986. Cited on page 159.

151 L. H. Ford & T. A. Roman, *Quantum field theory constrains traversable wormhole geometries*, arxiv.org/abs/gr-qc/9510071 or Physical Review D **53**, pp. 5496–5507, 1996. Cited on page 159.

152 B. S. Kay, M. Radzikowski & R. M. Wald, *Quantum field theory on spacetimes with a compactly generated Cauchy horizon*, arxiv.org/abs/gr-qc/9603012 or Communications in Mathematical Physics 183 pp. 533–556, 1997. Cited on page 159.

153 M. J. Pfenning & L. H. Ford, *The unphysical nature of 'warp drive'*, Classical and Quantum Gravity **14**, pp. 1743–1751, 1997. Cited on page 159.

154 A excellent technical introduction to nuclear physics is Bogdan Povh, Klaus Rith, Christoph Scholz & Frank Zetsche, *Teilchen und Kerne*, Springer, 5th edition, 1999. It is also available in English translation. Cited on page 162.

155 For magnetic resonance imaging films of the heart beat, search for 'cardiac MRI' on the internet. See for example www.youtube.com/watch?v=58l6oFhfZU. Cited on page 164.

156 See the truly unique paper by C. Bamberg, G. Rademacher, F. Güttler, U. Teichgräber, M. Cremer, C. Bührer, C. Spies, L. Hinkson, W. Henrich, K. D. Kalache & J. W. Dudenhausen, *Human birth observed in real-time open magnetic resonance imaging*, American Journal of Obstetrics & Gynecology **206**, p. 505e1-505e6, 2012. Cited on page 164.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

located on Earth moves with over one million kilometres per hour through the cosmic background radiation; we also observe that consciousness moves along with it.

The brain is a quantum system: it is based on molecules and electrical currents. The changes in consciousness that appear when matter is taken away from the brain – in operations or accidents – or when currents are injected into the brain – in accidents, experiments or misguided treatments – have been described in great detail by the medical profession. Also the observed influence of chemicals on the brain – from alcohol to hard drugs – makes the same point. The brain is a quantum system.

Modern imaging machines can detect which parts of the brain work when sensing, remembering or thinking. Not only is sight, noise and thought processed in the brain; we can follow these processes with measurement apparatus. The best imaging machines are Page 162 based on magnetic resonance, as described below. Another, more questionable imaging technique, positron tomography, works by letting people swallow radioactive sugar. Both techniques confirm the findings on the location of thought and on its dependence on chemical fuel. In addition, we already know that memory depends on the particle nature of matter. All these observations depend on the quantum of action.

Today, we are thus in the same situation as material scientists were a century ago: they knew that matter is made of charged particles, but they could not say *how* matter is built up. Similarly, we know today that consciousness is made from the signal propagation and signal processing in the brain; we know that consciousness is an electrochemical process. But we do not know yet the details of *how* the signals make up consciousness. Unravelling the workings of this fascinating quantum system is the aim of neurology. This is one of the great challenges of twenty-first century science.

Can you add a few arguments to the ones given here, showing that consciousness is a physical process? Can you show in particular that not only the consciousness of others, but also your own consciousness is a quantum process? Can you show, in addition, that Challenge 31 s despite being a quantum process, coherence plays no essential role in consciousness?

In short, our consciousness is a consequence of the matter that makes us up. Consciousness and pleasure depend on matter, its interactions and the quantum of action.

Why can we observe motion? – Again

Studying nature can be one of the most intense pleasures of life. All pleasures are based on our ability to observe or detect motion. And our human condition is central to this ability. In particular, in our adventure so far we found the following connections: We experience motion

- only because we are of finite size, and in particular, because we are large compared to our quantum mechanical wavelength (so that we do not experience wave effects in everyday life),
- only because we are large compared to a black hole of our same mass (so that we have useful interactions with our environment),
- only because we are made of a large but finite number of atoms (to produce memory and enable observations),
- only because we have a limited memory (so that we can clear it),
- only because we have a finite but moderate temperature (finite so that we have a lifetime, not zero so that we can be working machines),

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

— only because we are a mixture of liquids and solids (enabling us to move and thus to experiment),
— only because we are approximately electrically neutral (thus avoiding that our sensors get swamped),
— only because our brain forces us to approximate space and time by continuous entities (otherwise we would not form these concepts),
— only because our brain cannot avoid describing nature as made of different parts (otherwise we would not be able to talk or think),
— only because our ancestors reproduced,
— only because we are animals (and thus have a brain),
— only because life evolved here on Earth,
— only because we live in a relatively quiet region of our galaxy (which allowed evolution), and
— only because the human species evolved long after the big bang (when the conditions were more friendly to life).

If any of these conditions – and many others – were not fulfilled, we would not observe motion; we would have no fun studying physics. In fact, we can also say: if any of these conditions were not fulfilled, motion would not exist. In many ways motion is thus an illusion, as Zeno of Elea had claimed a long time ago. Of course, motion is a *inevitable* illusion, one that is shared by many other animals and machines. To say the least, the observation and the concept of motion is a result of the properties and limitations of the human condition. A complete description of motion and nature must take this connection into account. Before we attempt that in the last volume of this adventure, we explore a few additional details.

Vol. I, page 15

Curiosities and fun challenges about quantum experience

Most clocks used in everyday life, those built inside the human body and those made by humans, are electromagnetic. Any clock on the wall, be it mechanical, quartz controlled, radio or solar controlled, is based on electromagnetic effects. Do you know an exception?

Challenge 32 s

* *

The sense of smell is quite complex. For example, the substance that smells most badly to humans is *skatole*, also called, with his other name, *3-methylindole*. This is the molecule to which the human nose is most sensitive. Skatole makes faeces smell bad; it is a result of haemoglobin entering the digestive tract through the bile. Skatole does not smell bad to all animals; in contrast to humans, flies are attracted by its smell. Skatole is also produced by some plants for this reason.

On the other hand, *small* levels of skatole do not smell bad to humans. Skatole is also used by the food industry in small quantities to give smell and taste to vanilla ice cream – though under the other name.

* *

It is worth noting that human senses detect energies of quite different magnitudes. The eyes can detect light energies of about 1 aJ, whereas the sense of touch can detect only

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Igor Novikov, *Black Holes and the Universe*, Cambridge University Press 1990. Cited on pages 150 and 154.

131 The original paper is W. G. Unruh, *Experimental black hole evaporation?*, Physical Review Letters **46**, pp. 1351–1353, 1981. A good explanation with good literature overview is the one by Matt Visser, *Acoustical black holes: horizons, ergospheres and Hawking radiation*, arxiv.org/abs/gr-qc/9712010. Cited on page 151.

132 Optical black holes are explored in W. G. Unruh & R. Schützhold, *On slow light as a black hole analogue*, Physical Review D **68**, p. 024008, 2003, preprint at arxiv.org/abs/gr-qc/0303028. Cited on page 151.

133 T. Damour & R. Ruffini, *Quantum electrodynamical effects in Kerr–Newman geometries*, Physical Review Letters **35**, pp. 463–466, 1975. Cited on page 153.

134 These were the Vela satellites; their existence and results were announced officially only in 1974, even though they were working already for many years. Cited on page 152.

135 An excellent general introduction into the topic of gamma ray bursts is S. Klose, J. Greiner & D. Hartmann, *Kosmische Gammastrahlenausbrüche – Beobachtungen und Modelle*, Teil I und II, Sterne und Weltraum March and April 2001. Cited on pages 152 and 153.

136 When the gamma-ray burst encounters the matter around the black hole, it is broadened. The larger the amount of matter, the broader the pulse is. See G. Preparata, R. Ruffini & S.-S. Xue, *The dyadosphere of black holes and gamma-ray bursts*, Astronomy and Astrophysics **338**, pp. L87–L90, 1998, R. Ruffini, J. D. Salmonson, J. R. Wilson & S.-S. Xue, *On the pair electromagnetic pulse of a black hole with electromagnetic structure*, Astronomy and Astrophysics **350**, pp. 334–343, 1999, R. Ruffini, J. D. Salmonson, J. R. Wilson & S.-S. Xue, *On the pair electromagnetic pulse from an electromagnetic black hole surrounded by a baryonic remnant*, Astronomy and Astrophysics **359**, pp. 855–864, 2000, and C. L. Bianco, R. Ruffini & S.-S. Xue, *The elementary spike produced by a pure e^+e^- pair-electromagnetic pulse from a black hole: the PEM pulse*, Astronomy and Astrophysics **368**, pp. 377–390, 2001. For a very personal account by Ruffini on his involvement in gamma-ray bursts, see his paper *Black hole formation and gamma ray bursts*, arxiv.org/abs/astro-ph/0001425. Cited on page 153.

137 See the publication by D.W. Fox & al., *Early optical emission from the γ-ray burst of 4 October 2002*, Nature **422**, pp. 284–286, 2003. See also arxiv.org/abs/astro-ph/0301377, arxiv.org/abs/astro-ph/0301262 and arxiv.org/abs/astro-ph/0303539. Cited on page 152.

138 Negative heat capacity has also been found in atom clusters and in nuclei. See, e.g., M. Schmidt & al., *Negative heat capacity for a cluster of 147 sodium atoms*, Physical Review Letters **86**, pp. 1191–1194, 2001. Cited on page 154.

139 H.-P. Nollert, *Quasinormal modes: the characteristic 'sound' of black holes and neutron stars*, Classical and Quantum Gravity **16**, pp. R159–R216, 1999. Cited on page 154.

140 On the membrane description of black holes, see Kip S. Thorne, Richard H. Price & Douglas A. MacDonald, editors, *Black Holes: the Membrane Paradigm*, Yale University Press, 1986. Cited on page 154.

141 Page wrote a series of papers on the topic; a beautiful summary is Don N. Page, *How fast does a black hole radiate information?*, International Journal of Modern Physics **3**, pp. 93–106, 1994, which is based on his earlier papers, such as *Information in black hole radiation*, Physical Review Letters **71**, pp. 3743–3746, 1993. See also his preprint at arxiv.org/abs/hep-th/9305040. Cited on page 155.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

at arxiv.org/abs/hep-ph/0502081 and A. Yu. Voronin, H. Abele, S. Baessler, V. V. Nesvizhevsky, A. K. Petukhov, K. V. Protasov & A. Westphal, *Quantum motion of a neutron in a wave-guide in the gravitational field*, Physical Review D 73, p. 044029, 2006, preprint at arxiv.org/abs/quant-ph/0512129. Cited on page 141.

119 H. Rauch, W. Treimer & U. Bonse, *Test of a single crystal neutron interferometer*, Physics Letters A 47, pp. 369–371, 1974. Cited on page 142.

120 R. Colella, A. W. Overhauser & S. A. Werner, *Observation of gravitationally induced quantum mechanics*, Physical Review Letters 34, pp. 1472–1475, 1975. This experiment is usually called the COW experiment. Cited on page 142.

121 Ch. J. Bordé & C. Lämmerzahl, *Atominterferometrie und Gravitation*, Physikalische Blätter 52, pp. 238–240, 1996. See also A. Peters, K. Y. Chung & S. Chu, *Observation of gravitational acceleration by dropping atoms*, Nature 400, pp. 849–852, 26 August 1999. Cited on page 142.

122 J. D. Bekenstein, *Black holes and entropy*, Physical Review D 7, pp. 2333–2346, 1973. Cited on page 145.

123 R. Bousso, *The holographic principle*, Review of Modern Physics 74, pp. 825–874, 2002, also available as arxiv.org/abs/hep-th/0203101. The paper is an excellent review; however, it has some argumentation errors, as explained on page 146. Cited on page 146.

124 This is clearly argued by S. Carlip, *Black hole entropy from horizon conformal field theory*, Nuclear Physics B Proceedings Supplement 88, pp. 10–16, 2000. Cited on page 146.

125 S. A. Fulling, *Nonuniqueness of canonical field quantization in Riemannian space-time*, Physical Review D 7, pp. 2850–2862, 1973, P. Davies, *Scalar particle production in Schwarzchild and Rindler metrics*, Journal of Physics A: General Physics 8, pp. 609–616, 1975, W. G. Unruh, *Notes on black hole evaporation*, Physical Review D 14, pp. 870–892, 1976. Cited on page 146.

126 About the possibility to measure Fulling–Davies–Unruh radiation directly, see for example the paper by H. Rosu, *On the estimates to measure Hawking effect und Unruh effect in the laboratory*, International Journal of Modern Physics D3 p. 545, 1994. arxiv.org/abs/gr-qc/9605032 or the paper P. Chen & T. Tajima, *Testing Unruh radiation with ultra-intense lasers*, Physical Review Letters 83, pp. 256–259, 1999. Cited on page 147.

127 E. T. Akhmedov & D. Singleton, *On the relation between Unruh and Sokolov–Ternov effects*, preprint at arxiv.org/abs/hep-ph/0610391; see also E. T. Akhmedov & D. Singleton, *On the physical meaning of the Unruh effect*, preprint at arxiv.org/abs/0705.2525. Unfortunately, as Bell and Leinaas mention, the Sokolov–Ternov effect cannot be used to confirm the expression of the black hole entropy, because the radiation is not thermal, and so a temperature of the radiation is hard to define. Nevertheless, C. Schiller predicts (October 2009) that careful analysis of the spectrum could be used (1) to check the proportionality of entropy and area in black holes, and (2) to check the transformation of temperature in special relativity. Cited on page 147.

128 W. G. Unruh & R. M. Wald, *Acceleration radiation and the generalised second law of thermodynamics*, Physical Review D 25, pp. 942–958 , 1982. Cited on page 148.

129 R. M. Wald, *The thermodynamics of black holes*, Living Reviews of Relativity 2001, www-livingreviews.org/lrr-2001-6. Cited on page 149.

130 For example, if neutrinos were massless, they would be emitted by black holes more frequently than photons. For a delightful popular account from a black hole expert, see

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Challenge 33 s energies as small as about 10 μJ. Is one of the two systems relativistic?

* *

The human construction plan is stored in the DNA. The DNA is structured into 20 000 genes, which make up about 2 % of the DNA, and 98 % non-coding DNA, once called 'junk DNA'. Humans have as many genes as worms; plants have many more. Only around 2010 it became definitely clear, through the international 'Encode' project, what the additional 98 % of the DNA do: they switch genes on and off. They form the *administration* of the genes and work mostly by binding to specific proteins.

Research suggests that most genetic defects, and thus of genetic diseases, are not due to errors in genes, but in errors of the control switches. All this is an ongoing research field.

* *

Even at perfect darkness, the eye does not yield a black impression, but a slightly brighter one, called *eigengrau*. This is a result of noise created inside the eye, probably triggered by spontaneous decay of rhodopsin, or alternatively, by spontaneous release of neurotransmitters.

* *

The high sensitivity of the ear can be used to *hear* light. To do this, take an empty 750 ml jam glass. Keeping its axis horizontal, blacken the upper half of the inside with a candle. The lower half should remain transparent. After doing this, close the jam glass with its lid, and drill a 2 to 3 mm hole into it. If you now hold the closed jam glass with the hole to your ear, keeping the black side up, and shining into it from below with a 50 W light
Challenge 34 s bulb, something strange happens: you hear a 100 Hz sound. Why?

* *

Most senses work already before birth. It is well-known since many centuries that playing the violin to a pregnant mother every day during the pregnancy has an interesting effect. Even if nothing is told about it to the child, it will become a violin player later on. In fact, most musicians are 'made' in this way.

* *

There is ample evidence that not using the senses is damaging. People have studied what happens when in the first years of life the vestibular sense – the one used for motion detection and balance restoration – is not used enough. Lack of rocking is extremely hard to compensate later in life. Equally dangerous is the lack of use of the sense of touch. Babies, like all small mammals, that are generally and systematically deprived of these
Ref. 37 experiences tend to violent behaviour during the rest of their life.

* *

The importance of ion channels in the human body can not be overstressed. Ion channels malfunctions are responsible for many infections, for certain types of diabetes and
Ref. 38 for many effects of poisons. But above all, ion channels, and electricity in general, are essential for life.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

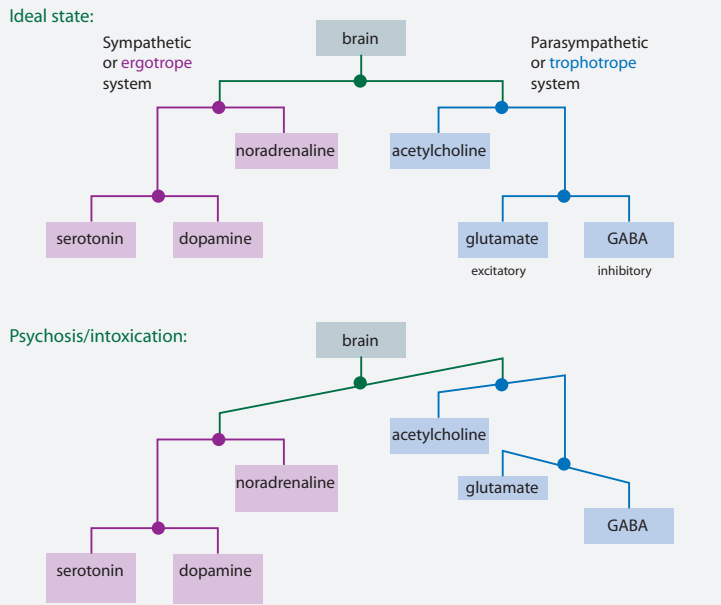


FIGURE 15 The 'neurochemical mobile' model of well-being, with one of the way it can get out of balance.

* *

Our body contains many systems that avoid unpleasant outcomes. For example, it was discovered in 2006 that saliva contains a strong pain killer, much stronger than morphine; it is now called *opiorphin*. It prevents that small bruises inside the mouth disturb us too much. Opiorphine also acts as an antidepressant. Future research has to show whether food addiction is related to this chemical.

* *

It is still unknown why people – and other mammals – *yawn*. This is still a topic of research.

* *

Nature has invented the senses to increase pleasure and avoid pain. But neurologists have found out that nature has gone even further; there is a dedicated *pleasure system* in the brain, shown in Figure 16, whose function is to decide which experiences are pleasurable and which not. The main parts of the pleasure system are the *ventral tegmental area* in

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

G. W. 't Hooft, M. B. van der Mark & C. W. J. Beenakker, *Observation of the optical analogue of quantized conductance of a point contact*, Nature **350**, pp. 594–595, 18 April 1991, and the longer version E. A. Montie, E. C. Cosman, G. W. 't Hooft, M. B. van der Mark & C. W. J. Beenakker, *Observation of the optical analogue of the quantised conductance of a point contact*, Physica B **175**, pp. 149–152, 1991. For more details on this experiment, see the volume *Light, Charges and Brains* of the Motion Mountain series. Cited on page 133.

110 Research on how humans move is published in the journals Human Movement Science and also in Human Movement. Cited on page 137.

111 See, for example, the paper by D. A. Bryant, *Electron acceleration in the aurora*, Contemporary Physics **35**, pp. 165–179, 1994. A recent development is D. L. Chandler, *Mysterious electron acceleration explained*, found at web.mit.edu/newsoffice/2012/plasma-phenomenon-explained-0227.html; it explains the results of the paper by J. Egedal, W. Daughton & A. Le, *Large-scale acceleration by parallel electric fields during magnetic reconnection*, Nature Physics 2012. Cited on page 137.

112 The is a recent research field; discharges above clouds are described, e.g., on www.spritesandjets.com and on en.wikipedia.org/wiki/Sprite_(lightning). See also eurosprite.blogspot.com. Cited on page 137.

113 About Coulomb explosions and their importance for material processing with lasers, see for example D. Müller, *Picosecond lasers for high-quality industrial micromachining*, Photonics Spectra pp. 46–47, November 2009. Cited on page 137.

114 See, e.g., L.O'C. Drury, *Acceleration of cosmic rays*, Contemporary Physics **35**, pp. 231–242, 1994. Cited on page 137.

115 See Dirk Kreimer, *New mathematical structures in renormalizable quantum field theories*, arxiv.org/abs/hep-th/0211136 or Annals of Physics **303**, pp. 179–202, 2003, and the erratum ibid., **305**, p. 79, 2003. Cited on page 137.

116 See, for example, the paper by M. Urban, *A particle mechanism for the index of refraction*, preprint at arxiv.org/abs/0709.1550. Cited on page 138.

117 S. Fray, C. Alvarez Diez, T. W. Hänsch & M. Weitz, *Atomic interferometer with amplitude gratings of light and its applications to atom based tests of the equivalence principle*, Physical Review Letters **93**, p. 240404, 2004, preprint at arxiv.org/abs/physics/0411052. The idea for the experiment is old and can be traced back to the proposal, made in the 1950s, to build an atomic fountain. Cited on page 140.

118 The original papers on neutron behaviour in the gravitational field are all worth reading. The original feat was reported in V. V. Nesvizhevsky, H. G. Boerner, A. K. Petoukhov, H. Abele, S. Baessler, F. Ruess, Th. Stoeferle, A. Westphal, A. M. Gagarski, G. A. Petrov & A. V. Strelkov, *Quantum states of neutrons in the Earth's gravitational field*, Nature **415**, pp. 297–299, 17 January 2002. Longer explanations are found in V. V. Nesvizhevsky, H. G. Boerner, A. M. Gagarsky, A. K. Petoukhov, G. A. Petrov, H. Abele, S. Baessler, G. Divkovic, F. J. Ruess, Th. Stoeferle, A. Westphal, A. V. Strelkov, K. V. Protasov & A. Yu. Voronin, *Measurement of quantum states of neutrons in the Earth's gravitational field*, Physical Review D **67**, p. 102002, 2003, preprint at arxiv.org/abs/hep-ph/0306198, and in V. V. Nesvizhevsky, A. K. Petukhov, H. G. Boerner, T. A. Baranova, A. M. Gagarski, G. A. Petrov, K. V. Protasov, A. Yu. Voronin, S. Baessler, H. Abele, A. Westphal & L. Lucovac, *Study of the neutron quantum states in the gravity field*, European Physical Journal C **40**, pp. 479–491, 2005, preprint

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

I. Klich, A. Mann & M. Revzen, *Repulsive Casimir forces*, Physical Review Letters **89**, p. 033001, 2002. However, none of these effects has been verified yet. Cited on page 125.

99 The effect was discovered by K. Scharnhorst, *On propagation of light in the vacuum between plates*, Physics Letters B **236**, pp. 354–359, 1990. See also G. Barton, *Faster-than-c light between parallel mirrors: the Scharnhorst effect rederived*, Physics Letters B **237**, pp. 559–562, 1990, and P. W. Milonni & K. Svozil, *Impossibility of measuring faster-than-c signalling by the Scharnhorst effect*, Physics Letters B **248**, pp. 437–438, 1990. The latter corrects an error in the first paper. Cited on page 125.

100 D.L. Burke & al., *Positron production in multiphoton light-by-light scattering*, Physical Review Letters **79**, pp. 1626–1629, 1997. A simple summary is given in Bertram Schwarzschild, *Gamma rays create matter just by plowing into laser light*, Physics Today **51**, pp. 17–18, February 1998. Cited on page 130.

101 M. Kardar & R. Golestanian, *The 'friction' of the vacuum, and other fluctuation-induced forces*, Reviews of Modern Physics **71**, pp. 1233–1245, 1999. Cited on page 131.

102 G. Gour & L. Sriramkumar, *Will small particles exhibit Brownian motion in the quantum vacuum?*, arxiv.org/abs/quant/phys/9808032 Cited on page 131.

103 P. A. M. Dirac, *The requirements of fundamental physical theory*, European Journal of Physics **5**, pp. 65–67, 1984. This article transcribes a speech by Paul Dirac just before his death. Disturbed by the infinities of quantum electrodynamics, he rejects as wrong the theory which he himself found, even though it correctly describes all experiments. The humility of a great man who is so dismissive of his main and great achievement was impressive when hearing him, and still is impressive when reading the talk. Cited on page 132.

104 H. Euler & B. Kockel, Naturwissenschaften **23**, p. 246, 1935, H. Euler, Annalen der Physik **26**, p. 398, 1936, W. Heisenberg & H. Euler, *Folgerung aus der Diracschen Theorie des Electrons*, Zeitschrift für Physik **98**, pp. 714–722, 1936. Cited on page 133.

105 Th. Stoehlker & al., *The 1s Lamb shift in hydrogenlike uranium measured on cooled, decelerated ions beams*, Physical Review Letters **85**, p. 3109, 2000. Cited on page 133.

106 M. Roberts & al., *Observation of an electric octupole transition in a single ion*, Physical Review Letters **78**, pp. 1876–1879, 1997. A lifetime of 3700 days was determined. Cited on page 133.

107 See the instructive paper by J. Młyńczak, J. Kubicki & K. Kopczyński *Stand-off detection of alcohol in car cabins*, Journal of Applied Remote Sensing **8**, p. 083627, 2014. Cited on page 119.

108 The fluid helium based quantum gyroscope was first used to measure the rotation of the Earth by the French research group O. Avenel & E. Varoquaux, *Detection of the Earth rotation with a superfluid double-hole resonator*, Czechoslovak Journal of Physics (Supplement S6) **48**, pp. 3319–3320, 1996. The description of the set-up is found in Yu. Mukharsky, O. Avenel & E. Varoquaux, *Observation of half-quantum defects in superfluid* ^{3}He – B, Physical Review Letters **92**, p. 210402, 2004. The gyro experiment was later repeated by the Berkeley group, K. Schwab, N. Bruckner & R. E. Packard, *Detection of the Earth's rotation using superfluid phase coherence*, Nature **386**, pp. 585–587, 1997. For an review of this topic, see O. Avenel, Yu. Mukharsky & E. Varoquaux, *Superfluid gyrometers*, Journal of Low Temperature Physics **135**, p. 745, 2004. Cited on page 120.

109 K. Schwab, E. A. Henriksen, J. M. Worlock & M. L. Roukes, *Measurement of the quantum of thermal conductance*, Nature **404**, p. 974, 2000. For the optical analog of the experiment, see the beautiful paper by E. A. Montie, E. C. Cosman,

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

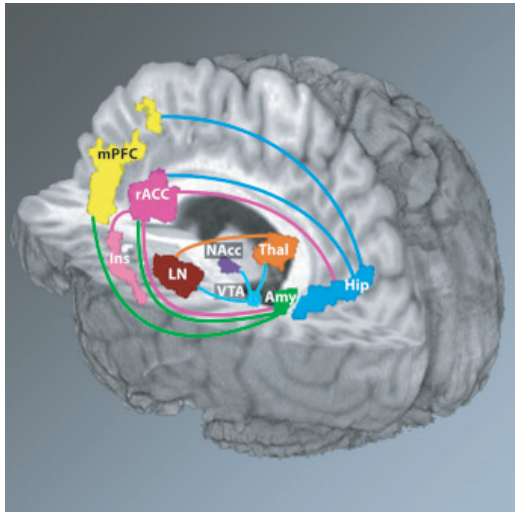


FIGURE 16 The location of the ventral tegmental area (VTA) and of the nucleus accumbens (NAcc) in the brain. The other regions involved in pleasure and addiction are Amy, the amygdala, Hip, the hippocampus, Thal, the thalamus, rACC, the rostral anterior cingulate cortex, mPFC, the medial prefrontal cortex, Ins, the insula, and LN, the lentiform nucleus (courtesy NIH).

the midbrain and the *nucleus accumbens* in the forebrain. The two parts regulate each other mainly through *dopamine* and *GABA*, two important neurotransmitters. Research has shown that dopamine is produced whenever pleasure exceeds expectations. Nature has thus developed a special signal for this situation.

In fact, well-being and pleasure are controlled by a large number of neurotransmitters and by many additional regulation circuits. Researchers are trying to model the pleasure system with hundreds of coupled differential equations, with the distant aim being to understand addiction and depression, for example. On the other side, also simple models of the pleasure system are possible. One, shown in Figure 15, is the 'neurochemical mobile' model of the brain. In this model, well-being is achieved whenever the six most important neurotransmitters* are in relative equilibrium. The different possible departures from equilibrium, at each joint of the mobile, can be used to describe depression, schizophrenia, psychosis, the effect of nicotine or alcohol intake, alcohol dependency, delirium, drug addiction, detoxication, epilepsy and more.

Ref. 39

* Neurotransmitters come in many types. They can be grouped into *mono- and diamines* – such as dopamine, serotonin, histamine, adrenaline – *acetylcholine*, *amino acids* – such as glycine, GABA and glutamate – *polypeptides* – such as oxytocin, vasopressin, gastrin, the opiods, the neuropetides etc. – *gases* – such as NO and CO – and a number of molecules that do not fit into the previous classes – such as anandamide or NAAG.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

* *

The pleasure system in the brain is not only responsible for addiction. It is also responsible, as Helen Fisher showed through MRI brain scans, for romantic love. Romantic love, directed to one single other person, is a state that is created in the ventral tegmental area and in the nucleus accumbens. Romantic love is thus a part of the reptilian brain; indeed, romantic love is found in many animal species. Romantic love is a kind of positive addiction, and works like cocaine. In short, in life, we can all choose between addiction and love.

Ref. 40

* *

An important aspect of life is death. When we die, conserved quantities like our energy, momentum, angular momentum and several other quantum numbers are redistributed. They are redistributed because conservation means that nothing is lost. What does all this imply for what happens after death?

Challenge 35 s

* *

We all know the smell that appears in the open field at the start of a summer rainfall, or the smell of fresh earth. It is due to a substance called *geosmin*, a bicyclic alcohol that is produced by bacteria in the soil. The bacteria produce it when it rains. For reasons not fully understood, the human nose is especially sensitive to the smell of geosmin: we are able to smell it at concentrations below 10^{-10}.

* *

Also plants have sensors. Plants can sense light, touch, gravity, chemicals, as well as electric fields and currents. Many plants grow differently when touched; roots sense and conduct electric signals and then grow accordingly; obviously, plants grow against gravity and towards light. Above all, plants are known to be able to distinguish many different chemicals in the air, above all, ethene (ethylene), which is also an important plant hormone.

* *

Many plants have built-in sensors and clocks that measure the length of the day. For example, *spinach* does not grow in the tropics, because in order to flower, spinach must sense for at least fourteen days in a row that the day is at least 14 hours long – and this never happens in the tropics. This property of plants, called *photoperiodism*, was discovered in 1920 by Wightman Garner and Harry Allard while walking across tobacco fields. They discovered – and proved experimentally – that tobacco plants and soya plants only flower when the length of the day gets sufficiently short, thus around September. Garner and Allard found that plants could be divided into species that flower when days are short – such as chrysanthemum or coffee – others that flower when days are long – such as carnation or clover – and still others that do not care about the length of the day at all – such as roses or tomatoes. The measurement precision for the length of the day is around 10 min. The day length sensor itself was discovered only much later; it is located in the leaves of the plant, is called the *phytochrome system* and is based on specialised proteins. The proteins are able to measure the ratio between bright red and dark red light and control the moment of flower opening in such plants.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

temperature quantum Hall effect in graphene, Science **315**, p. 1379, 2007. Cited on page 107.

82 See for example the overview by M. Born & T. Jüstel, *Umweltfreundliche Lichtquellen*, Physik Journal **2**, pp. 43–49, 2003. Cited on page 108.

83 K. An, J. J. Childs, R. R. Desari & M. S. Field, *Microlaser: a laser with one atom in an optical resonator*, Physical Review Letters **73**, pp. 3375–3378, 19 December 1994. Cited on page 114.

84 J. Kasparian, *Les lasers femtosecondes : applications atmosphériques*, La Recherche pp. RE14 1–7, February 2004/ See also the www.teramobile.org website. Cited on page 115.

85 A. Takita, H. Yamamoto, Y. Hayasaki, N. Nishida & H. Misawa, *Three-dimensional optical memory using a human fingernail*, Optics Express **13**, pp. 4560–4567, 2005. They used a Ti:sapphire oscillator and a Ti:sapphire amplifier. Cited on page 115.

86 The author predicted laser umbrellas in 2011. Cited on page 115.

87 W. Guo & H. Maris, *Observations of the motion of single electrons in liquid helium*, Journal of Low Temperature Physics **148**, pp. 199–206, 2007. Cited on page 117.

88 The story is found on many places in the internet. Cited on page 119.

89 S. L. Boersma, *Aantrekkende kracht tussen schepen*, Nederlands tidschrift voor natuuurkunde **67**, pp. 244–246, Augustus 2001. See also his paper S. L. Boersma, *A maritime analogy of the Casimir effect*, American Journal of Physics **64**, pp. 539–541, 1996. Cited on page 122.

90 P. Ball, *Popular physics myth is all at sea – does the ghostly Casimir effect really cause ships to attract each other?*, online at www.nature.com/news/2006/060501/full/news060501-7.html. Cited on pages 122 and 125.

91 A. Larraza & B. Denardo, *An acoustic Casimir effect*, Physics Letters A **248**, pp. 151–155, 1998. See also A. Larraza, *A demonstration apparatus for an acoustic analog of the Casimir effect*, American Journal of Physics **67**, pp. 1028–1030, 1999. Cited on page 124.

92 H. B. G. Casimir, *On the attraction between two perfectly conducting bodies*, Proceedings of the Koninklijke Nederlandse Akademie van Wetenschappen **51**, pp. 793–795, 1948. Cited on page 124.

93 H. B. G. Casimir & D. Polder, *The influence of retardation on the London–Van der Waals forces*, Physical Review **73**, pp. 360–372, 1948. Cited on page 124.

94 B. W. Derjaguin, I. I. Abrikosova & E. M. Lifshitz, *Direct measurement of molecular attraction between solids separated by a narrow gap*, Quaterly Review of the Chemical Society (London) **10**, pp. 295–329, 1956. Cited on page 124.

95 M. J. Sparnaay, *Attractive forces between flat plates*, Nature **180**, pp. 334–335, 1957. M. J. Sparnaay, *Measurements of attractive forces between flat plates*, Physica (Utrecht) **24**, pp. 751–764, 1958. Cited on page 124.

96 S. K. Lamoreaux, *Demonstration of the Casimir force in the 0.6 to 6 μm range*, Physical Review Letters **78**, pp. 5–8, 1997. U. Mohideen & A. Roy, *Precision measurement of the Casimir force from 0.1 to 0.9 μm*, Physical Review Letters **81**, pp. 4549–4552, 1998. Cited on page 124.

97 A. Lambrecht, *Das Vakuum kommt zu Kräften*, Physik in unserer Zeit **36**, pp. 85–91, 2005. Cited on page 124.

98 T. H. Boyer, *Van der Waals forces and zero-point energy for dielectric and permeable materials*, Physical Review A **9**, pp. 2078–2084, 1974. This was taken up again in O. Kenneth,

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

69 Ingo Dierking, *Textures of Liquid Crystals*, Wiley-VCH, 2003. Cited on page 95.

70 The *photon hall effect* was discovered by Geert Rikken, Bart van Tiggelen & Anja Sparenberg, *Lichtverstrooiing in een magneetveld*, Nederlands tijdschrift voor natuurkunde **63**, pp. 67–70, maart 1998. Cited on page 96.

71 C. Strohm, G. L. J. A. Rikken & P. Wyder, *Phenomenological evidence for the phonon Hall effect*, Physical Review Letters **95**, p. 155901, 2005. Cited on page 97.

72 E. Chibowski, L. Hołysz, K. Terpiłowski, *Effect of magnetic field on deposition and adhesion of calcium carbonate particles on different substrates*, Journal of Adhesion Science and Technology **17**, pp. 2005–2021, 2003, and references therein. Cited on page 97.

73 K. S. Novoselov, D. Jiang, F. Schedin, T. Booth, V. V. Khotkevich, S. V. Morozov & A. K. Geim, *Two Dimensional Atomic Crystals*, Proceedings of the National Academy of Sciences **102**, pp. 10451–10453, 2005. See also the talk by Andre Geim, *QED in a pencil trace*, to be downloaded at online.kitp.ucsb.edu/online/graphene_m07/geim/ or A. C. Neto, F. Guinea & N. M. Peres, *Drawing conclusions from graphene*, Physics World November 2006. Cited on pages 97, 98, and 414.

74 R.R. Nair & al., *Fine structure constant defines visual transparency of graphene*, Science **320**, p. 1308, 2008. Cited on page 99.

75 The first paper was J. Bardeen, L. N. Cooper & J. R. Schrieffer, *Microscopic Theory of Superconductivity*, Physical Review **106**, pp. 162–164, 1957. The full, so-called BCS theory, is then given in the masterly paper J. Bardeen, L. N. Cooper & J. R. Schrieffer, *Theory of Superconductivity*, Physical Review **108**, pp. 1175–1204, 1957. Cited on page 103.

76 A. P. Finne, T. Araki, R. Blaauwgeers, V. B. Eltsov, N. B. Kopnin, M. Krusius, L. Skrbek, M. Tsubota & G. E. Volovik, *An intrinsic velocity-independent criterion for superfluid turbulence*, Nature **424**, pp. 1022–1025, 2003. Cited on page 105.

77 The original prediction, which earned Laughlin a Nobel Prize in Physics, is in R. B. Laughlin, *Anomalous quantum Hall effect: an incompressible quantum fluid with fractionally charged excitations*, Physical Review Letters **50**, pp. 1395–1398, 1983. Cited on page 107.

78 The first experimental evidence is by V. J. Goldman & B. Su, *Resonance tunnelling in the fractional quantum Hall regime: measurement of fractional charge*, Science **267**, pp. 1010–1012, 1995. The first unambiguous measurements are by R. de Picciotto & al., *Direct observation of a fractional charge*, Nature **389**, pp. 162–164, 1997, and L. Saminadayar, D. C. Glattli, Y. Jin & B. Etienne, *Observation of the e*,3 fractionally charged Laughlin quasiparticle/ Physical Review Letters **79**, pp. 2526–2529, 1997. or arxiv.org/abs/cond-mat/9706307. Cited on page 107.

79 The discovery of the original quantum Hall effect, which earned von Klitzing the Nobel Prize in Physics, was published as K. von Klitzing, G. Dorda & M. Pepper, *New method for high-accuracy determination of the fine-structure constant based on quantised Hall resistance*, Physical Review Letters **45**, pp. 494–497, 1980. Cited on page 107.

80 The fractional quantum Hall effect was discovered by D. C. Tsui, H. L. Stormer & A. C. Gossard, *Two-dimensional magnetotransport in the extreme quantum limit*, Physical Review Letters **48**, pp. 1559–1562, 1982. Tsui and Stormer won the Nobel Prize in Physics with this paper. Cited on page 107.

81 K. S. Novoselov, Z. Jiang, Y. Zhang, S. V. Morozov, H. L. Stormer, U. Zeitler, J. C. Mann, G. S. Boebinger, P. Kim & A. K. Geim, *Room-*

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Summary on biology and pleasure

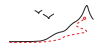
To ensure the successful reproduction of living beings, evolution has pursued miniaturization as much as possible. Molecular motors, including molecular pumps, are the smallest motors known so far; they work as quantum ratchets. Molecular motors are found in huge numbers in every living cell. In short:

▷ Every human consists of trillions of machines.

To increase pleasure and avoid pain, evolution has also supplied the human body also with numerous sensors, sensor mechanisms, and a pleasure system deep inside the brain. In short, nature has invented *pleasure* as a guide for behaviour. Neurologists have thus proven what Epicurus said 23 centuries ago and Sigmund Freud repeated one century ago:

▷ Pleasure controls human life.*

All biological pleasure sensors and pleasure systems are based on quantum motion, in particular on chemistry and materials science. We therefore explore both fields in the following.



* But Epicurus also said: 'It is impossible to live a pleasant life without living wisely and honourably and justly, and it is impossible to live wisely and honourably and justly without living pleasantly.' This is one of his *Principal Doctrines*.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Chapter 2

CHANGING THE WORLD WITH QUANTUM EFFECTS

The discovery of quantum effects has changed everyday life. It has allowed he distribution of speech, music and films. The numerous possibilities of elecommunications and of the internet, the progress in chemistry, materials science, electronics and medicine would not have been possible without quantum effects. Many other improvements of our everyday life are due to quantum physics, and many are still expected. In the following, we give a short overview of this vast field.

CHEMISTRY – FROM ATOMS TO DNA

> "Bier macht dumm.**"
>
> Albert Einstein

It is an old truth that Schrödinger's equation contains all of chemistry. With quantum theory, for the first time people were able to calculate the strengths of chemical bonds, and what is more important, the angle between them. Quantum theory thus explains the *shape* of molecules and thus indirectly, the shape of all matter. In fact, the correct statement is: the *Dirac* equation contains all of chemistry. The relativistic effects that distinguish the two equations are necessary, for example, to understand why gold is yellow and does not rust or why mercury is liquid. Ref. 41

To understand molecules and everyday matter, the first step is to understand atoms. The early quantum theorists, lead by Niels Bohr, dedicated their life to understanding their atoms and their detailed structure. The main result of their efforts is what you learn in secondary school: in atoms with more than one electron, the various electron clouds form spherical layers around the nucleus. The electron layers can be grouped into groups of related clouds that are called *shells*. For electrons outside the last fully occupied shell, the nucleus and the inner shells, the atomic *core*, can often be approximated as a single charged entity.

Shells are numbered from the inside out. This *principal quantum number*, usually written n, is deduced and related to the quantum number that identifies the states in the hydrogen atom. The relation is shown in Figure 17.

Quantum theory shows that the first atomic shell has room for two electrons, the second for 8, the third for 18, and the general n-th shell for $2n^2$ electrons. The (neutral)

** 'Beer makes stupid.'

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

58 The switchable mirror effect was discovered by J. N. Huiberts, R. Griessen, J. H. Rector, R. J. Wijngarden, J. P. Dekker, D. G. de Groot & N. J. Koeman, *Yttrium and lanthanum hydride films with switchable optical properties*, Nature **380**, pp. 231–234, 1996. A good introduction is R. Griessen, *Schaltbare Spiegel aus Metallhydriden*, Physikalische Blätter **53**, pp. 1207–1209, 1997. Cited on page 86.

59 V. F. Weisskopf, *Of atoms, mountains and stars: a study in qualitative physics*, Science **187**, p. 605, 1975. Cited on page 87.

60 K. Schwab, E. A. Henriksen, J. M. Worlock & M. L. Roukes, *Measurement of the quantum of thermal conductance*, Nature **404**, pp. 974–977, 2000. Cited on page 90.

61 K. Autumn, Y. Liang, T. Hsich, W. Zwaxh, W. P. Chan, T. Kenny, R. Fearing & R. J. Full, *Adhesive force of a single gecko foot-hair*, Nature **405**, pp. 681–685, 2000. Cited on page 90.

62 A. B. Kesel, A. Martin & T. Seidl, *Getting a grip on spider attachment: an AFM approach to microstructure adhesion in arthropods*, Smart Materials and Structures **13**, pp. 512–518, 2004. Cited on page 91.

63 See the article on www.bio-pro.de/magazin/wissenschaft/archiv_2005/index.html?lang=en&artikelid=/artikel/03049/index.html. Cited on page 91.

64 See the beautiful article by R. Ritchie, M. J. Buehler & P. Hansma, *Plasticity and toughness in bones*, Physics Today **82**, pp. 41–47, 2009. See also the fascinating review articles P. Fratzl, *Von Knochen, Holz und Zähnen*, Physik Journal **1**, pp. 49–55, 2002, and P. Fratzl & R. Weinkamer, *Nature's hierarchical materials*, Progress in Material Science **52**, pp. 1263–1334, 2007. Cited on page 91.

65 H. Inaba, T. Saitou, K. -I. Tozaki & H. Hayashi, *Effect of the magnetic field on the melting transition of H2O and D2O measured by a high resolution and supersensitive differential scanning calorimeter*, Journal of Applied Physics **96**, pp. 6127–6132, 2004. Cited on page 91.

66 The graph for temperature is taken from J. Jouzel & al., *Orbital and millennial Antarctic climate variability over the past 800,000 years*, Science **317**, pp. 793–796, 2007. The graph for CO_2 is combined from six publications: D.M. Etheridge & al., *Natural and anthropogenic changes in atmospheric CO_2 over the last 1000 years from air in Antarctic ice and firn*, Journal of Geophysical Research **101**, pp. 4115–4128, 1996, J.R. Petit & al., *Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica*, Nature **399**, pp. 429–436, 1999, A. Indermühle & al., *Atmospheric CO_2 concentration from 60 to 20 kyr BP from the Taylor Dome ic cores, Antarctica*, Geophysical Research Letters **27**, pp. 735–738, 2000, E. Monnin & al., *Atmospheric CO_2 concentration over the last glacial termination*, Science **291**, pp. 112–114, 2001, U. Siegenthaler & al., *Stable carbon cycle-climate relationship during the late pleistocene*, Science **310**, pp. 1313–1317, 2005, D. Lüthi & al., *High-resolution carbon dioxide concentration record 650,000-800,000 years before present*, Nature **453**, pp. 379–382, 2008. Cited on page 93.

67 H. Oerlemans, *De afkoeling van de aarde*, Nederlands tijdschrift voor natuurkunde pp. 230–234, 2004. This excellent paper by one of the experts of the field also explains that the Earth has two states, namely today's *tropical* state and the *snowball* state, when it is covered with ice. And there is hysteresis for the switch between the two states. Cited on page 93.

68 R. Hemley & al., presented these results at the International Conference on New Diamond Science in Tsukuba (Japan) 2005. See figures at www.carnegieinstitution.org/diamond-13may2005. Cited on page 93.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

42 On the internet, the 'spherical' periodic table is credited to Timothy Stowe; but there is no reference for that claim, except an obscure calendar from a small chemical company. The original table (containing a number errors) used to be found at the chemlab.pc.maricopa.edu/periodic/stowetable.html website; it is now best found by searching for images called 'stowetable' with any internet search engine. Cited on page 59.

43 For good figures of atomic orbitals, take any modern chemistry text. Or go to csi.chemie.tu-darmstadt.de/ak/immel/. Cited on page 60.

44 For experimentally determined pictures of the orbitals of dangling bonds, see for example F. Giessibl & al., *Subatomic features on the silicon (111)-(7x7) surface observed by atomic force microscopy*, Science **289**, pp. 422–425, 2000. Cited on page 60.

45 L. Gagliardi & B. O. Roos, *Quantum chemical calculations show that the uranium molecule U_2 has a quintuple bond*, Nature **433**, pp. 848–851, 2005. B. O. Roos, A. C. Borin & L. Gagliardi, *Reaching the maximum multiplicity of the covalent chemical bond*, Angewandte Chemie, International Edition **46**, pp. 1469–1472, 2007. Cited on page 62.

46 H. -W. Fink & C. Escher, *Zupfen am Lebensfaden – Experimente mit einzelnen DNS-Molekülen*, Physik in unserer Zeit **38**, pp. 190–196, 2007. Cited on page 62.

47 This type of atomic bond became well-known through the introduction by D. Kleppner, *The most tenuous of molecules*, Physics Today **48**, pp. 11–12, 1995. Cited on page 66.

48 Exploring the uses of physics and chemistry in forensic science is fascinating. For a beautiful introduction to this field with many stories and a lot of physics, see the book by Patrick Voss-de Haan, *Physik auf der Spur*, Wiley-VCH, 2005. Cited on page 67.

49 See, for example, the extensive explanations by Rafal Swiecki on his informatvie website www.minelinks.com. Cited on page 69.

50 T. Gu, M. Li, C. McCammon & K. K. M. Lee, *Redox-induced lower mantle density contrast and effect on mantle structure and primitive oxygen*, Nature Geoscience **9**, pp. 723–727, 2016. Cited on page 71.

51 See the website by Tom Hales on www.math.lsa.umich.edu/~hales/countdown. An earlier book on the issue is the delightful text by Max Leppmaier, *Kugelpackungen von Kepler bis heute*, Vieweg Verlag, 1997. Cited on page 73.

52 For a short overview, also covering binary systems, see C. Bechinger, H. -H. von Grünberg & P. Leiderer, *Entropische Kräfte - warum sich repulsiv wechselwirkende Teilchen anziehen können*, Physikalische Blätter **55**, pp. 53–56, 1999. Cited on page 73.

53 H. -W. Fink & G. Ehrlich, *Direct observation of three-body interactions in adsorbed layers: Re on W(110)*, Physical Review Letters **52**, pp. 1532–1534, 1984, and H. -W. Fink & G. Ehrlich, *Pair and trio interactions between adatoms: Re on W(110)*, Journal of Chemical Physics **61**, pp. 4657–4665, 1984. Cited on pages 73 and 74.

54 See for example the textbook by A. Pimpinelli & J. Villain, *Physics of Crystal Growth*, Cambridge University Press, 1998. Cited on page 74.

55 Y. Furukawa, *Faszination der Schneekristalle - wie ihre bezaubernden Formen entstehen*, Chemie in unserer Zeit **31**, pp. 58–65, 1997. His website www.lowtem.hokudai.ac.jp/~frkw/index_e.html gives more information on the topic of snow crystals. Cited on page 74.

56 L. Bindi, P. J. Steinhardt, N. Yai & P. J. Lu, *Natural Quasicrystal*, Science **324**, pp. 1306–1309, 2009. Cited on page 81.

57 The present attempts to build cheap THz wave sensors – which allow seeing through clothes – is described by D. Clery, *Brainstorming their way to an imaging revolution*, Science **297**, pp. 761–763, 2002. Cited on page 84.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

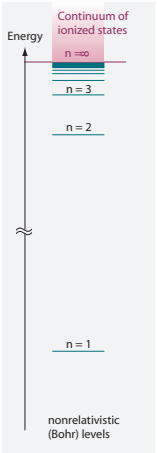


FIGURE 17 The principal quantum numbers in hydrogen.

atom with one electron is hydrogen, the atom with two electrons is called helium. Every chemical element has a specific number of electrons (and the same number of protons, as we will see). A way to picture this connection is shown in Figure 18. It is called the
Ref. 42 *periodic table of the elements*. The standard way to show the table is found on page 345 and, more vividly, in Figure 19. (For a periodic table with a video about each element, see www.periodicvideos.com.)

Experiments show that different atoms that share the *same* number of electrons in their outermost shell show *similar* chemical behaviour. Chemists know that the chemical behaviour of an element is decided by the ability of its atoms to from bonds. For example, the elements with one electron in their outer s shell are the *alkali metals* lithium, sodium, potassium, rubidium, caesium and francium; hydrogen, the exception, is conjectured to be metallic at high pressures. The elements with filled outermost shells are the *noble gases* helium, neon, argon, krypton, xenon, radon and ununoctium.

Atomic bonds

When two atoms approach each other, their electron clouds are deformed and mixed. The reason for these changes is the combined influence of the two nuclei. These cloud changes are highest for the outermost electrons: they form chemical *bonds*.

Bonds can be pictured, in the simplest approximation, as cloud overlaps that *fill* the outermost shell of both atoms. These overlaps lead to a gain in energy. The energy gain is the reason that fire is hot. In wood fire, chemical reactions between carbon and oxygen atoms lead to a large release of energy. After the energy has been released, the atomic bond produces a fixed distance between the atoms, as shown in Figure 20. This distance is due to an energy minimum: a lower distance would lead to electrostatic repulsion

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

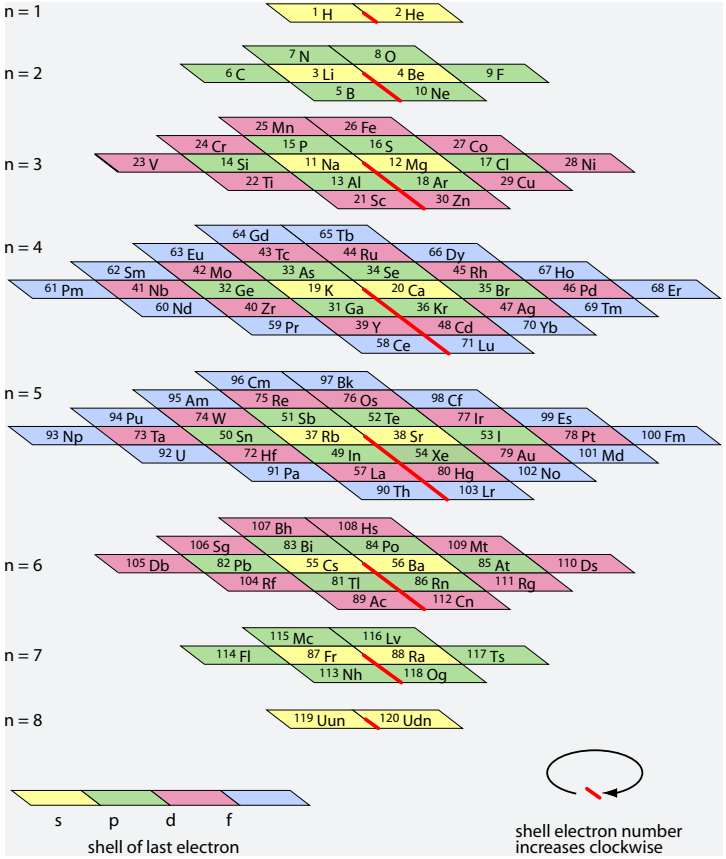


FIGURE 18 An unusual form of the periodic table of the elements.

between the atomic cores, a higher distance would increase the electron cloud energy.

Many atoms can bind to more than one neighbours. In this case, energy minimization also leads to specific bond angles, as shown in Figure 21. Maybe you remember those funny pictures of school chemistry about orbitals and dangling bonds. Such dangling bonds can now be measured and observed. Several groups were able to image them using scanning force or scanning tunnelling microscopes, as shown in Figure 22.

Ref. 43

Ref. 44

The repulsion between the clouds of each bond explains why angle values near that of tetrahedral skeletons ($2 \arctan \sqrt{2} = 109.47°$) are so common in molecules. For example,

Challenge 36 e

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

S. M. Rao, A. R. Mayer & D. L. Harrington, *The evolution of brain activation during temporal processing*, Nature Neuroscience **4**, pp. 317–323, 2001. Cited on page 44.

26 See, for example, Jan Hilgevoord, *Time in quantum mechanics*, American Journal of Physics **70**, pp. 301–306, 2002. Cited on page 44.

27 E. J. Zimmerman, *The macroscopic nature of space-time*, American Journal of Physics **30**, pp. 97–105, 1962. Cited on page 45.

28 See P.D. Peşić, *The smallest clock*, European Journal of Physics **14**, pp. 90–92, 1993. Cited on page 45.

29 The possibilities for precision timing using single-ion clocks are shown in W.H. Oskay & al., *Single-atom clock with high accuracy*, Physical Review Letters **97**, p. 020801, 2006. Cited on page 46.

30 A pretty example of a quantum mechanical system showing exponential behaviour at all times is given by H. Nakazato, M. Namiki & S. Pascazio, *Exponential behaviour of a quantum system in a macroscopic medium*, Physical Review Letters **73**, pp. 1063–1066, 1994. Cited on page 48.

31 See the delightful book about the topic by Paolo Facchi & Saverio Pascazio, *La regola d'oro di Fermi*, Bibliopolis, 1999. An experiment observing deviations at short times is S. R. Wilkinson, C. F. Bharucha, M. C. Fischer, K. W. Madison, P. R. Morrow, Q. Niu, B. Sundaram & M. G. Raizen, Nature **387**, p. 575, 1997. Cited on page 48.

32 See, for example, R. Efron, *The duration of the present*, Annals of the New York Academy of Sciences **138**, pp. 713–729, 1967. Cited on page 48.

33 W. M. Itano, D. J. Heinzen, J. J. Bollinger & D. J. Wineland, *Quantum Zeno effect*, Physical Review A **41**, pp. 2295–2300, 1990. M. C. Fischer, B. Gutiérrez-Medina & M. G. Raizen, *Observation of the Quantum Zeno and Anti-Zeno effects in an unstable system*, Physical Review Letters **87**, p. 040402, 2001, also www-arxiv.org/abs/quant-ph/0104035. Cited on page 50.

34 See P. Facchi, Z. Hradil, G. Krenn, S. Pascazio & J. Řeháček *Quantum Zeno tomography*, Physical Review A **66**, p. 012110, 2002. Cited on page 50.

35 See P. Facchi, H. Nakazato & S. Pascazio *From the quantum Zeno to the inverse quantum Zeno effect*, Physical Review Letters **86**, pp. 2699–2702, 2001. Cited on page 50.

36 H. Kobayashi & S. Kohshima, *Unique morphology of the human eye*, Nature **387**, pp. 767–768, 1997. No citations.

37 James W. Prescott, *Body pleasure and the origins of violence*, The Futurist Bethseda, 1975, also available at www.violence.de/prescott/bullettin/article.html. Cited on page 53.

38 Frances Ashcroft, *The Spark of Life: Electricity in the Human Body*, Allen Lane, 2012. Cited on page 53.

39 Felix Tretter & Margot Albus, *Einführung in die Psychopharmakotherapie – Grundlagen, Praxis, Anwendungen*, Thieme, 2004. Cited on page 55.

40 See the talk on these experiments by Helen Fisher on www.ted.org and the information on helenfisher.com. Cited on page 56.

41 See for example P. Pyykkö, *Relativity, gold, closed-shell interactions, and CsAu.NH3*, Angewandte Chemie, International Edition **41**, pp. 3573–3578, 2002, or L. J. Norrby, *Why is mercury liquid? Or, why do relativistic effects not get into chemistry textbooks?*, Journal of Chemical Education **68**, pp. 110–113, 1991. Cited on page 58.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Become the Parent You Never Had - a Treatment for Extremes of Fear, Anger and Guilt, Real Options Press, 1986. A good complement to these texts is the approach presented by Bert Hellinger, *Zweierlei Glück*, Carl Auer Verlag, 1997. Some of his books are also available in English. The author presents a simple and efficient technique for reducing entanglement with one's family past. Another good book is Phil Stutz & Barry Michels, *The Tools – Transform Your Problems into Courage, Confidence, and Creativity*, Random House, 2012.

The next step, namely full mastery in the enjoyment of life, can be found in any book written by somebody who has achieved mastery in any one topic. The topic itself is not important, only the passion is. A few examples:

A. de la Garanderie, *Le dialogue pédagogique avec l'élève*, Centurion, 1984, A. de la Garanderie, *Pour une pédagogie de l'intelligence*, Centurion, 1990, A. de la Garanderie, *Réussir ça s'apprend*, Bayard, 1994. De la Garanderie explains how the results of teaching and learning depend in particular on the importance of evocation, imagination and motivation.

Plato, *Phaedrus*, Athens, 380 bce.

Françoise Dolto, *La cause des enfants*, Laffont, 1985, and her other books. Dolto (b. 1908 Paris, d. 1988 Paris), a child psychiatrist, is one of the world experts on the growth of the child; her main theme was that growth is only possible by giving the highest possible responsibility to every child during its development.

In the domain of art, many had the passion to achieve full pleasure. A good piece of music, a beautiful painting, an expressive statue or a good film can show it. On a smaller scale, the art to typeset beautiful books, so different from what many computer programs do by default, the best introduction are the works by Jan Tschichold (b. 1902 Leipzig, d. 1974 Locarno), the undisputed master of the field. Among the many books he designed are the beautiful Penguin books of the late 1940s; he also was a type designer, e.g. of the *Sabon* typeface. A beautiful summary of his views is the short but condensed text Jan Tschichold, *Ausgewählte Aufsätze über Fragen der Gestalt des Buches und der Typographie*, Birkhäuser Verlag, Basel, 1993. An extensive and beautiful textbook on the topic is Hans Peter Willberg & Friedrich Forssman, *Lesetypographie*, Verlag Hermann Schmidt, Mainz, 1997. See also Robert Bringhurst, *The Elements of Typographic Style*, Hartley & Marks, 2004.

Many scientists passionately enjoyed their occupation. Any biography of Charles Darwin will purvey his fascination for biology, of Friedrich Bessel for astronomy, of Albert Einstein for physics and of Linus Pauling for chemistry. Cited on page 41.

22 The group of John Wearden in Manchester has shown by experiments with humans that the accuracy of a few per cent is possible for any action with a duration between a tenth of a second and a minute. See J. McCrone, *When a second lasts forever*, New Scientist pp. 53–56, 1 November 1997. Cited on page 42.

23 The chemical clocks in our body are described in John D. Palmer, *The Living Clock*, Oxford University Press, 2002, or in A. Ahlgren & F. Halberg, *Cycles of Nature: An Introduction to Biological Rhythms*, National Science Teachers Association, 1990. See also the www.msi.umn.edu/~halberg/introd website. Cited on page 42.

24 D.J Morré & al., *Biochemical basis for the biological clock*, Biochemistry **41**, pp. 11941–11945, 2002. Cited on page 42.

25 An introduction to the sense of time as result of clocks in the brain is found in R. B. Ivry & R. Spencer, *The neural representation of time*, Current Opinion in Neurobiology **14**, pp. 225–232, 2004. The interval timer is explain in simple words in K. Wright, *Times in our lives*, Scientific American pp. 40–47, September 2002. The mri research used is

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

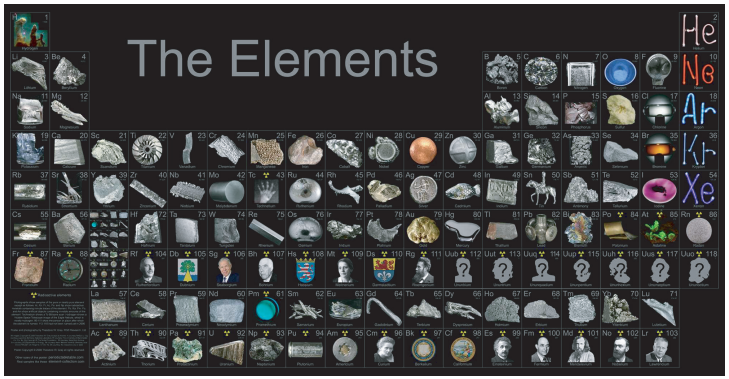


FIGURE 19 A modern periodic table of the elements (© Theodore Gray, for sale at www.theodoregray.com).

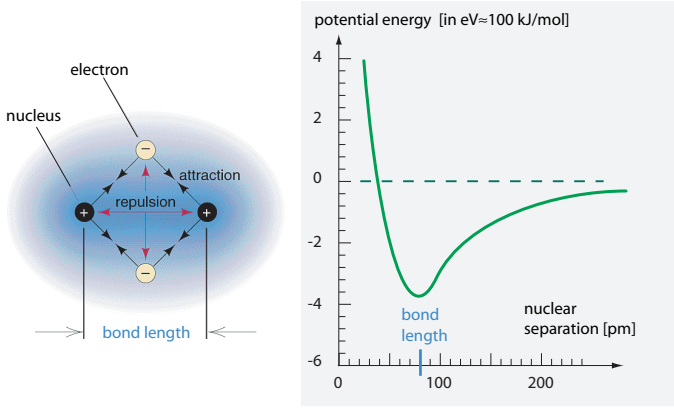


FIGURE 20 The forming of a chemical bond between two atoms, and the related energy minimum (left hand image © chemistry4gcms2011.wikispaces.com).

the H–O–H angle in water molecules is 107°.

Atoms can also be connected by *multiple* bonds. Double bonds appear in carbon dioxide, or CO_2, which is therefore often written as O = C = O, triple bonds appear in carbon monoxide, CO, which is often written as C ≡ O. Both double and triple bonds are common in organic compounds. (In addition, the well-known hexagonal benzene ring molecule C_6H_6, like many other compounds, has a one-and-a-half-fold bond.) Higher bonds are rare but do exist; quadruple bonds occur among transition metal atoms such

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

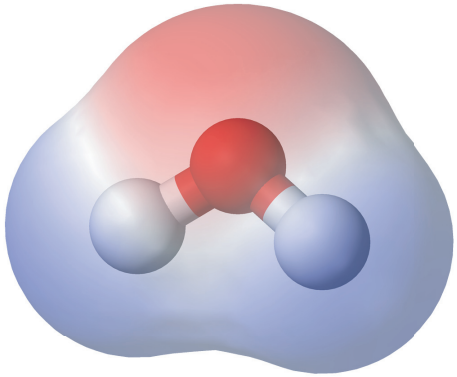


FIGURE 21 An artistic illustration of chemical bond angles when several atoms are involved: in a water molecule, with its charge distribution due to its covalent bonds, blue colour at the two ends indicates positive charge, and the red colour in upper vertex indicates negative charge. The central drawing shows a typical structural rendering of the water molecule (© Benjah-bmm27).

as rhenium or tungsten. Research also confirmed that the uranium U_2 molecule, among
Ref. 45 others, has a quintuple bond, and that the tungsten W_2 molecule has a hextuple bond.

Ribonucleic acid and deoxyribonucleic acid

Probably the most fascinating molecule of all is human deoxyribonucleic acid, better known with its abbreviation DNA. The nucleic acids where discovered in 1869 by the physician Friedrich Miescher (b. 1844 Basel, d. 1895 Davos) in white blood cells. He also found it in cell nuclei, and thus called the substance 'Nuklein'. In 1874 he published an important study showing that the molecule is contained in spermatozoa, and discussed the question if this substance could be related to heredity. With his work, Miescher paved the way to a research field that earned many colleagues Nobel Prizes (though not for himself, as he died before they were established). They changed the name to 'nucleic acid'.

DNA is, as shown in Figure 23, a polymer. A polymer is a molecule built of many similar units. In fact, DNA is among the longest molecules known. Human DNA molecules, for example, can be up to 5 cm in length. Inside each human cell there are 46 chromosomes. In other words, inside each human cell there are molecules with a total length of 2 m. The way nature keeps them without tangling up and knotting is a fascinating topic in itself. All DNA molecules consist of a double helix of sugar derivates, to which four nuclei acids are attached in irregular order. Nowadays, it is possible to make images of
Ref. 46 single DNA molecules; an example is shown in Figure 24.

At the start of the twentieth century it became clear that Desoxyribonukleinsäure (DNS) – translated as deoxyribonucleic acid (DNA) into English – was precisely what Erwin Schrödinger had predicted to exist in his book *What Is Life?* As central part of the chromosomes contained the cell nuclei, DNA is responsible for the storage and reproduction of the information on the construction and functioning of Eukaryotes. The

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

12 The first papers on bacteria from salt deposits were V. R. Ott & H. J. Dombrwoski, *Mikrofossilien in den Mineralquellen zu Bad Nauheim*, Notizblatt des Hessischen Landesamtes für Bodenforschung **87**, pp. 415–416, 1959, H. J. Dombrowski, *Bacteria from Paleozoic salt deposits*, Annals of the New York Academy of Sciences **108**, pp. 453–460, 1963. A recent confirmation is R. H. Vreeland, W. D. Rosenzweig & D. W. Powers, *Isolation of a 250 million-year-old halotolerant bacterium from a primary salt crystal*, Nature **407**, pp. 897–899, 2000. Cited on page 31.

13 This is explained in D. Graur & T. Pupko, *The permian bacterium that isn't*, Molecular Biology and Evolution **18**, pp. 1143–1146, 2001, and also in M. B. Hebsgaard, M. J. Phillips & E. Willerslev, *Geologically ancient DNA: fact or artefact?*, Trends in Microbiology **13**, pp. 212–220, 2005. Cited on page 31.

14 Gabriele Walker, *Snowball Earth – The Story of the Great Global Catastrophe That Spawned Life as We Know It*, Crown Publishing, 2003. No citations.

15 J. D. Rummel, J. H. Allton & D. Morrison, *A microbe on the moon? Surveyor III and lessons learned for future sample return missions*, preprint at www.lpi.usra.edu/meetings/sssr2011/pdf/5023.pdf. Cited on page 31.

16 The table and the evolutionary tree are taken from J. O. McInerney, M. Mullarkey, M. E. Wernecke & R. Powell, *Bacteria and archaea: molecular techniques reveal astonishing diversity*, Biodiversity **3**, pp. 3–10, 2002. The evolutionary tree might still change a little in the coming years. Cited on page 32.

17 The newest estimate is by R. Sender, S. Fuchs & R. Milo, *Revised estimates for the number of human and bacteria cells in the body*, PLOS Biology **14**, p. e1002533, 2016, free preprint at biorxiv.org/content/early/2016/01/06/036103. The first professional estimate was by E. Bianconi, A. Piovesan, F. Facchin, A. Beraudi, R. Casadei, F. Frabetti, L. Vitale, M. C. Pelleri, S. Tassani, F. Piva, S. Perez-Amodio, P. Strippoli & S. Canaider, *An estimation of the number of cells in the human body*, Annals of Human Biology **40**, pp. 463–471, 2013, also available for free online. A typical older and more optimistic estimate is E. K. Costello, C. L. Lauber, M. Hamady, N. Fierer, J. I. Gordon & R. Knight, *Bacterial community variation in human body habitats across space and time*, Science Express 5 November 2009. Cited on page 33.

18 E. Puttonen, C. Briese, G. Mandlburger, M. Wieser, M. Pfennigbauer, A. Zlinsky & N. Pfeifer, *Quantification of overnight movement of birch (Betula pendula) branches and foliage with short interval terrestrial laser scanning*, Frontiers in Plant Science 7, 2016, free download at journal.frontiersin.org. A video of the tree motion is also available there. Cited on page 37.

19 This is taken from the delightful children text Hans J. Press, *Spiel das Wissen schafft*, Ravensburger Buchverlag 1964, 2004. Cited on page 38.

20 The discovery of a specific taste for fat was published by F. Laugerette, P. Passilly-Degrace, B. Patris, I. Niot, M. Febbraio, J. P. Montmayeur & P. Besnard, *CD36 involvement in orosensory detection of dietary lipids, spontaneous fat preference, and digestive secretions*, Journal of Clinical Investigation **115**, pp. 3177–3184, 2005. Cited on page 40.

21 There is no standard procedure to learn to enjoy life to the maximum. A good foundation can be found in those books which teach the ability to those which have lost it.

The best experts are those who help others to overcome traumas. Peter A. Levine & Ann Frederick, *Waking the Tiger – Healing Trauma – The Innate Capacity to Transform Overwhelming Experiences*, North Atlantic Books, 1997. Geoff Graham, *How to*

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

BIBLIOGRAPHY

> Gedanken sind nicht stets parat. Man schreibt auch, wenn man keine hat.*
> Wilhelm Busch, *Aphorismen und Reime.*

1 The use of radioactivity for breeding of new sorts of wheat, rice, cotton, roses, pineapple and many more is described by B. S. Ahloowalia & M. Maluszynski, *Induced mutations – a new paradigm in plant breeding*, Euphytica **11**, pp. 167–173, 2004. Cited on page 21.

2 See John T. Bonner, *Why Size Matters: From Bacteria to Blue Whales*, Princeton University Press, 2011. Cited on page 21.

3 See the book by Peter Läuger, *Electrogenic Ion Pumps*, Sinauer, 1991. Cited on page 21.

4 The motorized screw used by viruses was described by A.A. Simpson & al., *Structure of the bacteriophage phi29 DNA packaging motor*, Nature **408**, pp. 745–750, 2000. Cited on page 22.

5 S. M. Block, *Real engines of creation*, Nature **386**, pp. 217–219, 1997. Cited on page 22.

6 Early results and ideas on molecular motors are summarised by B. Goss Levi, *Measured steps advance the understanding of molecular motors*, Physics Today pp. 17–19, April 1995. Newer results are described in R. D. Astumian, *Making molecules into motors*, Scientific American pp. 57–64, July 2001. Cited on pages 22 and 23.

7 R. Bartussek & P. Hänggi, *Brownsche Motoren*, Physikalische Blätter **51**, pp. 506–507, 1995. See also R. Alt-Haddou & W. Herzog, *Force and motion generation of myosin motors: muscle contraction*, Journal of Electromyography and kinesiology **12**, pp. 435–445, 2002. Cited on page 24.

8 N. Hirokawa, S. Niwa & Y. Tanaka, *Molecular motors in neurons: transport mechanisms and roles in brain function, development, and disease*, Neuron **68**, pp. 610–638, 2010. Cited on page 25.

9 J. Weber & A. E. Senior, *ATP synthesis driven by proton transport in F1Fo-ATP synthase*, FEBS letters **545**, pp. 61–70, 2003. Cited on page 26.

10 This truly fascinating research result, worth a Nobel Prize, is summarized in N. Hirokawa, Y. Tanaka & Y. Okada, *Left-right determination: involvement of molecular motor KIF3, cilia, and nodal flow*, Cold Spring Harbor Perspectives in Biology **1**, p. a000802, 2009, also available at www.cshperspectives.org. The website also links to numerous captivating films of the involved microscopic processes, found at beta.cshperspectives.cshlp.org. Cited on page 28.

11 R. J. Cano & M. K. Borucki, *Revival and identification of bacterial spores in 25- to 40-million-year-old Dominican amber*, Science **26**, pp. 1060–1064, 1995. Cited on page 31.

* 'Thoughts are not always available. Many write even without them.'

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

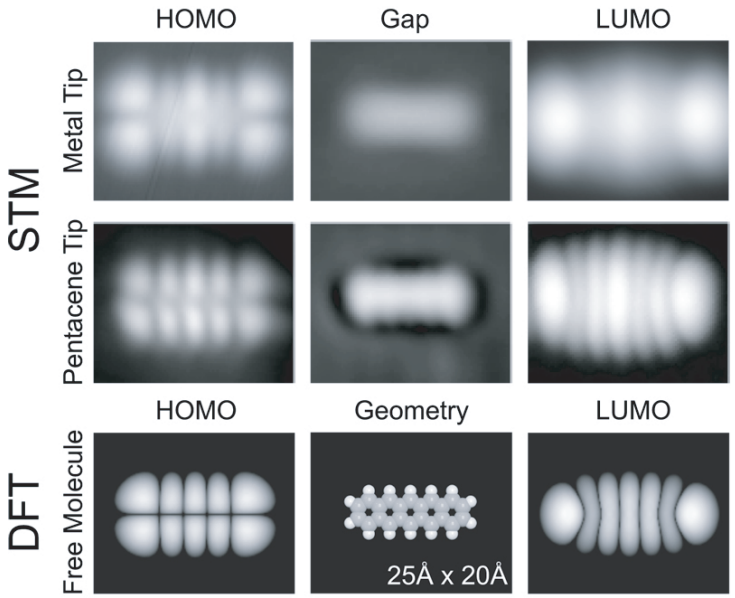


FIGURE 22 Top two rows: measured chemical bonds in the pentacene molecule, using different techniques; bottom row: textbook calculations and illustrations of the same experiment (© IBM).

information is coded in the ordering of the four nucleic acids. DNA is the carrier of hereditary information. DNA determines in great part how the single cell we all once have been grows into the complex human machine we are as adults. For example, DNA determines the hair colour, predisposes for certain illnesses, determines the maximum size one can grow to, and much more. Of all known molecules, human DNA is thus most intimately related to human existence. The large size of the molecules is the reason that understanding its full structure and its full contents is a task that will occupy scientists for several generations to come.

To experience the wonders of DNA, have a look at the animations of DNA copying and of other molecular processes at the unique website www.wehi.edu.au/education/wehitv.

Curiosities and fun challenges about chemistry

Among the fascinating topics of chemistry are the studies of substances that influence humans: toxicology explores *poisons*, pharmacology explores *medicines* (pharmaceutical drugs) and endocrinology explores *hormones*.

Over 50 000 poisons are known, starting with water (usually kills when drunk in amounts larger than about 10 l) and table salt (can kill when 100 g are ingested) up to

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

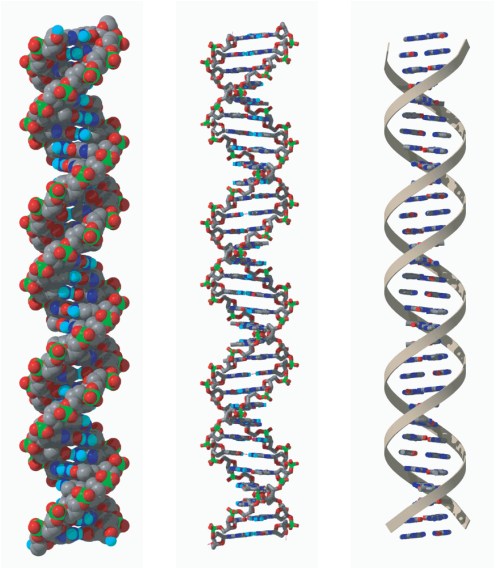


FIGURE 23 Several ways to picture B-DNA, all in false colours (© David Deerfield).

polonium 210 (kills in doses as low as 5 ng, far less than a spec of dust). Most countries have publicly accessible poison databases; see for example www.gsbl.de.

Challenge 37 e

Can you imagine why 'toxicology', the science of poisons, actually means 'bow science' in Greek? In fact, not all poisons are chemical. Paraffin and oil for lamps, for example, regularly kill children who taste it because some oil enters the lung and forms a thin film over the alveoles, preventing oxygen intake. This so-called *lipoid pneumonia* can be deadly even when only a *single drop* of oil is in the mouth and then inhaled by a child. Paraffin should never be present in homes with children.

In the 1990s, the biologist Binie Ver Lipps discovered a substance, a simple polypeptide, that helps against venoms of snakes and other poisonous animals. The medical industry worldwide refuses to sell the substance – it could save many lives – because it is too cheap.

* *

Whether a substance is a poison depends on the animal ingesting it. Chocolate is poison for dogs, but not for children. Poisonous mushrooms are edible for snails; bitten mushrooms are thus not a sign of edibility.

* *

Hormones are internal signalling substances produced by the human body. Chemically,

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Challenge 203, page 363: Take out your head, then pull one side of your pullover over the corresponding arm, continue pulling it over the over arm; then pull the other side, under the first, to the other arm as well. Put your head back in. Your pullover (or your trousers) will be inside out.

Challenge 204, page 363: Both can be untied.

Challenge 208, page 368: The transformation from one manifold to another with different topology can be done with a tiny change, at a so-called *singular point*. Since nature shows a minimum action, such a tiny change cannot be avoided.

Challenge 209, page 370: The product $M^\dagger M$ is Hermitean, and has positive eigenvalues. Thus H is uniquely defined and Hermitean. U is unitary because $U^\dagger U$ is the unit matrix.



Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Challenge 169, page 308: Large raindrops are pancakes with a massive border bulge. When the size increases, e.g. when a large drop falls through vapour, the drop splits, as the central membrane is then torn apart.

Challenge 170, page 308: It is a drawing; if it is interpreted as an image of a three-dimensional object, it either does not exist, or is not closed, or is an optical illusion of a torus.

Challenge 171, page 308: See T. Fink & Y. Mao, *The 85 Ways to Tie a Tie*, Broadway Books, 2000.

Challenge 172, page 308: See T. Clarke, *Laces high*, Nature Science Update 5th of December, 2002, or www.nature.com/nsu/021202/021202-4.html.

Challenge 175, page 310: In fact, nobody has even tried to do so yet. It may also be that the problem makes no sense.

Challenge 177, page 316: Most macroscopic matter properties fall in this class, such as the change of water density with temperature.

Challenge 179, page 322: Before the speculation can be fully tested, the relation between particles and black holes has to be clarified first.

Challenge 180, page 323: Never expect a correct solution for personal choices. Do what you yourself think and feel is correct.

Challenge 185, page 330: Planck limits can be exceeded for extensive observables for which many particle systems can exceed single particle limits, such as mass, momentum, energy or electrical resistance.

Challenge 187, page 332: Do not forget the relativistic time dilation.

Challenge 188, page 332: The formula with $n - 1$ is a better fit. Why?

Challenge 192, page 339: The slowdown goes *quadratically* with time, because every new slowdown adds to the old one!

Challenge 193, page 340: No, only properties of parts of the universe are listed. The universe itself has no properties, as shown in the last volume.

Vol. VI, page 110

Challenge 194, page 342: The gauge coupling constants, via the Planck length, determine the size of atoms, the strength of chemical bonds and thus the size of all things.

Challenge 195, page 357: Covalent bonds tend to produce full shells; this is a smaller change on the right side of the periodic table.

Challenge 196, page 359: The solution is the set of all two by two matrices, as each two by two matrix specifies a linear transformation, if one defines a transformed point as the product of the point and this matrix. (Only multiplication with a fixed matrix can give a linear transformation.) Can you recognize from a matrix whether it is a rotation, a reflection, a dilation, a shear, or a stretch along two axes? What are the remaining possibilities?

Challenge 199, page 359: The (simplest) product of two functions is taken by point-by-point multiplication.

Challenge 200, page 360: The norm $\|f\|$ of a real function f is defined as the supremum of its absolute value:

$$\|f\| = \sup_{x \in \mathrm{R}} |f(x)| \,. \tag{154}$$

In simple terms: the maximum value taken by the absolute of the function is its norm. It is also called 'sup'-norm. Since it contains a supremum, this norm is only defined on the subspace of *bounded* continuous functions on a space X, or, if X is compact, on the space of all continuous functions (because a continuous function on a compact space must be bounded).

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

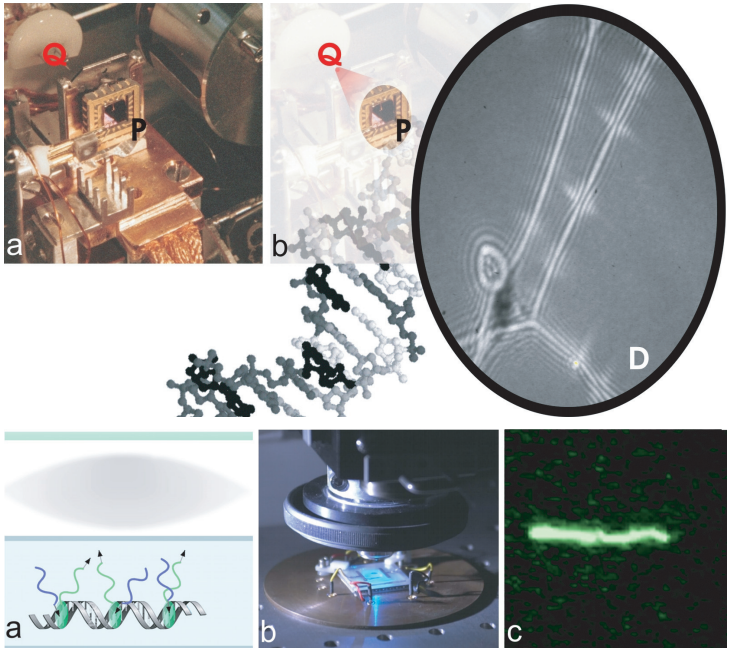


FIGURE 24 Two ways to image single DNA molecules: by holography with electrons emitted from atomically sharp tips (top) and by fluorescence microscopy, with a commercial optical microscope (bottom) (© Hans-Werner Fink/Wiley VCH).

they can be peptides, lipids or monoamines. Hormones induce mood swings, organize the fight, flight or freeze responses, stimulate growth, start puberty, control cell death and ageing, activate or inhibit the immune system, regulate the reproductive cycle and activate thirst, hunger and sexual arousal.

* *

Challenge 38 s When one mixes 50 ml of distilled water and 50 ml of ethanol (alcohol), the volume of the mixture has less than 100 ml. Why?

* *

Why do *organic* materials, i.e., materials that contain several carbon atoms, usually burn at much lower temperature than *inorganic* materials, such as aluminium or magnesium?

Challenge 39 ny

* *

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

A cube of sugar does not burn. However, if you put some cigarette ash on top of it, it burns. Why? Challenge 40 ny

* *

Sugars are essential for life. One of the simplest sugars is *glucose*, also called *dextrose* or *grape sugar*. Glucose is a so-called *monosaccharide*, in contrast to cane sugar, which is a disaccharide, or starch, which is a polysaccharide.

The digestion of glucose and the burning, or combustion, of glucose follow the same chemical reaction:

$$C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O + 2808\,\mathrm{kJ} \tag{8}$$

This is the simplest and main reaction that fuels the muscle and brain activities in our body. The reaction is the reason we have to eat even if we do not grow in size any more. The required oxygen, O_2, is the reason that we breathe in, and the resulting carbon dioxide, CO_2, is the reason that we breathe out. Life, in contrast to fire, is thus able to 'burn' sugar at 37°. That is one of the great wonders of nature. Inside cells, the energy gained from the digestion of sugars is converted into adenosinetriphosphate (ATP) and then converted into motion of molecules.

* *

Chemical reactions can be slow but still dangerous. Spilling mercury on aluminium will lead to an amalgam that reduces the strength of the aluminium part after some time. That is the reason that bringing mercury thermometers on aeroplanes is strictly forbidden.

* *

Two atoms can form bound states by a number of effects that are weaker than electron bonds. A famous one is the bound state formed by two sodium atoms at a distance of around 60 Bohr radii, thus much larger than usual bond distances. The bond appears due to the continuous exchange of a photon between the two atoms. Ref. 47

* *

What happens if you take the white powder potassium iodide – KJ – and the white powder lead nitrate – $Pb(NO_3)_2$ – and mix them with a masher? (This needs to be done with proper protection and supervision.) Challenge 41 s

* *

Writing on paper with a pen filled with lemon juice instead of ink produces invisible writing. Later on, the secret writing can be made visible by carefully heating the paper on top of a candle flame.

* *

How is the concentration of *ozone*, with the chemical composition O_3, maintained in the high atmosphere? It took many years of research to show that the coolants used in refrigerators, the so-called fluoro-chloro-hydrocarbons or FCHCs, slowly destroyed this important layer. The reduction of ozone has increased the rate of skin cancer all across

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Challenge 138, page 209: The nuclei of nitrogen and carbon have a high electric charge which strongly repels the protons.

Challenge 140, page 218: See the paper by C.J. Hogan mentioned in Ref. 270.

Challenge 141, page 221: Touching something requires getting near it; getting near means a small time and position indeterminacy; this implies a small wavelength of the probe that is used for touching; this implies a large energy.

Challenge 144, page 228: The processes are electromagnetic in nature, thus electric charges give the frequency with which they occur.

Challenge 145, page 237: Designing a nuclear weapon is not difficult. University students can do it, and even have done so a few times. The first students who did so were two physics graduates in 1964, as told on www.guardian.co.uk/world/2003/jun/24/usa.science. It is not hard to conceive a design and even to build it. By far the hardest problem is getting or making the nuclear material. That requires either an extensive criminal activity or a vast technical effort, with numerous large factories, extensive development, and coordination of many technological activities. Most importantly, such a project requires a large financial investment, which poor countries cannot afford without great sacrifices for all the population. The problems are thus not technical, but financial.

Challenge 149, page 268: In 2008, an estimated 98 % of all physicists agreed. Time will tell whether they are right.

Challenge 151, page 280: A mass of 100 kg and a speed of 8 m/s require 43 m^2 of wing surface.

Challenge 154, page 287: The issue is a red herring. The world has three dimensions.

Challenge 155, page 290: The largest rotation angle $\Delta\varphi$ that can be achieved in one stroke C is found by maximizing the integral

$$\Delta\varphi = -\int_C \frac{a^2}{a^2+b^2}\mathrm{d}\theta \tag{151}$$

Since the path C in shape space is closed, we can use Stokes' theorem to transform the line integral to a surface integral over the surface S enclosed by C in shape space:

$$\Delta\varphi = \int_S \frac{2ab^2}{(a^2+b^2)^2}\mathrm{d}a\,\mathrm{d}\theta\,. \tag{152}$$

The maximum angle is found by noting that θ can vary at most between 0 and π, and that a can vary at most between 0 and ∞. This yields

$$\Delta\varphi_{\max} = \int_{\theta=0}^{\pi}\int_{a=0}^{\infty} \frac{2ab^2}{(a^2+b^2)^2}\mathrm{d}a\,\mathrm{d}\theta = \pi\,. \tag{153}$$

Challenge 157, page 294: A cloud is kept afloat and compact by convection currents. Clouds without convection can often be seen in the summer: they diffuse and disappear. The details of the internal and external air currents depend on the cloud type and are a research field on its own.

Challenge 162, page 300: Lattices are not isotropic, lattices are not Lorentz invariant.

Challenge 164, page 303: The infinite sum is not defined for numbers; however, it is defined for a knotted string.

Challenge 165, page 304: The research race for the solution is ongoing, but the goal is still far.

Challenge 166, page 305: This is a simple but hard question. Find out!

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

— wait to be pushed by the transformation of the Sun into a red giant;
— wait to be hit by a meteorite.

Challenge 92, page 135: A method to move on perfect ice using self-organization, chaos theory, and biophysics:

— wait that the currents in the brain interact with the magnetic field of the Earth by controlling your thoughts.

Challenge 93, page 135: Methods to move on perfect ice using quantum gravity:

— accelerate your pocket mirror with your hand;
— deviate the Unruh radiation of the Earth with a pocket mirror;
— wait for proton decay to push you through the recoil.

Challenge 95, page 142: This is a trick question: if you can say why, you can directly move to the last volume of this adventure and check your answer. The gravitational potential changes the phase of a wave function, like any other potential does; but the reason *why* this is the case will only become clear in the last volume of this series.

Challenge 100, page 144: No. Bound states of massless particles are always unstable.

Challenge 101, page 146: This is easy only if the black hole size is inserted into the entropy bound by Bekenstein. A simple deduction of the black hole entropy that includes the factor 1/4 is not yet at hand; more on this in the last volume.

Challenge 102, page 146: An entropy limit implies an information limit; only a given information can be present in a given region of nature. This results in a memory limit.

Challenge 103, page 146: In natural units, the exact expression for entropy is $S = 0.25A$. If each Planck area carried one bit (degree of freedom), the entropy would be $S = \ln W = \ln(2^A) = A \ln 2 = 0.693A$. This close to the exact value.

Challenge 107, page 152: The universe has about 10^{22} stars; the Sun has a luminosity of about 10^{26} W; the total luminosity of the visible matter in the universe is thus about 10^{48} W. A gamma-ray burster emits up to $3 \cdot 10^{47}$ W.

Challenge 113, page 154: They are carried away by the gravitational radiation.

Challenge 119, page 158: No system is known in nature which emits or absorbs only one graviton at a time. This is another point speaking against the existence of gravitons.

Challenge 123, page 167: Two stacked foils show the same effect as one foil of the same total thickness. Thus the surface plays no role.

Challenge 125, page 172: The electron is held back by the positive charge of the nucleus, if the number of protons in the nucleus is sufficient, as is the case for those nuclei we are made of.

Challenge 127, page 180: The half-time $t_{1/2}$ is related to the life-time τ by $t_{1/2} = \tau \ln 2$.

Challenge 128, page 181: The number is small compared with the number of cells. However, it is possible that the decays are related to human ageing.

Challenge 130, page 184: By counting decays and counting atoms to sufficient precision.

Challenge 132, page 185: The radioactivity necessary to keep the Earth warm is low; lava is only slightly more radioactive than usual soil.

Challenge 133, page 197: There is no way to conserve both energy and momentum in such a decay.

Challenge 134, page 197: The combination of high intensity X-rays and UV rays led to this effect.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

the world. By forbidding the most dangerous refrigerator coolants all over the world, it is hoped that the ozone concentration can recover. The first results are encouraging. In 1995, Paul Crutzen, Mario Molina and Sherwood Rowland received the Nobel Price for Chemistry for the research that led to these results and policy changes.

* *

In 2008, it was shown that perispinal infusion of a single substance, *etanercept*, reduced Alzheimer's symptoms in a patient with late-onset Alzheimer's disease, within a few minutes. Curing Alzheimer's disease is one of the great open challenges for modern medicine. In 2013, Jens Pahnke found that an extract of *Hypericum* has positive effects on the cognition and memory of Alzheimer patients. The extract is already available as free medication, for other uses, with the name LAIF900.

* *

Cyanoacrylate is a fascinating substance. It is the main ingredient of instant glue, the glue that starts to harden after a few seconds of exposure to moisture. The smell of evaporating cyanoacrylate glue is strong and known to everybody who has used this kind of adhesive. The vapour also has another use: they make finger prints visible. You can try this at home!

Ref. 48

Challenge 42 e

* *

Fireworks fascinate many. A great challenge of firework technology is to produce forest green and greenish blue colours. Producers are still seeking to solve the problem. For more information about fireworks, see the cc.oulu.fi/~kempmp website.

MATERIALS SCIENCE

> Did you know that one cannot use a boiled egg as a toothpick?
>
> Karl Valentin

We mentioned several times that the quantum of action explains all properties of matter. Many researchers in physics, chemistry, metallurgy, engineering, mathematics and biology have cooperated in the proof of this statement. In our mountain ascent we have only a little time to explore this vast but fascinating topic. Let us walk through a selection.

Why does the floor not fall?

We do not fall through the mountain we are walking on. Some interaction keeps us from falling through. In turn, the continents keep the mountains from falling through them. Also the liquid magma in the Earth's interior keeps the continents from sinking. All these statements can be summarized in two ideas: First, atoms do not penetrate each other: despite being mostly empty clouds, atoms keep a distance. Secondly, atoms cannot be compressed in size. Both properties are due to Pauli's exclusion principle between electrons. The fermion character of electrons avoids that atoms shrink or interpenetrate – on Earth.

Vol. IV, page 135

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

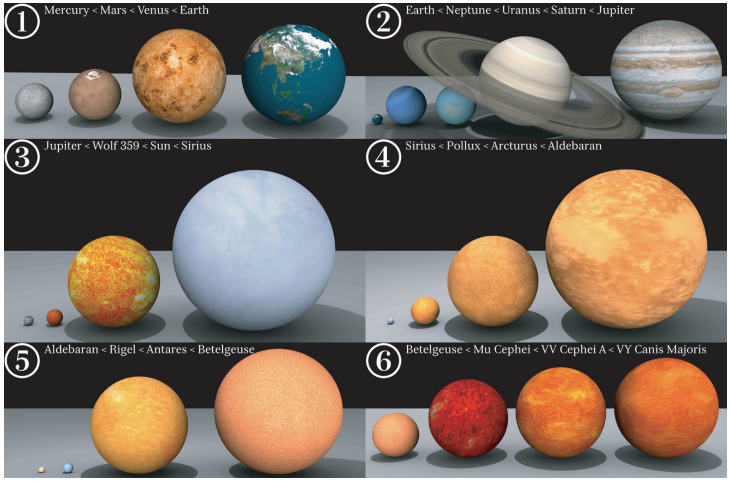


FIGURE 25 A comparison of star sizes (© Dave Jarvis).

In fact, not all floors keep up due to the fermion character of electrons. Atoms are not impenetrable at all pressures. At sufficiently large pressures, atoms can collapse, and form new types of floors. Such floors do not exist on Earth. Some people have spent their whole life to understand why such other floors, namely *surfaces of stars*, do not fall, or when they do, how it happens.

The floors and the sizes of all astronomic objects are due to quantum effects. Figure 25 illustrates the range of sizes that are found in astronomic objects. In each object, a quantum effect leads to an internal pressure which fixes the floor, and thus the size of the object.

In solid or liquid planets, the size is given by the incompressibility of condensed matter, which in turn is due to Pauli's exclusion principle. The effective internal pressure of condensed matter is often called the *Pauli pressure*. In gaseous planets, such a Jupiter, and in *usual stars*, such as in the Sun, the gas pressure takes the role that the incompressibility of solids and liquids has for smaller planets. The gas pressure is due to the heat stored in them; the heat is usually released by internal nuclear reactions.

Light pressure does play a role in determining the size of *red giants*, such as Betelgeuse; but for average stars, light pressure is negligible.

Other quantum effects appear in *dense* stars. Whenever light pressure, gas pressure and the electronic Pauli pressure cannot keep atoms from interpenetrating, atoms are compressed until all electrons are pushed into the protons. Protons then become neutrons, and the whole star has the same mass density of atomic nuclei, namely about $2.3 \cdot 10^{17}\,\mathrm{kg/m^3}$. A drop weighs about 200 000 tons. In these so-called *neutron stars*, the floor – or better, the size – is also determined by Pauli pressure; however, it is the Pauli

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

— jump vertically repeatedly: the Coriolis acceleration will lead to horizontal motion;
— wait to be moved by the Sun or the Moon, like the tides are;
— 'swim' in the air using hands and feet;
— wait to be hit by a bird, a flying wasp, inclined rain, wind, lava, earthquake, plate tectonics, or any other macroscopic object (all objects pushing count only as one solution);
— wait to be moved by the change in gravity due to convection in Earth's mantle;
— wait to be moved by the gravitation of some comet passing by;
— counts only for kids: spit, sneeze, cough, fart, pee; or move your ears and use them as wings.

Note that gluing your tongue is not possible on perfect ice.

Challenge 88, page 135: Methods to move on perfect ice using thermodynamics and electrodynamics:

— use the radio/TV stations nearby to push you around;
— use your portable phone and a mirror;
— switch on a pocket lamp, letting the light push you;
— wait to be pushed around by Brownian motion in air;
— heat up one side of your body: black body radiation will push you;
— heat up one side of your body, e.g. by muscle work: the changing airflow or the evaporation will push you;
— wait for one part of the body to be cooler than the other and for the corresponding black body radiation effects;
— wait for the magnetic field of the Earth to pull on some ferromagnetic or paramagnetic metal piece in your clothing or in your body;
— wait to be pushed by the light pressure, i.e. by the photons, from the Sun or from the stars, maybe using a pocket mirror to increase the efficiency;
— rub some polymer object to charge it electrically and then move it in circles, thus creating a magnetic field that interacts with the one of the Earth.

Note that perfect frictionless surfaces do not melt.

Challenge 89, page 135: Methods to move on perfect ice using general relativity:

— move an arm to emit gravitational radiation;
— deviate the cosmic background radiation with a pocket mirror;
— wait to be pushed by gravitational radiation from star collapses;
— wait for the universe to contract.

Challenge 90, page 135: Methods to move on perfect ice using quantum effects:

— wait for your wave function to spread out and collapse at the end of the ice surface;
— wait for the pieces of metal in the clothing to attract to the metal in the surrounding through the Casimir effect;
— wait to be pushed around by radioactive decays in your body.

Challenge 91, page 135: Methods to move on perfect ice using materials science, geophysics and astrophysics:

— be pushed by the radio waves emitted by thunderstorms and absorbed in painful human joints;
— wait to be pushed around by cosmic rays;
— wait to be pushed around by the solar wind;
— wait to be pushed around by solar neutrinos;

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Challenge 75, page 129: Mirrors do not usually work for matter; in addition, if they did, matter, because of its rest energy, would require much higher acceleration values.

Challenge 78, page 131: The classical radius of the electron, which is the size at which the field energy would make up the full electron mass, is about 137 times smaller, thus much smaller, than the Compton wavelength of the electron.

Challenge 79, page 133: The overhang can have any value whatsoever. There is no limit. Taking the indeterminacy relation into account introduces a limit as the last brick or card must not allow the centre of gravity, through its indeterminacy, to be over the edge of the table.

Challenge 80, page 133: A larger charge would lead to a field that spontaneously generates electron positron pairs, the electron would fall into the nucleus and reduce its charge by one unit.

Challenge 82, page 133: The Hall effect results from the deviation of electrons in a metal due to an applied magnetic field. Therefore it depends on their speed. One gets values around 1 mm. Inside atoms, one can use Bohr's atomic model as approximation.

Challenge 83, page 133: The steps are due to the particle nature of electricity and all other moving entities.

Challenge 84, page 134: If we could apply the Banach–Tarski paradox to vacuum, it seems that we could split, without any problem, one ball of vacuum into *two* balls of vacuum, each with the same volume as the original. In other words, one ball with vacuum energy E could not be distinguished from two balls of vacuum energy $2E$.

Vol. I, page 57

We used the Banach–Tarski paradox in this way to show that chocolate (or any other matter) possesses an intrinsic length. But it is *not* clear that we can now deduce that the vacuum has an intrinsic length. Indeed, the paradox cannot be applied to vacuum for *two* reasons. First, there indeed is a maximum energy and minimum length in nature. Secondly, there is no place in nature without vacuum energy; so there is no place were we could put the second ball. We thus do not know why the Banach–Tarski paradox for vacuum cannot be applied, and thus cannot use it to deduce the existence of a minimum length in vacuum.

Vol. I, page 331

It is better to argue in the following way for a minimum length in vacuum. If there were no intrinsic length cut-off, the vacuum energy would be infinite. Experiments however, show that it is finite.

Challenge 85, page 134: Mud is a suspension of sand; sand is not transparent, even if made of clear quartz, because of the scattering of light at the irregular surface of its grains. A suspension cannot be transparent if the index of refraction of the liquid and the suspended particles is different. It is never transparent if the particles, as in most sand types, are themselves not transparent.

Challenge 86, page 134: The first answer is probably no, as composed systems cannot be smaller than their own compton wavelength; only elementary systems can. However, the universe is not a system, as it has no environment. As such, its length is not a precisely defined concept, as an environment is needed to measure and to define it. (In addition, gravity must be taken into account in those domains.) Thus the answer is: in those domains, the question makes no sense.

Challenge 87, page 134: Methods to move on perfect ice from mechanics:

- if the ice is perfectly flat, rest is possible only in one point – otherwise you oscillate around that point, as shown in challenge 26;
- do nothing, just wait that the higher centrifugal acceleration at body height pulls you away;
- to rotate yourself, just rotate your arm above your head;
- throw a shoe or any other object away;
- breathe in vertically, breathing out (or talking) horizontally (or vice versa);
- wait to be moved by the centrifugal acceleration due to the rotation of the Earth (and its oblateness);

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Page 186

pressure between neutrons, triggered by the nuclear interactions. These neutron stars are all around 10 km in radius.

If the pressure increases still further, the star becomes a *black hole*, and never stops collapsing. Black holes have no floor at all; they still have a constant size though, determined by the horizon curvature.

Vol. II, page 262

The question whether other star types exist in nature, with other floor forming mechanisms – such as the conjectured *quark stars* – is still a topic of research.

Rocks and stones

If a geologist takes a stone in his hands, he is usually able to give the age of the stone, within an error of a few per cent, simply by looking at it. The full story behind this astonishing ability forms a large part of geology, but the general lines should also be known to every physicist.

Generally speaking, the mass density of the Earth decreases from the centre towards the surface. The *upper mantle*, below the solid crust of the Earth, is mostly composed of *peridotite*, a dense, obviously igneous rock with a density of around $3.3\,\mathrm{g/cm^3}$. The *oceanic crust*, with a thickness between 5 and 10 km, is mainly composed of igneous rocks such as basalt, diabase and gabbro. These rocks are somewhat less dense, around $3\,\mathrm{g/cm^3}$, and are typically 200 million years old. The *continental crust* has a depth of 30 to 50 km, consists of lighter rocks, around $2.7\,\mathrm{g/cm^3}$, such as granite. The age of the continental crust varies strongly; on average it is 2000 million years old, with a range from extremely young rocks to some older than 4300 million years. The continental crust contains most of the incompatible elements.

Every stone arrives in our hand through the *rock cycle(s)*. The main rock cycle is a process that transforms magma from the interior of the Earth into *igneous (or magmatic) rocks* through cooling and crystallization. Igneous rocks, such as basalt, can transform through erosion, transport and deposition into *sedimentary rocks*, such as sandstone. (Sedimentary rocks can also form from biogenic base materials.) Either of these two rock types can be transformed through high pressures or temperatures into *metamorphic rocks*, such as marble. Finally, most rocks are generally – but not always – transformed back into magma.

The main rock cycle takes around 110 to 170 million years. For this reason, rocks that are older than this age are less common on Earth. Any stone that we collect during a walk is the product of erosion of one of the rock types. A geologist can usually tell, just by looking at the stone, the type of rock it belongs to; if he sees or knows the original environment, he can also give the age and often tell the story of the formation, without any laboratory.

In the course of millions of years, minerals float upwards from the mantle or are pushed down the crust, they are transformed under heat and pressure, they dissolve or precipitate, and they get enriched in certain locations. These captivating stories about minerals are explored in detail by geologists. Geologists can tell where to find beaches with green sand (made of olivine); they can tell how contact between sedimentary limestone with molten igneous rocks leads to marble, ruby and other gemstones, and under which precise conditions; they can also tell from small crystals of quartz that enclose coesite that in earlier times the rock has been under extremely high pressure – either

Ref. 49

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 26 Igneous rocks (top three rows): gabbro, andesite, permatite, basalt, pumice, porphyry, obsidian, granite, tuff; sedimentary rocks (centre): clay, limestone, sandstone; and (below) two specimen of a metamorphic rock: marble (© Siim Sepp at www.sandatlas.org, Wikimedia).

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Challenge 49, page 88: These developments are just starting; the results are still far from the original one is trying to copy, as they have to fulfil a second condition, in addition to being a 'copy' of original feathers or of latex: the copy has to be cheaper than the original. That is often a much tougher request than the first.

Challenge 50, page 88: About 0.2 m.

Challenge 52, page 89: Since the height of the potential is always finite, walls can always be overcome by tunnelling.

Challenge 53, page 90: The lid of a box can never be at rest, as is required for a tight closure, but is always in motion, due to the quantum of action.

Challenge 55, page 90: The unit of thermal conductance is $T\pi^2k^2/3\hbar$, where T is temperature and k is the Boltzmann constant.

Challenge 56, page 91: Extremely slender structures are not possible for two reasons: First, because structures built of homogeneous materials do not to achieve such ratios; secondly, the bending behaviour of plants is usually not acceptable in human-built structures.

Challenge 57, page 93: The concentrations and can be measured from polar ice caps, by measuring how the isotope concentration changes over depth. Both in evaporation and in condensation of water, the isotope ratio depends on the temperature. The measurements in Antarctica and in Greenland coincide, which is a good sign of their trustworthiness.

Challenge 58, page 94: In the summer, tarmac is soft.

Challenge 61, page 113: The one somebody else has thrown away. Energy costs about 10 cents/kWh. For new lamps, the fluorescent lamp is the best for the environment, even though it is the least friendly to the eye and the brain, due to its flickering.

Challenge 62, page 118: This old dream depends on the precise conditions. How flexible does the display have to be? What lifetime should it have? The newspaper like display is many years away and maybe not even possible.

Challenge 63, page 118: There is only speculation on the answer; the tendency of most researchers is to say no.

Challenge 64, page 118: The challenge here is to find a cheap way to deflect laser beams in a controlled way. Cheap lasers are already available.

Challenge 65, page 118: No, as it is impossible because of momentum conservation and because of the no-cloning theorem.

Challenge 66, page 119: There are companies trying to sell systems based on quantum cryptology; but despite the technical interest, the commercial success is questionable.

Challenge 67, page 119: I predicted since the year 2000 that mass-produced goods using this technology (at least 1 million pieces sold) will not be available before 2025.

Challenge 68, page 119: Maybe, but for extremely high prices.

Challenge 69, page 120: The set-up is affordable: it uses a laser at 3.39 µm, a detector and some optics on a tripod. Sensitivity to alcohol absorption is excellent. Only future will tell.

Challenge 71, page 125: For example, you could change gravity between two mirrors.

Challenge 72, page 125: As usual in such statements, either group or phase velocity is cited, but not the corresponding energy velocity, which is always below c.

Challenge 74, page 128: Echoes do not work once the speed of sound is reached and do not work well when it is approached. Both the speed of light and that of sound have a finite value. Moving with a mirror still gives a mirror image. This means that the speed of light cannot be reached. If it cannot be reached, it must be the same for all observers.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

men have an X chromosome as well. That explains that still other measurements suggest that all humans share a pool of at least 99.9 % of common genes.

Challenge 18, page 34: Chemical processes, including diffusion and reaction rates, are strongly temperature dependent. They affect the speed of motion of the individual and thus its chance of survival. Keeping temperature in the correct range is thus important for evolved life forms.

Challenge 19, page 34: The first steps are not known at all. Subsequent processes that added the complexity of cells are better understood.

Challenge 20, page 34: Since all the atoms we are made of originate from outer space, the answer is yes. But if one means that biological cells came to Earth from space, the answer is no, as most cells do not like vacuum. The same is true for DNA.

In fact, life and reproduction are properties of complex systems. In other words, asking whether life comes from outer space is like asking: 'Could car insurance have originated in outer space?'

Challenge 22, page 40: Haven't you tried yet? Physics is an experimental science.

Challenge 30, page 48: Exponential decays occur when the probability of decay is constant over time. For humans, this is not the case. Why not?

Challenge 31, page 51: There are no non-physical processes: anything that can be observed is a physical process. Consciousness is due to processes in the brain, thus inside matter; thus it is a quantum process. At body temperature, coherence has lifetimes much smaller than the typical thought process.

Challenge 32, page 52: Radioactive dating methods can be said to be based on the nuclear interactions, even though the detection is again electromagnetic.

Challenge 33, page 53: All detectors of light can be called relativistic, as light moves with maximal speed. Touch sensors are not relativistic following the usual sense of the word, as the speeds involved are too small. The energies are small compared to the rest energies; this is the case even if the signal energies are attributed to electrons only.

Challenge 34, page 53: The noise is due to the photoacoustic effect; the periodic light periodically heats the air in the jam glass at the blackened surface and thus produces sound. See M. EULER, *Kann man Licht hören?*, Physik in unserer Zeit 32, pp. 180–182, 2001.

Challenge 35, page 56: It implies that neither resurrection nor reincarnation nor eternal life are possible.

Challenge 38, page 65: The ethanol disrupts the hydrogen bonds between the water molecules so that, on average, they can get closer together. A video of the experiment is found at www.youtube.com/watch?v=LUW7a7H-KuY.

Challenge 41, page 66: You get an intense yellow colour due to the formation of lead iodide (PbI_2).

Challenge 43, page 73: The usual way to pack oranges on a table is the densest way to pack spheres.

Challenge 44, page 74: Just use a paper drawing. Draw a polygon and draw it again at latter times, taking into account how the sides grow over time. You will see by yourself how the faster growing sides disappear over time.

Challenge 46, page 84: With a combination of the methods of Table 7, this is indeed possible. In fact, using cosmic rays to search for unknown chambers in the pyramids has been already done in the 1960s. The result was that no additional chambers exist. Ref. 304

Challenge 48, page 88: For example, a heavy mountain will push down the Earth's crust into the mantle, makes it melt on the bottom side, and thus lowers the position of the top.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 4 The types of rocks and stones.

TYPE	PROPERTIES	SUBTYPE	EXAMPLE
Igneous rocks (magmatites)	formed from magma, 95 % of all rocks	volcanic or extrusive	basalt (ocean floors, Giant's Causeway), andesite, obsidian
		plutonic or intrusive	granite, gabbro
Sedimentary rocks (sedimentites)	often with fossils, a few %	clastic	shale, siltstone, sandstone
		biogenic	limestone, chalk, dolostone
		precipitate	halite, gypsum
Metamorphic rocks (metamorphites)	transformed by heat and pressure, a few %	foliated	slate, schist, gneiss (Himalayas)
		non-foliated (grandoblastic or hornfelsic)	marble, skarn, quartzite
Meteorites	from the solar system	rock meteorites	
		iron meteorites	

because it once was at a depth of the order of 70 km, or because of an asteroid impact, or because of an atomic bomb explosion.

From the point of view of materials science, rocks are mixtures of minerals. Even though more than 5000 minerals are known, only about 200 form rocks. These rock-forming minerals can be grouped in a few general types. The main group are the silica-based rocks. They contain SiO_4 tetrahedra and form around 92 % of all rocks. The remaining 8 % of rocks are of different composition, such as carbonates or oxides. Table 5 gives more details. The table covers the minerals found on the Earth's crust. However, the most common mineral in absolute is *Bridgmanite*, a form of $MgSiO_3$. About one third of the Earth is made of Bridgmanite, a silicate perovskite; it is formed in the lower mantle, at temperatures of around 1800 °C and pressures above 24 GPa. The mineral never appears on the Earth's crust. Recent research suggests that some forms of Bridgmanite may even have contributed, when it rose to the surface by convection, to the oxygen in the atmosphere. Ref. 50

From the point of view of chemistry, rocks are even more uniform. 99 % of all rocks are made of only nine elements. Table 6 shows the details.

Almost all minerals are crystals. *Crystals* are solids with a regular arrangement of atoms and are a fascinating topic by themselves.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 5 The mineralogic composition of rocks and stones in the Earth's crust.

Group	Mineral	Volume fraction
Inosilicates	*single chain* silicates: pyroxenes, e.g., diopside	11(2) %
	double chain silicates: amphiboles/hornblende, e.g., tremolite	5(1) %
Phyllosilicates	*sheet* silicates:	10 (2) %
	clays, e.g., kaolinite, talc	5(1) %
	mica-based minerals, e.g., biotite, muscovite	5(1) %
Tectosilicates	*volume* silicates:	65(5) %
	quartz, tridymite, cristobalite, coesite	11(1) %
	the plagioclase feldspar series, e.g., albite	43(4) %
	the alkali feldspars, e.g., orthoclase	14(2) %
Other silicates	with *isolated*, *double* or *cyclic* silica groups, e.g., olivine, beryl and garnets, or amorphous silicates, e.g., opal	3(1) %
Oxide-based rocks	e.g., magnetite, hematite, bauxite	5(1) %
Carbonate-based rocks	e.g., calcite, dolomite	
Sulfate-based rocks	e.g., gypsum, anhydrite	
Halide-based rocks	e.g., rock salt or halite, fluorite	
Other rocks		
	phosphates, e.g., apatite	1(0.5) %
	sulfides, e.g., pyrite	
	native metals, e.g., gold	
	borates, e.g.,	
	and many others.	

Crystal formation

Have you ever admired a quartz crystal or some other crystalline material? The beautiful shape and atomic arrangement has formed spontaneously, as a result of the motion of atoms under high temperature and pressure, during the time that the material was deep under the Earth's surface. The details of crystal formation are complex and interesting.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

CHALLENGE HINTS AND SOLUTIONS

Challenge 1, page 10: Do not hesitate to be demanding and strict. The next edition of the text will benefit from it.

Challenge 2, page 17: A *virus* is an example. It has no own metabolism. By the way, the ability of some viruses to form crystals is *not* a proof that they are not living beings, in contrast to what is often said. Apart from viruses, also *prions*, *viroids* and *virusoids* are examples of non-living systems that can reproduce. Another, quite different border example between life and non-living matter is provided by the *tardigrades*. These little animals, about 1 mm in size, can loose all their water, remain in this dry – or ''dead'' – state for years, and then start living again when a drop of water is added to them.

Challenge 3, page 18: The navigation systems used by flies are an example.

Challenge 6, page 22: The thermal energy kT is about 4 zJ and a typical relaxation time is 0.1 ps.

Challenge 10, page 30: The argument is correct.

Challenge 8, page 30: This is not possible at present. If you know a way, publish it. It would help a sad single mother who has to live without financial help from the father, despite a lawsuit, as it was yet impossible to decide which of the two candidates is the right one.

Challenge 9, page 30: Also identical twins count as different persons and have different fates. Imprinting in the womb is different, so that their temperament will be different. The birth experience will be different; this is the most intense experience of every human, strongly determining his fears and thus his character. A person with an old father is also quite different from that with a young father. If the womb is not that of his biological mother, a further distinction of the earliest and most intensive experiences is given.

Challenge 11, page 30: Be sure to publish your results.

Challenge 12, page 31: Yes, but only very young ones. Why?

Challenge 13, page 31: The reason of animal symmetry is simple: without symmetry, they would not be able to move in a *straight* line.

Challenge 14, page 31: Life's chemicals are synthesized inside the body; the asymmetry has been inherited along the generations. The common asymmetry thus shows that all life has a common origin.

Challenge 15, page 31: Well, men are more similar to chimpanzees than to women. More seriously, the above data, even though often quoted, are wrong. Newer measurements by Roy Britten in 2002 have shown that the difference in genome between humans and chimpanzees is about 5 % (See R. J. Britten, *Divergence between samples of chimpanzee and human DNA sequences is 5 %, counting indels*, Proceedings of the National Academy of Sciences **99**, pp. 13633–13635, 15th of October, 2002.) In addition, though the difference between man and woman is smaller than one whole chromosome, the large size of the X chromosome, compared with the small size of the Y chromosome, implies that men have about 3 % less genetic material than women. However, all

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

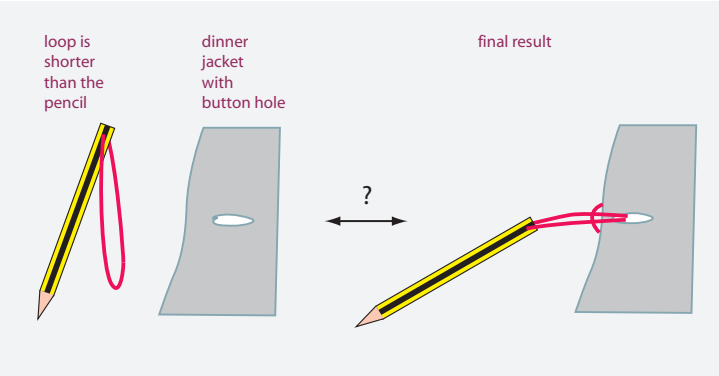


FIGURE 189 A well-known magic dexterity trick: make your friend go mad by adding a pencil to his dinner jacket.

— finding criteria distinguishing P and NP numerical problems;
— proving the Riemann hypothesis stating that the non-trivial zeros of the zeta function lie on a line;
— proving the Hodge conjectures;
— proving the connection between Yang–Mills theories and a mass gap in quantum field theory.

Vol. VI, page 325

The Poincaré conjecture was solved in 2002 by Grigori Perelman; on each of the other six topics, substantial progress can buy you a house.



Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 6 The chemical composition of rocks and stones in the Earth's crust.

ELEMENT	VOLUME FRACTION
Oxygen	46.7(1.0) %
Silicon	27.6(0.6) %
Aluminium	8.1(0.1) %
Iron	5(1) %
Calcium	4.3(0.7) %
Sodium	2.5(0.2) %
Potassium	2.0(0.5) %
Magnesium	2.5(0.4) %
Titanium	0.5(0.1) %
Other elements	0.8(0.8) %

Are regular crystal lattices *energetically optimal*? This simple question leads to a wealth of problems. We might start with the much simpler question whether a regular dense packing of spheres is the most *dense* packing possible. Its density is $\pi/\sqrt{18}$, i.e., a bit over 74 %. Even though this was conjectured to be the maximum possible value already in 1609 by Johannes Kepler, the statement was proven only in 1998 by Tom Hales. The proof is difficult because in small volumes it is possible to pack spheres up to almost 78 %. To show that over large volumes the lower value is correct is a tricky business.

Challenge 43 s
Ref. 51

Next, does a regular crystal of solid spheres, in which the spheres do *not* touch, really have the *highest possible entropy*? This simple problem has been the subject of research only from the 1990s onwards. Interestingly, *for low temperatures*, regular sphere arrangements indeed show the largest possible entropy. At low temperatures, spheres in a crystal can oscillate around their average position and be thus more disordered than if they were in a liquid; in the liquid state the spheres would block each other's motion and would not allow reaching the entropy values of a solid.

Many similar results deduced from the research into these so-called *entropic forces* show that the transition from solid to liquid is – at least in part – simply a geometrical effect. For the same reason, one gets the surprising result that even slightly repulsing spheres (or atoms) can form crystals and melt at higher temperatures. These are beautiful examples of how classical thinking can explain certain material properties, using from quantum theory only the particle model of matter.

Ref. 52

But the energetic side of crystal formation provides other interesting questions. Quantum theory shows that it is possible that *two* atoms repel each other, while *three* attract each other. This beautiful effect was discovered and explained by Hans-Werner Fink in 1984. He studied rhenium atoms on tungsten surfaces and showed, as observed, that they cannot form dimers – two atoms moving together – but readily form trimers. This is an example contradicting classical physics; the effect is impossible if one pictures atoms as immutable spheres, but becomes possible when one remembers that the electron clouds around the atoms rearrange depending on their environment.

Ref. 53

For an exact study of crystal energy, the interactions between all atoms have to be

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

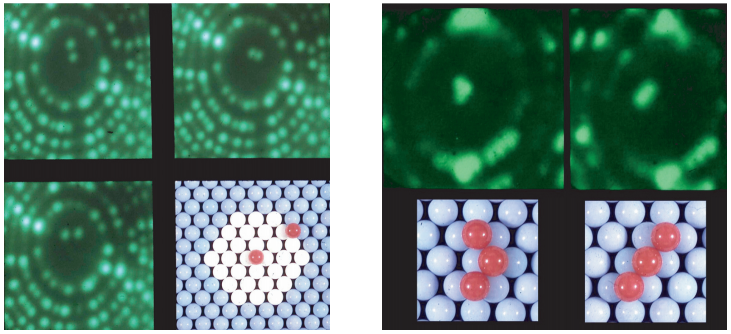


FIGURE 27 On tungsten tips, rhenium atoms, visible at the centre of the images, do not form dimers (left) but do form trimers (right) (© Hans-Werner Fink/APS, from Ref. 53).

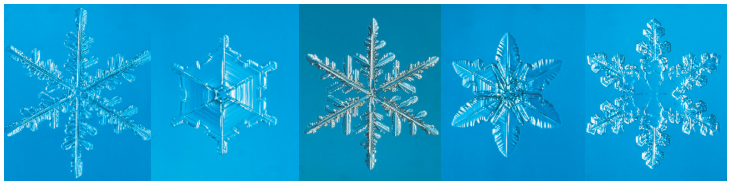


FIGURE 28 Some snow flakes (© Furukawa Yoshinori).

included. The simplest question about crystal energy is to determine whether a regular array of alternatively charged spheres has lower energy than some irregular collection. Already such simple questions are still topic of research; the answer is still open.

The previous topics concerned bulk crystals. The next topic is the face formation in crystals. Can you confirm that crystal faces are those planes with the *slowest* growth speed, because all fast growing planes are eliminated? The finer details of the process form a complete research field in itself.

Challenge 44 s
Ref. 54

However, not always the slowest growing planes win out during crystal growth. Figure 28 shows some well-known exceptions: snow flakes. Explaining the shapes of snow flakes is possible today. Furukawa Yoshinori is one of the experts in the field, heading a dedicated research team. These explanations also settle the question of symmetry: why are crystals often symmetric, instead of asymmetric? This is a topic of self-organization, as mentioned already in the section of classical physics. It turns out that the symmetry is an automatic result of the way molecular systems grow under the combined influence of diffusion and non-linear growth processes. But as usual, the details are still a topic of research.

Ref. 55

Vol. I, page 413

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 37 (Continued) Properties of the most important real and complex Lie groups.

Lie group	Description	Properties[a]	Lie algebra	Description of Lie algebra	Dimension
$SO(n, \mathbb{C})$	special orthogonal group: complex orthogonal matrices with determinant 1	for $n \geqslant 2$ not compact; not simply connected; $\pi_0 = 0$, for $n = 2$: $\pi_1 = \mathbb{Z}$, for $n \geq 2$: $\pi_1 = \mathbb{Z}_2$; non-Abelian for $n > 2$, $SO(2, \mathbb{C})$ is Abelian and isomorphic to $\mathbb{C}^\times$	$so(n, \mathbb{C})$	skew-symmetric n-by-n complex matrices, with Lie bracket the commutator; for $n = 3$ and $n \geqslant 5$ simple and semisimple	$n(n-1)/2$
$Sp(2n, \mathbb{C})$	symplectic group: complex symplectic matrices	not compact; $\pi_0 = \pi_1 = 0$	$sp(2n, \mathbb{C})$	complex matrices that satisfy $JA + A^T J = 0$ where J is the standard skew-symmetric matrix;[b] simple and semi-simple	$n(2n+1)$

a. The *group of components* π_0 of a Lie group is given; the order of π_0 is the number of components of the Lie group. If the group is trivial (0), the Lie group is connected. The *fundamental group* π_1 of a connected Lie group is given. If the group π_1 is trivial (0), the Lie group is simply connected. This table is based on that in the Wikipedia, at en.wikipedia.org/wiki/Table_of_Lie_groups.
b. The standard skew-symmetric matrix J of rank $2n$ is $J_{kl} = \delta_{k,n+l} - \delta_{k+n,l}$.
c. Complex Lie groups and Lie algebras can be viewed as real Lie groups and real Lie algebras of twice the dimension.

MATHEMATICAL CURIOSITIES AND FUN CHALLENGES

Challenge 210 ny

A theorem of topology says: you cannot comb a hairy football. Can you prove it?

* *

Topology is fun. If you want to laugh for half an hour, fix a modified pencil, as shown in Figure 189, to a button hole and let people figure out how to get it off again.

* *

There are at least six ways to earn a million dollars with mathematical research. The Clay Mathematics Institute at www.claymath.org offered such a prize for major advances in seven topics:

— proving the Birch and Swinnerton–Dyer conjecture about algebraic equations;
— proving the Poincaré conjecture about topological manifolds;
— solving the Navier–Stokes equations for fluids;

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 37 (Continued) Properties of the most important real and complex Lie groups.

Lie group	Description	Properties[a]	Lie algebra	Description of Lie algebra	Dimension
$\mathbb{C}^n$	group operation is addition	Abelian, simply connected, not compact; $\pi_0 = \pi_1 = 0$	$\mathbb{C}^n$	Abelian, thus Lie bracket is zero	n
$\mathbb{C}^\times$	non-zero complex numbers with multiplication	Abelian, not simply connected, not compact; $\pi_0 = 0$, $\pi_1 = \mathbb{Z}$	$\mathbb{C}$	Abelian, thus Lie bracket is zero	1
$GL(n, \mathbb{C})$	general linear group: invertible n-by-n complex matrices	simply connected, not compact; $\pi_0 = 0$, $\pi_1 = \mathbb{Z}$; for $n = 1$ isomorphic to $\mathbb{C}^\times$	$M(n, \mathbb{C})$	n-by-n matrices, with Lie bracket the commutator	n^2
$SL(n, \mathbb{C})$	special linear group: complex matrices with determinant 1	simply connected; for $n \geqslant 2$ not compact; $\pi_0 = \pi_1 = 0$; $SL(2, \mathbb{C})$ is isomorphic to $Spin(3, \mathbb{C})$ and $Sp(2, \mathbb{C})$	$sl(n, \mathbb{C})$	n-by-n matrices with trace 0, with Lie bracket the commutator; simple, semisimple; $sl(2, \mathbb{C})$ is isomorphic to $su(2, \mathbb{C}) \otimes \mathbb{C}$	$n^2 - 1$
$PSL(2, \mathbb{C})$	projective special linear group; isomorphic to the Möbius group, to the restricted Lorentz group $SO^+(3, 1, \mathbb{R})$ and to $SO(3, \mathbb{C})$	not compact; $\pi_0 = 0$, $\pi_1 = \mathbb{Z}_2$	$sl(2, \mathbb{C})$	2-by-2 matrices with trace 0, with Lie bracket the commutator; $sl(2, \mathbb{C})$ is isomorphic to $su(2, \mathbb{C}) \otimes \mathbb{C}$	3
$O(n, \mathbb{C})$	orthogonal group: complex orthogonal matrices	not connected; for $n \geqslant 2$ not compact; $\pi_0 = \mathbb{Z}_2$, no π_1	$so(n, \mathbb{C})$	skew-symmetric n-by-n complex matrices, with Lie bracket the commutator	$n(n-1)/2$

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Some interesting crystals

Every crystal, like every structure in nature, is the result of growth. Every crystal is thus the result of motion. To form a crystal whose regularity is as high as possible and whose shape is as symmetric as possible, the required motion is a *slow* growth of facets from the liquid (or gaseous) basic ingredients. The growth requires a certain pressure, temperature and temperature gradient for a certain time. For the most impressive crystals, the *gemstones*, the conditions are usually quite extreme; this is the reason for their durability. The conditions are realized in specific rocks deep inside the Earth, where the growth process can take thousands of years. Mineral crystals can form in all three types of rocks: igneous (magmatic), metamorphic, and sedimentary. Other crystals can be made in the laboratory in minutes, hours or days and have led to a dedicated industry. Only a few crystals grow from liquids at standard conditions; examples are gypsum and several other sulfates, which can be crystallized at home, potassium bitartrate, which appears in the making of wine, and the crystals grown inside plants or animals, such as teeth, bones or magnetosensitive crystallites.

Page 69

Growing, cutting, treating and polishing crystals is an important industry. Especially the growth of crystals is a science in itself. Can you show with pencil and paper that only the *slowest* growing facets are found in crystals? In the following, a few important crystals are presented.

Challenge 45 e



FIGURE 29 Quartz found at St. Gotthard, Switzerland, picture size 12 cm (© Rob Lavinsky).



FIGURE 30 Citrine found on Magaliesberg, South Africa, crystal height 9 cm (© Rob Lavinsky).



FIGURE 31 Amethystine and orange quartz found in the Orange River, Namibia, picture size 6 cm (© Rob Lavinsky).

* *

Quartz, *amethyst* (whose colour is due to radiation and iron Fe^{4+} impurities), *citrine* (whose colour is due to Fe^{3+} impurities), *smoky quartz* (with colour centres induced by radioactivity), *agate* and *onyx* are all forms of crystalline silicon dioxide or SiO_2. Quartz forms in igneous and in magmatic rocks; crystals are also found in many sedimentary rocks. Quartz crystals can sometimes be larger than humans. By the way, most amethysts

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

lose their colour with time, so do not waste money buying them.

Quartz is the most common crystal on Earth's crust and is also grown synthetically for many high-purity applications. The structure is rombohedral, and the ideal shape is a six-sided prism with six-sided pyramids at its ends. Quartz melts at 1986 K and is piezo- and pyroelectric. Its piezoelectricity makes it useful as electric oscillator and filter. A film of an oscillating clock quartz is found in the first volume. Quartz is also used for glass production, in communication fibres, for coating of polymers, in gas lighters, as source of silicon and for many other applications.

Vol. I, page 290



FIGURE 32 Corundum found in Laacher See, Germany, picture size 4 mm (© Stephan Wolfsried).



FIGURE 33 Ruby found in Jagdalak, Afghanistan, picture height 2 cm (© Rob Lavinsky).



FIGURE 34 Sapphire found in Ratnapura, Sri Lanka, size 1.6 cm (© Rob Lavinsky).

* *

Corundum, *ruby* and *sapphire* are crystalline variations of alumina, or Al_2O_3. Corundum is pure and colourless crystalline alumina, ruby is Cr doped and blue sapphire is Ti or Fe doped. They have trigonal crystal structure and melt at 2320 K. Natural gems are formed in metamorphic rocks. Yellow, green, purple, pink, brown, grey and salmon-coloured sapphires also exist, when doped with other impurities. The colours of natural sapphires, like that of many other gemstones, are often changed by baking and other treatments.

Corundum, ruby and sapphire are used in jewellery, as heat sink and growth substrate, and for lasers. Corundum is the second-hardest material known, just after diamond, and is therefore used as scratch-resistant 'glass' in watches and, since a short time, in mobile phones. Ruby was the first gemstone that was grown synthetically in gem quality, in 1892 by Auguste Verneuil (1856-1913), who made his fortune in this way. Modern synthetic single crystals of corundum can weigh 30 kg and more. Also alumina ceramics, which can be white or even transparent, are important in industrial and medical systems.

* *

Tourmaline is a frequently found mineral and can be red, green, blue, orange, yellow,

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 37 (Continued) Properties of the most important real and complex Lie groups.

Lie group	Description	Properties[a]	Lie algebra	Description of Lie algebra	Dimension
$SO(n,\mathbb{R})$ $= SO(n)$	special orthogonal group: real orthogonal matrices with determinant 1	connected, compact; for $n \geqslant 2$ not simply connected; $\pi_0 = 0$, for $n = 2$: $\pi_1 = \mathbb{Z}$, for $n \geq 2$: $\pi_1 = \mathbb{Z}_2$	$so(n,\mathbb{R})$ $= B_{\frac{n-1}{2}}$ or $D_{\frac{n}{2}}$	skew-symmetric n-by-n real matrices, with Lie bracket the commutator; for $n = 3$ and $n \geqslant 5$ simple and semisimple; $SO(4)$ is semisimple but not simple	$n(n-1)/2$
$Spin(n)$	spin group; double cover of $SO(n)$; $Spin(1)$ is isomorphic to Q_2, $Spin(2)$ to S^1	simply connected for $n \geqslant 3$, compact; for $n = 3$ and $n \geqslant 5$ simple and semisimple; for $n > 1$: $\pi_0 = 0$, for $n > 2$: $\pi_1 = 0$	$so(n,\mathbb{R})$	skew-symmetric n-by-n real matrices, with Lie bracket the commutator	$n(n-1)/2$
$Sp(2n,\mathbb{R})$	symplectic group: real symplectic matrices	not compact; $\pi_0 = 0$, $\pi_1 = \mathbb{Z}$	$sp(2n,\mathbb{R})$ $= C_n$	real matrices A that satisfy $JA + A^T J = 0$ where J is the standard skew-symmetric matrix;[b] simple and semisimple	$n(2n+1)$
$Sp(n)$ for $n \geqslant 3$	compact symplectic group: quaternionic $n \times n$ unitary matrices	compact, simply connected; $\pi_0 = \pi_1 = 0$	$sp(n)$	n-by-n quaternionic matrices A satisfying $A = -A^*$, with Lie bracket the commutator; simple and semisimple	$n(2n+1)$
$U(n)$	unitary group: complex $n \times n$ unitary matrices	not simply connected, compact; it is *not* a complex Lie group/algebra; $\pi_0 = 0$, $\pi_1 = \mathbb{Z}$; isomorphic to S^1 for $n = 1$	$u(n)$	n-by-n complex matrices A satisfying $A = -A^*$, with Lie bracket the commutator	n^2
$SU(n)$	special unitary group: complex $n \times n$ unitary matrices with determinant 1	simply connected, compact; it is *not* a complex Lie group/algebra; $\pi_0 = \pi_1 = 0$	$su(n)$	n-by-n complex matrices A with trace 0 satisfying $A = -A^*$, with Lie bracket the commutator; for $n \geqslant 2$ simple and semisimple	$n^2 - 1$
2. Complex groups[c]					complex

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 37 (Continued) Properties of the most important real and complex Lie groups.

Lie group	Description	Properties[a]	Lie algebra	Description of Lie algebra	Dimension
S^3	quaternions of absolute value 1, with multiplication, also known as Sp(1); topologically a 3-sphere	simply connected, compact; isomorphic to SU(2), Spin(3) and to double cover of SO(3); $\pi_0 = \pi_1 = 0$	Im(ℍ)	quaternions with zero real part, with Lie bracket the commutator; simple and semi-simple; isomorphic to real 3-vectors, with Lie bracket the cross product; also isomorphic to su(2) and to so(3)	3
$GL(n, \mathbb{R})$	general linear group: invertible n-by-n real matrices	not connected, not compact; $\pi_0 = \mathbb{Z}_2$, no π_1	$M(n, \mathbb{R})$	n-by-n matrices, with Lie bracket the commutator	n^2
$GL^+(n, \mathbb{R})$	n-by-n real matrices with positive determinant	simply connected, not compact; $\pi_0 = 0$, for $n = 2$: $\pi_1 = \mathbb{Z}$, for $n \geq 2$: $\pi_1 = \mathbb{Z}_2$; $GL^+(1, \mathbb{R})$ isomorphic to $\mathbb{R}^{>0}$	$M(n, \mathbb{R})$	n-by-n matrices, with Lie bracket the commutator	n^2
$SL(n, \mathbb{R})$	special linear group: real matrices with determinant 1	simply connected, not compact if $n > 1$; $\pi_0 = 0$, for $n = 2$: $\pi_1 = \mathbb{Z}$, for $n \geq 2$: $\pi_1 = \mathbb{Z}_2$; $SL(1, \mathbb{R})$ is a single point, $SL(2, \mathbb{R})$ is isomorphic to $SU(1, 1)$ and $Sp(2, \mathbb{R})$	$sl(n, \mathbb{R}) = A_{n-1}$	n-by-n matrices with trace 0, with Lie bracket the commutator	$n^2 - 1$
$O(n, \mathbb{R}) = O(n)$	orthogonal group: real orthogonal matrices; symmetry of hypersphere	not connected, compact; $\pi_0 = \mathbb{Z}_2$, no π_1	$so(n, \mathbb{R})$	skew-symmetric n-by-n real matrices, with Lie bracket the commutator; $so(3, \mathbb{R})$ is isomorphic to su(2) and to $\mathbb{R}^3$ with the cross product	$n(n-1)/2$

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 35 Left: raw crystals, or boules, of synthetic corundum, picture size c. 50 cm. Right: a modern, 115 kg corundum single crystal, size c. 50 cm (© Morion Company, GT Advanced).

pink or black, depending on its composition. The chemical formula is astonishingly complex and varies from type to type. Tourmaline has trigonal structure and usually forms columnar crystals that have triangular cross-section. It is only used in jewellery. Paraiba tourmalines, a very rare type of green or blue tourmaline, are among the most beautiful gemstones and can be, if natural and untreated, more expensive than diamonds.



FIGURE 36 Natural bicoloured tourmaline found in Paprok, Afghanistan, picture size 9 cm (© Rob Lavinsky).



FIGURE 37 Cut Paraiba tourmaline from Brazil, picture size 3 cm (© Manfred Fuchs).

* *

Garnets are a family of compounds of the type $X_2Y_3(SiO_4)_3$. They have cubic crystal structure. They can have any colour, depending on composition. They show no cleavage and their common shape is a rhombic dodecahedron. Some rare garnets differ in col-

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

our when looked at in daylight or in incandescent light. Natural garnets form in metamorphic rocks and are used in jewellery, as abrasive and for water filtration. Synthetic garnets are used in many important laser types.

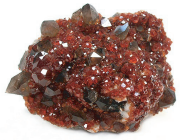


FIGURE 38 Red garnet with smoky quartz found in Lechang, China, picture size 9 cm (© Rob Lavinsky).



FIGURE 39 Green demantoid, a garnet owing its colour to chromium doping, found in Tubussis, Namibia, picture size 5 cm (© Rob Lavinsky).

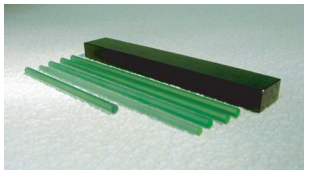


FIGURE 40 Synthetic Cr,Tm,Ho:YAG, a doped yttrium aluminium garnet, picture size 25 cm (© Northrop Grumman).

* *

Alexandrite, a chromium-doped variety of *chrysoberyl*, is used in jewellery and in lasers. Its composition is $BeAl_2O_4$; the crystal structure is orthorhombic. Chrysoberyl melts at 2140 K. Alexandrite is famous for its colour-changing property: it is green in daylight or fluorescent light but amethystine in incandescent light, as shown in Figure 38. The effect is due to its chromium content: the ligand field is just between that of chromium in red ruby and that in green emerald. A few other gems also show this effect, in particular the rare blue garnet and some Paraiba tourmalines.



FIGURE 41 Alexandrite found in the Setubal river, Brazil, crystal height 1.4 cm, illuminated with daylight (left) and with incandescent light (right) (© Trinity Mineral).

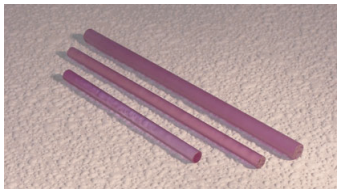


FIGURE 42 Synthetic alexandrite, picture size 20 cm (© Northrop Grumman).

* *

Perovskites are a large class of cubic crystals used in jewellery and in tunable lasers. Their general composition is XYO_3, XYF_3 or $XYCl_3$.

* *

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

groups. In fact, field theory *requires* compact Lie groups for gauge transformations. The only compact Lie groups are the torus groups T^n, $O(n)$, $U(n)$, $SO(n)$ and $SU(n)$, their double cover $Spin(n)$ and the $Sp(n)$. In contrast, $SL(n,\mathbb{R})$, $GL(n,\mathbb{R})$, $GL(n,\mathbb{C})$ and all others are not compact.

Besides being manifolds, Lie groups are obviously also groups. It turns out that most of their group properties are revealed by the behaviour of the elements which are very close (as points on the manifold) to the identity.

Every element of a compact and connected Lie group has the form $\exp(A)$ for some A. The elements A arising in this way form an algebra, called the *corresponding Lie algebra*. For any linear Lie group, every element of the connected subgroup can be expressed as a finite product of exponentials of elements of the corresponding Lie algebra. Mathematically, the vector space defined by the Lie algebra is tangent to the manifold defined by the Lie group, at the location of the unit element. In short, Lie algebras express the local properties of Lie groups near the identity. That is the reason for their importance in physics.

Page 361

TABLE 37 Properties of the most important real and complex Lie groups.

Lie group	Description	Properties[a]	Lie algebra	Description of Lie algebra	Dimension
1. Real groups					real
$\mathbb{R}^n$	Euclidean space with addition	Abelian, simply connected, not compact; $\pi_0 = \pi_1 = 0$	$\mathbb{R}^n$	Abelian, thus Lie bracket is zero; not simple	n
$\mathbb{R}^\times$	non-zero real numbers with multiplication	Abelian, not connected, not compact; $\pi_0 = \mathbb{Z}_2$, no π_1	$\mathbb{R}$	Abelian, thus Lie bracket is zero	1
$\mathbb{R}^{>0}$	positive real numbers with multiplication	Abelian, simply connected, not compact; $\pi_0 = \pi_1 = 0$	$\mathbb{R}$	Abelian, thus Lie bracket is zero	1
$S^1 = \mathbb{R}/\mathbb{Z} = U(1) = T = SO(2) = Spin(2)$	complex numbers of absolute value 1, with multiplication	Abelian, connected, not simply connected, compact; $\pi_0 = 0$, $\pi_1 = \mathbb{Z}$	$\mathbb{R}$	Abelian, thus Lie bracket is zero	1
$\mathbb{H}^\times$	non-zero quaternions with multiplication	simply connected, not compact; $\pi_0 = \pi_1 = 0$	$\mathbb{H}$	quaternions, with Lie bracket the commutator	4

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

compact torus are examples of non-linear Lie groups.) The important linear Lie groups for physics are the Lie subgroups of the general linear group GL(N,K), where K is a number field. This is defined as the set of all non-singular, i.e., invertible, N×N real, complex or quaternionic matrices. All the Lie groups discussed below are of this type.

Every *complex* invertible matrix A can be written in a unique way in terms of a unitary matrix U and a Hermitean matrix H:

$$A = U\mathrm{e}^{H} \,. \tag{150}$$

Challenge 209 s (H is given by $H = \frac{1}{2}\ln A^{\dagger}A$, and U is given by $U = A\mathrm{e}^{-H}$.)

The simple Lie groups U(1) and SO(2,ℝ) and the Lie groups based on the real and complex numbers are Abelian (see Table 37); all others are non-Abelian.

Lie groups are manifolds. Therefore, in a Lie group one can define the distance between two points, the tangent plane (or tangent space) at a point, and the notions of integration and differentiations. Because Lie groups are manifolds, Lie groups have the same kind of structure as the objects of Figures 184, 185 and 186. Lie groups can have any number of dimensions. Like for any manifold, their global structure contains important information; let us explore it.

Connectedness

It is not hard to see that the Lie groups SU(N) are simply connected for all $N = 2, 3 \ldots$; they have the topology of a 2N-dimensional sphere. The Lie group U(1), having the topology of the 1-dimensional sphere, or circle, is multiply connected.

The Lie groups SO(N) are *not* simply connected for any $N = 2, 3 \ldots$. In general, SO(N,K) is connected, and GL(N,ℂ) is connected. All the Lie groups SL(N,K) are connected; and SL(N,ℂ) is simply connected. The Lie groups Sp(N,K) are connected; Sp(2N,ℂ) is simply connected. Generally, all semi-simple Lie groups are connected.

The Lie groups O(N,K), SO(N,M,K) and GL(N,ℝ) are not connected; they contain two connected components.

Note that the Lorentz group is not connected: it consists of four separate pieces. Like the Poincaré group, it is not compact, and neither is any of its four pieces. Broadly speaking, the non-compactness of the group of space-time symmetries is a consequence of the non-compactness of space-time.

Compactness

A Lie group is *compact* if it is closed and bounded when seen as a manifold. For a given parametrization of the group elements, the Lie group is compact if all parameter ranges are closed and finite intervals. Otherwise, the group is called *non-compact*. Both compact and non-compact groups play a role in physics. The distinction between the two cases is important, because representations of compact groups can be constructed in the same simple way as for finite groups, whereas for non-compact groups other methods have to be used. As a result, physical observables, which always belong to a representation of a symmetry group, have different properties in the two cases: if the symmetry group is compact, observables have *discrete* spectra; otherwise they do not.

All groups of internal gauge transformations, such as U(1) and SU(n), form compact

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 43 Perovskite found in Hillesheim, Germany. Picture width 3 mm (© Stephan Wolfsried).

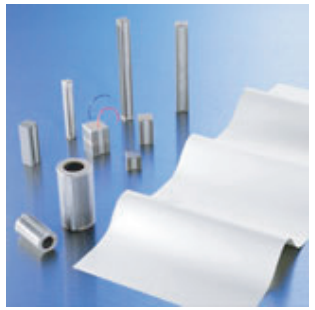


FIGURE 44 Synthetic PZT, or lead zirconium titanate, is a perovskite used in numerous products. Picture width 20 cm (© Ceramtec).

Diamond is a metastable variety of *graphite*, thus pure carbon. Theory says that graphite is the stable form; practice says that diamond is still more expensive. In contrast to graphite, diamond has face-centred cubic structure, is a large band gap semiconductor and typically has octahedral shape. Diamond burns at 1070 K; in the absence of oxygen it converts to graphite at around 1950 K. Diamond can be formed in magmatic and in metamorphic rocks. Diamonds can be synthesized in reasonable quality, though gemstones of large size and highest quality are not yet possible. Diamond can be coloured and be doped to achieve electrical conductivity in a variety of ways. Diamond is mainly used in jewellery, for hardness measurements and as abrasive.

* *

Silicon, Si, is not found in nature in pure form; all crystals are synthetic. The structure is face-centred cubic, thus diamond-like. It is moderately brittle, and can be cut in thin wafers which can be further thinned by grinding or chemical etching, even down to a thickness of 10 µm. Being a semiconductor, the band structure determines its black colour, its metallic shine and its brittleness. Silicon is widely used for silicon chips and electronic semiconductors. Today, human-sized silicon crystals can be grown free of dislocations and other line defects. (They will still contain some point defects.)

* *

Teeth are the structures that allowed animals to be so successful in populating the Earth. They are composed of several materials; the outer layer, the *enamel*, is 97 % hydroxylapatite, mixed with a small percentage of two proteins groups, the amelogenins and the enamelins. The growth of teeth is still not fully understood; neither the molecular level nor the shape-forming mechanisms are completely clarified. Hydroxylapatite is soluble in acids; addition of fluorine ions changes the hydroxylapatite to fluorapatite and greatly reduces the solubility. This is the reason for the use of fluorine in tooth paste.

Hydroxylapatite (or hydroxyapatite) has the chemical formula $Ca_{10}(PO_4)_6(OH)_2$, pos-

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 45 Natural diamond from Saha republic, Russia, picture size 4 cm (© Rob Lavinsky).

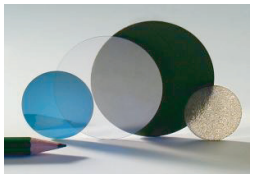


FIGURE 46 Synthetic diamond, picture size 20 cm (© Diamond Materials GmbH).



FIGURE 47 Ophthalmic diamond knife, picture size 1 cm (© Diamatrix Ltd.).

sesses hexagonal crystal structure, is hard (more than steel) but relatively brittle. It occurs as mineral in sedimentary rocks (see Figure 49), in bones, renal stones, bladders tones, bile stones, atheromatic plaque, cartilage arthritis and teeth. Hydroxylapatite is mined as a phosphorus ore for the chemical industry, is used in genetics to separate single and double-stranded DNA, and is used to coat implants in bones.

* *

Pure metals, such as *gold*, *silver* and even *copper*, are found in nature, usually in magmatic rocks. But only a few metallic compounds form crystals, such as *pyrite*. Monocrystalline pure metal crystals are all synthetic. Monocrystalline metals, for example iron, aluminium, gold or copper, are extremely soft and ductile. Either bending them repeatedly – a process called cold working – or adding impurities, or forming alloys makes them hard and strong. Stainless steel, a carbon-rich iron alloy, is an example that uses all three processes.

* *

In 2009, Luca Bindi of the Museum of Natural History in Florence, Italy, made headlines

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

(the Monster 'babies'), Ru, Ly, and ON.

The classification was finished in the 1980s after over 10 000 pages of publications. The proof is so vast that a special series of books has been started to summarize and explain it. The first three families are infinite. The last family, that of the sporadic groups, is the most peculiar; it consists of those finite simple groups which do not fit into the other families. Some of these sporadic groups might have a role in particle physics: possibly even the largest of them all, the so-called *Monster* group. This is still a topic of research. (The Monster group has about $8.1 \cdot 10^{53}$ elements; more precisely, its order is 808 017 424 794 512 875 886 459 904 961 710 757 005 754 368 000 000 000 or $2^{46} \cdot 3^{20} \cdot 5^9 \cdot 7^6 \cdot 11^2 \cdot 13^3 \cdot 17 \cdot 19 \cdot 23 \cdot 29 \cdot 31 \cdot 41 \cdot 47 \cdot 59 \cdot 71$.)

Of the *infinite* groups, only those with some finiteness condition have been studied. It is only such groups that are of interest in the description of nature. Infinite groups are divided into *discrete* groups and *continuous* groups. Discrete groups are an active area of mathematical research, having connections with number theory and topology. Continuous groups are divided into *finitely generated* and *infinitely generated* groups. Finitely generated groups can be finite-dimensional or infinite-dimensional.

The most important class of finitely generated continuous groups are the Lie groups.

Lie groups

In nature, the Lagrangians of the fundamental forces are invariant under gauge transformations and under continuous space-time transformations. These symmetry groups are examples of Lie groups, which are a special type of infinite continuous group. They are named after the great mathematician Sophus Lie (b. 1842 Nordfjordeid, d. 1899 Kristiania). His name is pronounced like 'Lee'.

A (real) *Lie group* is an infinite symmetry group, i.e., a group with infinitely many elements, which is also an analytic manifold. Roughly speaking, this means that the elements of the group can be seen as points on a smooth (hyper-) surface whose shape can be described by an analytic function, i.e., by a function so smooth that it can be expressed as a power series in the neighbourhood of every point where it is defined. The points of the Lie group can be multiplied according to the group multiplication. Furthermore, the coordinates of the product have to be analytic functions of the coordinates of the factors, and the coordinates of the inverse of an element have to be analytic functions of the coordinates of the element. In fact, this definition is unnecessarily strict: it can be proved that a Lie group is just a topological group whose underlying space is a finite-dimensional, locally Euclidean manifold.

A *complex Lie group* is a group whose manifold is complex and whose group operations are holomorphic (instead of analytical) functions in the coordinates.

In short, a Lie group is a well-behaved manifold in which points can be multiplied (and technicalities). For example, the circle $\boldsymbol{T} = \{z \in \mathbb{C} : |z| = 1\}$, with the usual complex multiplication, is a real Lie group. It is Abelian. This group is also called S^1, as it is the one-dimensional sphere, or U(1), which means 'unitary group of one dimension'. The other one-dimensional Lie groups are the multiplicative group of non-zero real numbers and its subgroup, the multiplicative group of positive real numbers.

So far, in physics, only *linear* Lie groups have played a role – that is, Lie groups which act as linear transformations on some vector space. (The cover of SL(2,ℝ) or the complex

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

There are three main tools to describe holes of manifolds and the relations among them: homotopy, homology and cohomology. These tools play an important role in the study of gauge groups, because any gauge group defines a manifold.

In other words, through homotopy and homology theory, mathematicians can *classify* manifolds. Given two manifolds, the properties of the holes in them thus determine whether they can be deformed into each other.

Physicists are now extending these results of standard topology. Deformation is a classical idea which assumes continuous space and time, as well as arbitrarily small action. In nature, however, quantum effects cannot be neglected. It is speculated that quantum effects can transform a physical manifold into one with a *different* topology: for example, a torus into a sphere. Can you find out how this can be achieved?

Challenge 208 d

Topological changes of physical manifolds happen via objects that are generalizations of manifolds. An *orbifold* is a space that is locally modelled by $\mathbb{R}^n$ modulo a finite group. Examples are the tear-drop or the half-plane. Orbifolds were introduced by Satake Ichiro in 1956; the name was coined by William Thurston. Orbifolds are heavily studied in string theory.

TYPES AND CLASSIFICATION OF GROUPS

Vol. I, page 271

We introduced mathematical *groups* early on because groups, especially symmetry groups, play an important role in many parts of physics, from the description of solids, molecules, atoms, nuclei, elementary particles and forces up to the study of shapes, cycles and patterns in growth processes.

Group theory is also one of the most important branches of modern mathematics, and is still an active area of research. One of the aims of group theory is the *classification* of all groups. This has been achieved only for a few special types. In general, one distinguishes between finite and infinite groups. Finite groups are better understood.

Every *finite* group is isomorphic to a subgroup of the symmetric group S_N, for some number N. Examples of finite groups are the crystalline groups, used to classify crystal structures, or the groups used to classify wallpaper patterns in terms of their symmetries. The symmetry groups of Platonic and many other regular solids are also finite groups.

Finite groups are a complex family. Roughly speaking, a general (finite) group can be seen as built from some fundamental bricks, which are groups themselves. These fundamental bricks are called *simple* (finite) groups. One of the high points of twentieth-century mathematics was the classification of the finite simple groups. It was a collaborative effort that took around 30 years, roughly from 1950 to 1980. The complete list of finite simple groups consists of

Ref. 303

1) the *cyclic groups* Z_p of prime group order;
2) the *alternating groups* A_n of degree n at least five;
3) the *classical linear groups*, $PSL(n; q)$, $PSU(n; q)$, $PSp(2n; q)$ and $P\Omega^{\epsilon}(n; q)$;
4) the *exceptional* or *twisted groups* of Lie type ${}^3D_4(q)$, $E_6(q)$, ${}^2E_6(q)$, $E_7(q)$, $E_8(q)$, $F_4(q)$, ${}^2F_4(2^n)$, $G_2(q)$, ${}^2G_2(3^n)$ and ${}^2B_2(2^n)$;
5) the 26 *sporadic groups*, namely M_{11}, M_{12}, M_{22}, M_{23}, M_{24} (the Mathieu groups), J_1, J_2, J_3, J_4 (the Janko groups), Co_1, Co_2, Co_3 (the Conway groups), HS, Mc, Suz (the Co_1 'babies'), Fi_{22}, Fi_{23}, Fi'_{24} (the Fischer groups), $F_1 = M$ (the Monster), F_2, F_3, F_5, He (= F_7)

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 48 A silicon crystal growing machine and two resulting crystals, with a length of c. 2 m (© www.pvatepla.com).

Ref. 56

across the world with his discovery of the first natural *quasicrystal*. Quasicrystals are materials that show non-crystallographic symmetries. Until 2009, only synthetic materials were known. Then, in 2009, after years of searching, Bindi discovered a specimen in his collection whose grains clearly show fivefold symmetry.

* *

There are about 4000 known mineral types. On the other hand, there are ten times as many obsolete mineral names, namely around 40 000. An official list can be found in

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 49 Hydroxylapatite found in Oxsoykollen, Snarum, Norway, length 65 mm (© Aksel Österlöf).



FIGURE 50 The main and the reserve teeth on the jaw bone of a shark, all covered in hydroxylapatite, picture size 15 cm (© Peter Doe).

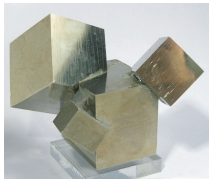


FIGURE 51 Pyrite, found in Navajún, Spain, picture width 5.7 cm (© Rob Lavinsky).



FIGURE 52 Silver from Colquechaca, Bolivia, picture width 2.5 cm (© Rob Lavinsky).



FIGURE 53 Synthetic copper single crystal, picture width 30 cm (© Lachlan Cranswick).

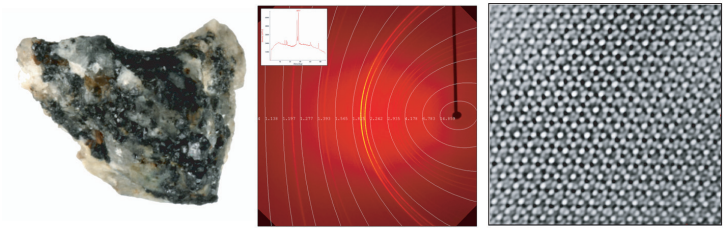


FIGURE 54 The specimen, found in the Koryak Mountains in Russia, is part of a triassic mineral, about 220 million years old; the black material is mostly khatyrkite ($CuAl_2$) and cupalite ($CuAl_2$) but also contains quasicrystal grains with composition $Al_{63}Cu_{24}Fe_{13}$ that have fivefold symmetry, as clearly shown in the X-ray diffraction pattern and in the transmission electron image. (© Luca Bindi).

various places on the internet, including www.mindat.org or www.minieralienatlas.de. To explore the world of crystal shapes, see the www.smorf.nl website. Around 40 new minerals are discovered each year. Searching for minerals and collecting them is a fascinating pastime.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

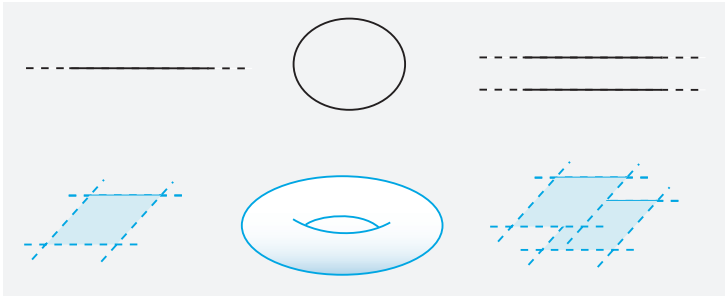


FIGURE 186 Simply connected (left), multiply connected (centre) and disconnected (right) manifolds of one (above) and two (below) dimensions.

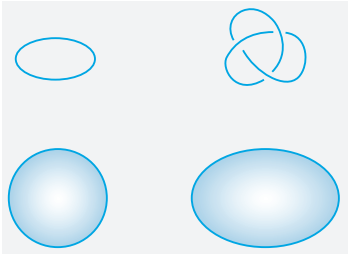


FIGURE 187 Examples of homeomorphic pairs of manifolds.



FIGURE 188 The first four two-dimensional compact connected orientable manifolds: 0-, 1-, 2- and 3-tori.

between them there is a continuous, one-to-one and onto mapping with a continuous inverse. The concept of homeomorphism is somewhat more general than that of rubber deformation, as can be seen from Figure 187. If the mapping and the manifolds are differentiable, one says that the two manifolds are *diffeomorphic*.

Holes, homotopy and homology

Only 'well-behaved' manifolds play a role in physics: namely those which are orientable and connected. In addition, the manifolds associated with observables, are always compact. The main non-trivial characteristic of connected compact orientable manifolds is that they contain 'holes' (see Figure 188). It turns out that a proper description of the holes of manifolds allows us to distinguish between all different, i.e., non-homeomorphic, types of manifold.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

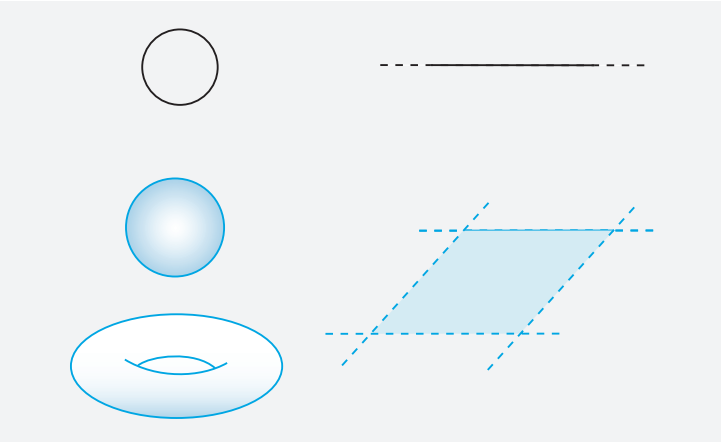


FIGURE 185 Compact (left) and non-compact (right) manifolds of various dimensions.

line. You can also try this with paper strips with different twist values, and investigate the regularities.

In two dimensions, closed manifolds (or surfaces), i.e., surfaces that are compact and without boundary, are always of one of three types:

— The simplest type are spheres with n attached handles; they are called *n-tori* or *surfaces of genus n*. They are orientable surfaces with *Euler characteristic* $2 - 2n$.
— The *projective planes* with n handles attached are non-orientable surfaces with Euler characteristic $1 - 2n$.
— The Klein bottles with n attached handles are non-orientable surfaces with Euler characteristic $-2n$.

Therefore Euler characteristic and orientability describe compact surfaces up to homeomorphism (and if surfaces are smooth, then up to diffeomorphism). Homeomorphisms are defined below.

Page 366

The two-dimensional compact manifolds or surfaces with boundary are found by removing one or more discs from a surface in this list. A compact surface can be embedded in $\mathbb{R}^3$ if it is orientable or if it has non-empty boundary.

In physics, the most important manifolds are space-time and Lie groups of observables. We study Lie groups below. Strangely enough, the topology of space-time is not known. For example, it is unclear whether or not it is simply connected. Obviously, the reason is that it is difficult to observe what happens at large distances form the Earth. However, a similar difficulty appears near Planck scales.

If a manifold is imagined to consist of rubber, connectedness and similar global properties are not changed when the manifold is deformed. This fact is formalized by saying that two manifolds are *homeomorphic* (from the Greek words for 'same' and 'shape') if

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

How can we look through matter?

Vol. IV, page 28

The quantum of action tells us that all obstacles have only finite potential heights. The quantum of action implies that matter is penetrable. That leads to a question: Is it possible to look through solid matter? For example, can we see what is hidden inside a mountain? To achieve this, we need a signal which fulfils two conditions: the signal must be able to *penetrate* the mountain, and it must be scattered in a *material-dependent* way. Indeed, such signals exist, and various techniques use them. Table 7 gives an overview of the possibilities.

TABLE 7 Signals penetrating mountains and other matter.

Signal	Penetration depth in stone	Achieved resolution	Material dependence	Use
Fluid signals				
Diffusion of gases, such as helium	*c.* 5 km	*c.* 100 m	medium	exploring vacuum systems and tube systems
Diffusion of water or liquid chemicals	*c.* 5 km	*c.* 100 m	medium	mapping hydrosystems
Sound signals				
Infrasound and earthquakes	100 000 km	100 km	high	mapping of Earth crust and mantle
Sound, explosions, short seismic waves	0.1 – 10 m	*c.* $\lambda/100$	high	oil and ore search, structure mapping in rocks, searching for underwater treasures in sunken ship with sub-bottom-profilers
Ultrasound		1 mm	high	medical imaging, acoustic microscopy, sonar, echo systems
Acousto-optic or photoacoustic imaging		1 mm	medium	blood stream imaging, mouse imaging
Electromagnetic signals				
Static magnetic field variations			medium	cable search, cable fault localization, search for structures and metal inside soil, rocks and the seabed
Electrical currents				soil and rock investigations, search for tooth decay
Electromagnetic sounding, 0.2 – 5 Hz				soil and rock investigations in deep water and on land
Radio waves	10 m	30 m to 1 mm	small	soil radar (up to 10 MW), magnetic resonance imaging, research into solar interior

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 7 (Continued) Signals penetrating mountains and other matter.

Signal	Penetration depth in stone	Achieved resolution	Material dependence	Use
Ultra-wide band radio	10 cm	1 mm	sufficient	searching for wires and tubes in walls, breast cancer detection
THz and mm waves	below 1 mm	1 mm		see through clothes, envelopes and teeth Ref. 57
Infrared	*c.* 1 m	0.1 m	medium	mapping of soil over 100 m
Visible light	*c.* 1 cm	0.1 µm	medium	imaging of many sorts, including breast tumour screening
X-rays	a few metres	5 µm	high	medicine, material analysis, airports, food production check
γ-rays	a few metres	1 mm	high	medicine
Matter particle signals				
Neutrons from a reactor	up to *c.* 1 m	1 mm	medium	tomography of metal structures, e.g., archaeologic statues or car engines
Muons created by cosmic radiation or technical sources	up to *c.* 300 m	0.1 m	small	finding caves in pyramids, imaging interior of trucks
Positrons	up to *c.* 1 m	2 mm	high	brain tomography
Electrons	up to *c.* 1 µm	10 nm	small	transmission electron microscopes
Neutrino beams	light years	none	very weak	studies of Sun
Radioactivity mapping	1 mm to 1 m			airport security checks
Gravitation				
Variation of g		50 m	low	oil and ore search

We see that many signals are able to penetrate a mountain, and even more signals are able to penetrate other condensed matter. To distinguish different materials, or to distinguish solids from liquids and from air, sound and radio waves are the best choice. In addition, any useful method requires a large number of signal sources and of signal receptors, and thus a large amount of money. Will there ever be a simple method that allows looking into mountains as precisely as X-rays allow looking into human bodies? For example, is it possible to map the interior of the pyramids? A motion expert should be able to give a definite answer. Challenge 46 s

One of the high points of twentieth century physics was the development of the best method so far to look into matter with dimensions of about a metre or less: magnetic resonance imaging. We will discuss it later on. Page 162

Various modern imaging techniques, such as X-rays, ultrasound imaging and several

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

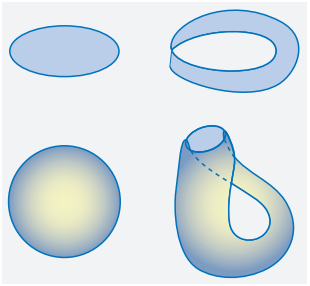


FIGURE 184 Examples of orientable and non-orientable manifolds of two dimensions: a disc, a Möbius strip, a sphere and a Klein bottle.

We thus need the concept of topological space, or of neighbourhood, if we want to express the idea that there are no jumps in nature. We also need the concept of topological space in order to be able to define limits.

Of the many special kinds of topological spaces that have been studied, one type is particularly important. A *Hausdorff space* is a topological space in which for any two points x and y there are disjoint open sets U and V such that x is in U and y is in V. A Hausdorff space is thus a space where, no matter how 'close' two points are, they can always be separated by open sets. This seems like a desirable property; indeed, non-Hausdorff spaces are rather tricky mathematical objects. (At Planck energy, it seems that vacuum appears to behave like a non-Hausdorff space; however, at Planck energy, vacuum is not really a space at all. So non-Hausdorff spaces play no role in physics.) A special case of Hausdorff space is well-known: the manifold.

Manifolds

In physics, the most important topological spaces are differential manifolds. Loosely speaking, a *differential manifold* – physicists simply speak of a *manifold* – is a set of points that looks like $\mathbb{R}^n$ under the microscope – at small distances. For example, a sphere and a torus are both two-dimensional differential manifolds, since they look locally like a plane. Not all differential manifolds are that simple, as the examples of Figure 184 show.

A differential manifold is called *connected* if any two points can be joined by a path lying in the manifold. (The term has a more general meaning in topological spaces. But the notions of connectedness and pathwise connectedness coincide for differential manifolds.) We focus on connected manifolds in the following discussion. A manifold is called *simply connected* if every loop lying in the manifold can be contracted to a point. For example, a sphere is simply connected. A connected manifold which is not simply connected is called *multiply connected*. A torus is multiply connected.

Manifolds can be *non-orientable*, as the well-known Möbius strip illustrates. Non-orientable manifolds have only one surface: they do not admit a distinction between front and back. If you want to have fun, cut a paper Möbius strip into two along a centre Challenge 207 e

$f(a)$. In this definition, the continuity of f is defined using the intuitive idea that the real numbers form the basic model of a set that has no gaps. Can you see the connection with the general definition given above? Challenge 206 ny

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

the operations that are performed on them are examples of deformations. Let us look at some more precise definitions. In order to define what a manifold is, we first need to define the concept of topological space.

Topological spaces

> En Australie, une mouche qui marche au plafond se trouve dans le même sens qu'une vache chez nous.
> Philippe Geluck, *La marque du chat*.

Ref. 302 The study of shapes requires a good definition of a set made of 'points'. To be able to talk about shape, these sets must be structured in such a way as to admit a useful concept of 'neighbourhood' or 'closeness' between the elements of the set. The search for the most general type of set which allows a useful definition of neighbourhood has led to the concept of topological space. There are two ways to define a topology: one can define the concept of *open set* and then define the concept of *neighbourhood* with their help, or the other way round. We use the second option, which is somewhat more intuitive.

A *topological space* is a finite or infinite set X of elements, called *points*, together with the neighbourhoods for each point. A *neighbourhood* N of a point x is a collection of subsets Y_x of X with the properties that

— x is in every Y_x;
— if N and M are neighbourhoods of x, so is $N \cap M$;
— anything containing a neighbourhood of x is itself a neighbourhood of x.

The choice of the subsets Y_x is free. The subsets Y_x for all points x, chosen in a particular definition, contain a neighbourhood for each of their points; they are called *open sets*. (A neighbourhood and an open set usually differ, but all open sets are also neighbourhoods. Neighbourhoods of x can also be described as subsets of X that contain an open set that contains x.)

One also calls a topological space a 'set with a topology'. In effect, a *topology* specifies the systems of 'neighbourhoods' of every point of the set. 'Topology' is also the name of the branch of mathematics that studies topological spaces.

For example, the real numbers together with all open intervals form the *usual* topology of $\mathbb{R}$. Mathematicians have generalized this procedure. If one takes *all* subsets of $\mathbb{R}$ – or any other basis set – as open sets, one speaks of the *discrete* topology. If one takes *only* the full basis set and the empty set as open sets, one speaks of the *trivial* or *indiscrete* topology.

The concept of topological space allows us to define continuity. A mapping from one topological space X to another topological space Y is *continuous* if the inverse image of every open set in Y is an open set in X. You may verify that this condition is not satisfied by a real function that makes a jump. You may also check that the term 'inverse' is necessary in the definition; otherwise a function with a jump would be continuous, as such a function may still map open sets to open sets.*

Challenge 205 e

* The Cauchy–Weierstass definition of continuity says that a real function $f(x)$ is continuous at a point a if (1) f is defined on an open interval containing a, (2) $f(x)$ tends to a limit as x tends to a, and (3) the limit is

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

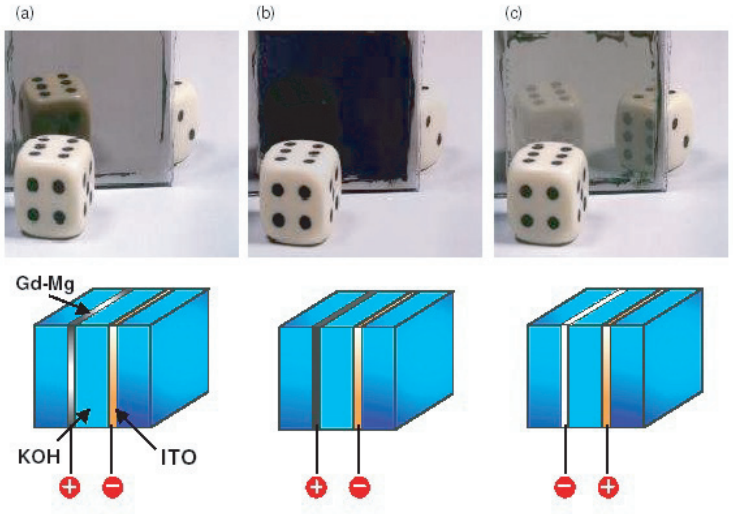


FIGURE 55 A switchable Mg-Gd mirror (© Ronald Griessen).

Vol. I, page 312 Vol. I, page 312 future ones, are useful in medicine. As mentioned before, the use of ultrasound imaging for prenatal diagnostics of embryos is not recommended. Studies have found that ultrasound produces extremely high levels of audible sound to the embryo, especially when the ultrasound is repeatedly switched on and off, and that babies react negatively to this loud noise.

Looking into the ground is important for another reason. It can help in *locating land mines*. Detecting land mines, especially metal-free mines, buried in the ground is a big technological challenge that is still unsolved. Many technologies have been tested: X-ray backscatter devices working at 350 to 450 keV, ground-penetrating radar and ultra-wideband radar, infrared detection, thermal or fast neutron bombardment and analysis, acoustic and sonar detection, electric impedance tomography, radio-frequency bombardment, nuclear quadrupole resonance, millimetre waves, visual detection, ion mobility spectrometers, using dogs, using rats, and explosive vapour detection with dedicated sensors. (And of course, for metallic mines, magnetometers and metal detectors are used.) But so far, the is still no solution in sight. Can you find one? If you do, get in touch with www.gichd.org.

What is necessary to make matter invisible?

You might have already imagined what adventures would be possible if you could be *invisible* for a while. In 1996, a team of Dutch scientists found a material, yttrium hydride or YH_3, that can be switched from mirror mode to transparent mode using an electrical

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Ref. 58 signal. A number of other materials were also discovered. An example of the effect for Mg-Gd layers is shown in Figure 55.

Switchable mirrors might seem a first step to realize the dream to become invisible and visible at will. In 2006, and repeatedly since then, researchers made the headlines in the popular press by claiming that they could build a *cloak of invisibility*. This is a blatant lie. This lie is frequently used to get funding from gullible people, such as buyers of bad science fiction books or the military. For example, it is often claimed that objects can be made invisible by covering them with metamaterials. The impossibility of this aim has
Vol. III, page 166 been already shown earlier on. But we now can say more.

Nature shows us how to realize invisibility. An object is invisible if it has no surface, no absorption and small size. In short, invisible objects are either small clouds or composed of them. Most atoms and molecules are examples. Homogeneous non-absorbing gases also realize these conditions. That is the reason that air is (usually) invisible. When air is not homogeneous, it can be visible, e.g. above hot surfaces.

In contrast to gases, solids or liquids do have surfaces. Surfaces are usually visible, even if the body is transparent, because the refractive index changes there. For example, quartz can be made so transparent that one can look through 1 000 km of it; pure quartz is thus *more* transparent than usual air. Still, objects made of pure quartz are visible to the eye, due to their refractive index. Quartz can be invisible only when submerged in liquids with the same refractive index.

In short, anything that has a shape cannot be invisible. If we want to become invisible, we must transform ourselves into a diffuse gas cloud of non-absorbing atoms. On the way to become invisible, we would lose all memory and all genes, in short, we would lose all our individuality, because an individual cannot be made of gas. An individual is defined through its boundary. There is no way that we can be invisible and alive at the same time; a way to switch back to visibility is even less likely. In summary, quantum theory shows that only the dead can be invisible. Quantum theory has a reassuring side: we already
Vol. IV, page 135 found that quantum theory forbids ghosts; we now find that it also forbids any invisible beings.

What moves inside matter?

All matter properties are due to the motion of the components of matter. Therefore, we can correctly argue that understanding the motion of electrons and nuclei implies understanding all properties of matter. Sometimes, however, it is more practical to explore the motion of collections of electrons or nuclei as a whole. Here is a selection of such collective motions. Collective motions that appear to behave like single particles are called *quasiparticles*.

In crystalline solids, sound waves can be described as the motion of *phonons*. For example, transverse phonons and longitudinal phonons describe many processes in semiconductors, in solid state lasers and in ultrasound systems. Phonons approximately behave as bosons.

Page 298 In metals, the motion of crystal defects, the so-called *dislocations* and *disclinations*, is central to understand their hardening and their breaking.

Also in metals, the charge waves of the conductive electron plasma, can be seen as composed of so-called *plasmons*. Plasmons are also important in the behaviour of high-

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

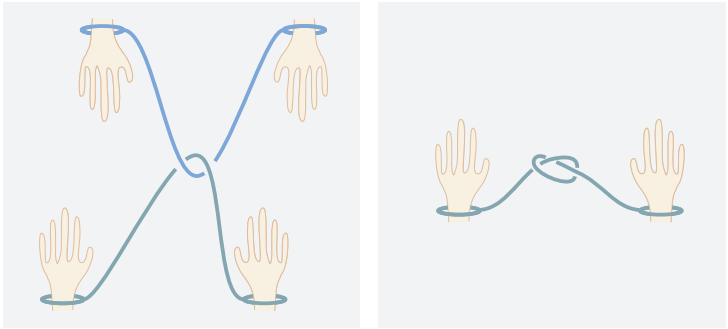


FIGURE 183 Which of the two situations can be untied without cutting?

symmetric matrices; and C_n is the algebra of the traceless matrices.

The exceptional Lie algebras are G_2, F_4, E_6, E_7, E_8. In all cases, the index gives the number of so-called *roots* of the algebra. The dimensions of these algebras are $A_n : n(n+2)$; B_n and $C_n : n(2n+1)$; $D_n : n(2n-1)$; $G_2 : 14$; $F_4 : 32$; $E_6 : 78$; $E_7 : 133$; $E_8 : 248$.

The simple and finite-dimensional *real* Lie algebras are more numerous; their classification follows from that of the complex Lie algebras. Moreover, corresponding to each
Ref. 300 complex Lie group, there is always one compact real one. Real Lie algebras are not so important in fundamental physics.

Of the large number of *infinite-dimensional* Lie algebras, only one is important in physics, the *Poincaré algebra*. A few other such algebras only appeared in failed attempts for unification.

TOPOLOGY – WHAT SHAPES EXIST?

> Topology is group theory.
>
> The Erlangen program

In a simplified view of topology that is sufficient for physicists, only one type of entity can possess shape: manifolds. *Manifolds* are generalized examples of pullovers: they are locally flat, can have holes and boundaries, and can often be turned inside out.

Challenge 203 s Pullovers are subtle entities. For example, can you turn your pullover inside out while your hands are tied together? (A friend may help you.) By the way, the same feat is also possible with your trousers, while your feet are tied together. Certain professors like to demonstrate this during topology lectures – of course with a carefully selected pair of underpants.

Ref. 301 Another good topological puzzle, the handcuff puzzle, is shown in Figure 183. Which
Challenge 204 s of the two situations can be untied without cutting the ropes?

For a mathematician, pullovers and ropes are everyday examples of manifolds, and

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

the choice of basis. The structure constants determine the Lie algebra completely. For example, the algebra of the Lie group SU(2), with the three generators defined by $T_a = \sigma^a/2i$, where the σ^a are the Pauli spin matrices, has the structure constants $C_{abc} = \varepsilon_{abc}$.*

Vol. IV, page 230

Classification of Lie algebras

Finite-dimensional Lie algebras are classified as follows. Every finite-dimensional Lie algebra is the (semidirect) sum of a semisimple and a solvable Lie algebra.

A Lie algebra is called *solvable* if, well, if it is not semisimple. Solvable Lie algebras have not yet been classified completely. They are not important in physics.

A *semisimple* Lie algebra is a Lie algebra which has no non-zero solvable ideal. Other equivalent definitions are possible, depending on your taste:

— a semisimple Lie algebra does not contain non-zero Abelian ideals;
— its Killing form is non-singular, i.e., non-degenerate;
— it splits into the direct sum of non-Abelian simple ideals (this decomposition is unique);
— every finite-dimensional linear representation is completely reducible;
— the one-dimensional cohomology of g with values in an arbitrary finite-dimensional g-module is trivial.

Finite-dimensional semisimple Lie algebras have been completely classified. They decompose uniquely into a direct sum of *simple* Lie algebras. Simple Lie algebras can be complex or real.

The simple finite-dimensional *complex* Lie algebras all belong to four infinite classes and to five exceptional cases. The infinite classes are also called *classical*, and are: A_n for $n \geqslant 1$, corresponding to the Lie groups SL($n+1$) and their compact 'cousins' SU($n+1$); B_n for $n \geqslant 1$, corresponding to the Lie groups SO($2n+1$); C_n for $n \geqslant 1$, corresponding to the Lie groups Sp($2n$); and D_n for $n \geqslant 4$, corresponding to the Lie groups SO($2n$). Thus A_n is the algebra of all skew-Hermitean matrices; B_n and D_n are the algebras of the

* Like groups, Lie algebras can be represented by matrices, i.e., by linear operators. Representations of Lie algebras are important in physics because many continuous symmetry groups are Lie groups.

The *adjoint representation* of a Lie algebra with basis $a_1 ... a_n$ is the set of matrices ad(a) defined for each element a by

$$[a, a_j] = \sum_c \mathrm{ad}(a)_{cj} a_c \,. \tag{147}$$

The definition implies that $\mathrm{ad}(a_i)_{jk} = c_{ij}^k$, where c_{ij}^k are the structure constants of the Lie algebra. For a real Lie algebra, all elements of ad(a) are real for all $a \in L$.

Note that for any Lie algebra, a scalar product can be defined by setting

$$X \cdot Y = \mathrm{Tr}(\,\mathrm{ad}X \cdot \mathrm{ad}Y\,) \,. \tag{148}$$

This scalar product is symmetric and bilinear. (Can you show that it is independent of the representation?) The corresponding bilinear form is also called the *Killing form*, after the mathematician Wilhelm Killing (b. 1847 Burbach, d. 1923 Münster), the discoverer of the 'exceptional' Lie groups. The Killing form is invariant under the action of any automorphism of the Lie algebra L. In a given basis, one has

$$X \cdot Y = \mathrm{Tr}((\mathrm{ad}X) \cdot (\mathrm{ad}Y)) = c_{lk}^i c_{si}^k x^l y^s = g_{ls} x^l y^s \tag{149}$$

where $g_{ls} = c_{lk}^i c_{si}^k$ is called the *Cartan metric tensor* of L.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

speed electronics.

In magnetic materials, the motion of spin orientation is often best described with the help of magnons. Understanding the motion of magnons and that of magnetic domain walls is useful to understand the magnetic properties of magnetic material, e.g., in permanent magnets, magnetic storage devices, or electric motors. Magnons behave approximately like bosons.

In semiconductors and insulators, the motion of *conduction electrons* and *electron holes*, is central for the description and design of most electronic devices. They behave as fermions with spin 1/2, elementary electric charge, and a mass that depends on the material, on the specific conduction band and on the specific direction of motion. The bound system of a conduction electron and a hole is called an *exciton*. It can have spin 0 or spin 1.

In polar materials, the motion of light through the material is often best described in terms of *polaritons*, i.e., the coupled motion of photons and dipole carrying material excitations. Polaritons are approximate bosons.

In dielectric crystals, such as in many inorganic ionic crystals, the motion of an electron is often best described in terms of *polarons*, the coupled motion of the electron with the coupled polarization region that surrounds it. Polarons are fermions.

In fluids, the motion of vortices is central in understanding turbulence or air hoses. Especially in superfluids, vortex motion is quantized in terms of *rotons* which determines flow properties. Also in fluids, bubble motion is often useful to describe mixing processes.

In superconductors, not only the motion of *Cooper pairs*, but also the motion of *magnetic flux tubes* determines the temperature behaviour. Especially in thin and flat superconductors – so-called 'two-dimensional' systems – such tubes have particle-like properties.

In all condensed matter systems, the motion of *surface states* – such as surface magnons, surface phonons, surface plasmons, surface vortices – has also to be taken into account.

Many other, more exotic *quasiparticles* exist in matter. Each quasiparticle in itself is an important research field where quantum physics and material science come together. To clarify the concepts, we mention that a *soliton* is not, in general, a quasiparticle. 'Soliton' is a mathematical concept; it applies to macroscopic waves with only one crest that remain unaltered after collisions. Many domain walls can be seen as solitons. But quasiparticles are concepts that describe physical observations similar to quantum particles.

Vol. I, page 315

In summary, all the mentioned examples of collective motion inside matter, both macroscopic and quantized, are of importance in electronics, photonics, engineering and medical applications. Many are quantized and their motion can be studied like the motion of real quantum particles.

Curiosities and fun challenges about materials science

What is the maximum height of a mountain? This question is of course of interest to all climbers. Many effects limit the height. The most important is that under heavy pressure, solids become liquid. For example, on Earth this happens for a mountain with a height of about 27 km. This is quite a bit more than the highest mountain known, which is

Ref. 59

Challenge 47 ny

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

the volcano Mauna Kea in Hawaii, whose top is about 9.45 km above the base. On Mars gravity is weaker, so that mountains can be higher. Indeed the highest mountain on Mars, Olympus mons, is 80 km high. Can you find a few other effects limiting mountain height?

Challenge 48 s

* *

Do you want to become rich? Just invent something that can be produced in the factory, is cheap and can fully substitute duck feathers in bed covers, sleeping bags or in badminton shuttlecocks. Another industrial challenge is to find an artificial substitute for latex, and a third one is to find a substitute for a material that is rapidly disappearing due to pollution: cork.

Challenge 49 r

* *

Materials differ in density, in elasticity, in strength, stiffness, toughness, melting temperature, heat insulation, electric resistivity, and many other parameters. To get an overview, the so-called *Ashby charts* are most useful, of which Figure 56 shows an example. The race to find materials that are lighter and stiffer than wood, in particular balsa wood, is still ongoing.

* *

How much does the Eiffel tower change in height over a year due to thermal expansion and contraction?

Challenge 50 s

* *

What is the difference between the makers of bronze age knifes and the builders of the Eiffel tower? Only their control of defect distributions. The main defects in metals are *disclinations* and *dislocations*. Disclinations are crystal defects in form of surfaces; they are the microscopic aspect of grain boundaries. Dislocations are crystal defects in form of curved lines; above all, their distribution and their motion in a metal determines the stiffness. For a picture of dislocations, see below.

Page 298

* *

Challenge 51 e What is the difference between solids, liquids and gases?

* *

One subject of materials science is the way a solid object breaks. The main distinction is between *brittle* fraction and *ductile* fraction. In brittle fraction, as in a breaking of a glass pane, the resulting edges are sharp and irregular; in ductile fraction, as occurs in hot glass, the edges are rounded and regular. The two fraction types also differ in their mechanisms, i.e., in the motion of the involved defects and atoms. This difference is important: when a car accident occurs at night, looking at the shapes of the fraction surface of the tungsten wire inside the car lamps with a microscope, it is easy to decide whether the car lamps were on or off at the time of the accident.

* *

Material science can also help to make erased information visible again. Many laborat-

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

prefer to define an (associative) K-algebra simply as a ring which contains K as a central subfield.

In physics, it is the algebras related to symmetries which play the most important role. We study them next.

Lie algebras

A Lie algebra is special type of algebra (and thus of vector space). Lie algebras are the most important type of non-associative algebras. A vector space L over the field $\mathbb{R}$ (or $\mathbb{C}$) with an additional binary operation $[\ ,\ ]$, called *Lie multiplication* or the *commutator*, is called a real (or complex) *Lie algebra* if this operation satisfies

$$\begin{aligned} [X,Y] &= -[Y,X] && \textit{antisymmetry} \\ [aX+bY,Z] &= a[X,Z]+b[Y,Z] && \textit{(left-)linearity} \\ [X,[Y,Z]]+[Y,[Z,X]]+[Z,[X,Y]] &= 0 && \textit{Jacobi identity} \end{aligned} \tag{144}$$

for all elements $X, Y, Z \in L$ and for all $a, b \in \mathbb{R}$ (or $\mathbb{C}$). (Lie algebras are named after Sophus Lie.) The first two conditions together imply bilinearity. A Lie algebra is called *commutative* if $[X,Y] = 0$ for all elements X and Y. The *dimension* of the Lie algebra is the dimension of the vector space. A subspace N of a Lie algebra L is called an *ideal** if $[L,N] \subset N$; any ideal is also a *subalgebra*. A *maximal ideal* M which satisfies $[L,M] = 0$ is called the *centre* of L.

Challenge 201 e

A Lie algebra is called a *linear* Lie algebra if its elements are linear transformations of another vector space V (intuitively, if they are 'matrices'). It turns out that every finite-dimensional Lie algebra is isomorphic to a linear Lie algebra. Therefore, there is no loss of generality in picturing the elements of finite-dimensional Lie algebras as matrices.

The name 'Lie algebra' was chosen because the *generators*, i.e., the infinitesimal elements of every Lie group, form a Lie algebra. Since all important symmetries in nature form Lie groups, Lie algebras appear very frequently in physics. In mathematics, Lie algebras arise frequently because from any associative finite-dimensional algebra (in which the symbol $\cdot$ stands for its multiplication) a Lie algebra appears when we define the *commutator* by

Page 371

$$[X,Y] = X \cdot Y - Y \cdot X \,. \tag{145}$$

(This fact gave the commutator its name.) Lie algebras are non-associative in general; but the above definition of the commutator shows how to build one from an associative algebra.

Since Lie algebras are vector spaces, the elements T_i of a *basis* of the Lie algebra always obey a relation of the form:

$$[T_i, T_j] = \sum_k c_{ij}^k T_k \,. \tag{146}$$

The numbers c_{ij}^k are called the *structure constants* of the Lie algebra. They depend on

Challenge 202 ny

* Can you explain the notation $[L,N]$? Can you define what a maximal ideal is and prove that there is only one?

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

which there is a mapping $* : A \to A,\ x \mapsto x^*$, called an *involution*, with the properties

$$\begin{aligned} (x^*)^* &= x \\ (x+y)^* &= x^* + y^* \\ (cx)^* &= \bar{c}x^* \quad \text{for all} \quad c \in \mathbb{C} \\ (xy)^* &= y^* x^* \end{aligned} \tag{142}$$

valid for all elements x, y of the algebra A. The element x^* is called the *adjoint* of x. Star algebras are the main type of algebra used in quantum mechanics, since quantum-mechanical observables form a $*$-algebra.

A C$*$-*algebra* is a Banach algebra over the complex numbers with an involution $*$ (a function that is its own inverse) such that the norm $\|x\|$ of an element x satisfies

$$\|x\|^2 = x^*\, x\,. \tag{143}$$

(A Banach algebra is a complete normed algebra; an algebra is *complete* if all Cauchy sequences converge.) In short, C$*$-*algebra* is a nicely behaved algebra whose elements form a continuous set and a complex vector space. The name C comes from 'continuous functions'. Indeed, the *bounded* continuous functions form such an algebra, with a properly defined norm. Can you find it?

Challenge 200 s

Every C$*$-algebra (pronounced 'Cee-star') contains a space of Hermitean elements (which have a real spectrum), a set of normal elements, a multiplicative group of unitary elements and a set of positive elements (with non-negative spectrum). In quantum theory, a physical system is described by a C$*$-algebra, and its Hermitean elements are the observables.

We should mention one important type of algebra used in mathematics. A *division algebra* is an algebra for which the equations $ax = b$ and $ya = b$ are uniquely solvable in x or y for all b and all $a \neq 0$. Obviously, all type of continuous numbers must be division algebras. Division algebras are thus one way to generalize the concept of a number. One of the important results of modern mathematics states that (finite-dimensional) division algebras can *only* have dimension 1, like the reals, dimension 2, like the complex numbers, dimension 4, like the quaternions, or dimension 8, like the octonions. There is thus no way to generalize the concept of (continuous) 'number' to other dimensions.

And now for some fun. Imagine a ring A which contains a number field K as a subring (or 'field of scalars'). If the ring multiplication is defined in such a way that a general ring element multiplied with an element of K is the same as the scalar multiplication, then A is a vector space, and thus an algebra – *provided* that every element of K commutes with every element of A. (In other words, the subring K must be *central*.)

For example, the quaternions $\mathbb{H}$ are a four-dimensional real division algebra, but although $\mathbb{H}$ is a two-dimensional complex vector space, it is *not* a complex algebra, because i does not commute with j (one has $ij = -ji = k$). In fact, there are no finite-dimensional complex division algebras, and the only finite-dimensional real associative division algebras are $\mathbb{R}$, $\mathbb{C}$ and $\mathbb{H}$.

Now, if you are not afraid of getting a headache, think about this remark: every K-algebra is also an algebra over its field of scalars. For this reason, some mathematicians

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

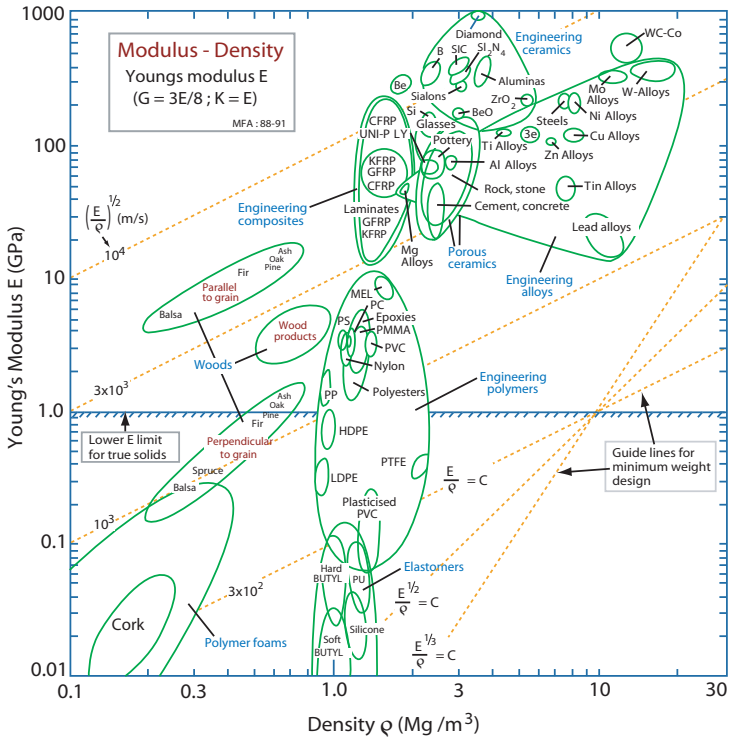


FIGURE 56 An overview of the elastic modulus and the density of materials. For structures that need to be light and stiff, a high ratio E / ρ^3 is required; the graph shows that wood is well optimized for this task. (© Carol Livermore/Michael Ashby).

ories are now able to recover data from erased magnetic hard disks. Other laboratories can make erased serial numbers in cars bodies visible again, either by heating the metal part or by using magnetic microscopy.

* *

Challenge 52 s

Quantum theory shows that tight walls do not exist. Every material is penetrable. Why?

* *

Quantum theory shows that even if tight walls would exist, the lid of a box made of such

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

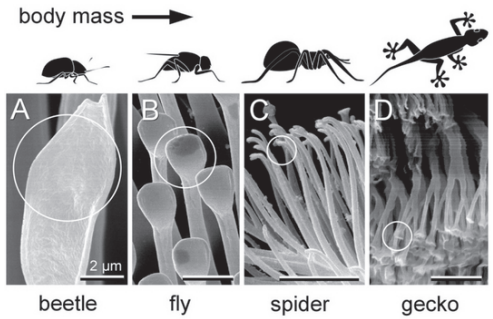


FIGURE 57 Insects and geckos stick to glass and other surfaces using the van der Waals force at the ends of a high number of spatulae (© Max Planck Gesellschaft).

Challenge 53 s walls can never be tightly shut. Can you provide the argument?

* *

In 1936, Henry Eyring proposed that the shear viscosity of a liquid η obeys

$$\eta \geqslant \rho\hbar \,, \tag{9}$$

Challenge 54 ny where ρ is the density of the fluid. Is the lower limit valid?

* *

Heat can flow. Like for all flows, quantum theory predicts that heat transport quantized. This implied that thermal conductance is quantized. And indeed, in the year 2000, experiments have confirmed the prediction. Can you guess the smallest unit of thermal conductance?

Ref. 60
Challenge 55 s

* *

Ref. 61
Vol. I, page 91

Robert Full has shown that van der Waals forces are responsible for the way that geckos walk on walls and ceilings. (A picture is found in Figure 56.) The gecko, a small reptile with a mass of about 100 g, uses an elaborate structure on its feet to perform the trick. Each foot has 500 000 hairs or setae, each split in up to 1000 small spatulae, and each spatula uses the van der Waals force (or alternatively, capillary forces) to stick to the surface. As a result of these 500 million sticking points, the gecko can walk on vertical glass walls or even on glass ceilings; the sticking force can be as high as 100 N per foot. The adhesion forces are so high that detaching the foot requires a special technique. The internet has slow-motion videos showing how geckos perform the feat, in each step they take.

Hairy feet as adhesion method are also used by jumping spiders (*Salticidae*). For example, *Evarcha arcuata* have hairs at their feet which are covered by hundred of thou-

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

for all vectors x, y, z and all scalars $c \in \mathrm{K}$. To stress their properties, algebras are also called *linear* algebras.

For example, the set of all linear transformations of an n-dimensional linear space (such as the translations on a plane, in space or in time) is a linear algebra, if the composition is taken as multiplication. So is the set of observables of a quantum mechanical system.*

An *associative algebra* is an algebra whose multiplication has the additional property that

$$x(yz) = (xy)z \quad \textit{associativity} \,. \tag{141}$$

Most algebras that arise in physics are associative** and unital. Therefore, in mathematical physics, a linear unital associative algebra is often simply called an algebra.

The set of multiples of the unit 1 of the algebra is called the *field of scalars* scal(A) of the algebra A. The field of scalars is also a subalgebra of A. The field of scalars and the scalars themselves behave in the same way.

Challenge 197 e We explore a few examples. The set of all polynomials in one variable (or in several variables) forms an algebra. It is commutative and infinite-dimensional. The constant polynomials form the field of scalars.

The set of $n \times n$ matrices, with the usual operations, also forms an algebra. It is n^2-dimensional. Those diagonal matrices (matrices with all off-diagonal elements equal to zero) whose diagonal elements all have the same value form the field of scalars. How is

Challenge 198 ny the scalar product of two matrices defined?

Challenge 199 s The set of all real-valued functions over a set also forms an algebra. Can you specify the multiplication? The constant functions form the field of scalars.

A *star algebra*, also written $*$*-algebra*, is an algebra over the *complex* numbers for

* *Linear transformations* are mappings from the vector space to itself, with the property that sums and scalar multiples of vectors are transformed into the corresponding sums and scalar multiples of the transformed vectors. Can you specify the set of all linear transformations of the plane? And of three-dimensional space? And of Minkowski space?

Challenge 196 s

All linear transformations transform some special vectors, called *eigenvectors* (from the German word *eigen* meaning 'self') into multiples of themselves. In other words, if T is a transformation, e a vector, and

$$T(e) = \lambda e \tag{140}$$

where λ is a scalar, then the vector e is called an *eigenvector* of T, and λ is associated *eigenvalue*. The set of all eigenvalues of a transformation T is called the *spectrum* of T. Physicists did not pay much attention to these mathematical concepts until they discovered quantum theory. Quantum theory showed that observables are transformations in Hilbert space, because any measurement interacts with a system and thus transforms it. Quantum-mechanical experiments also showed that a measurement result for an observable must be an eigenvalue of the corresponding transformation. The state of the system after the measurement is given by the eigenvector corresponding to the measured eigenvalue. Therefore every expert on motion must know what an eigenvalue is.

Vol. IV, page 87
Vol. IV, page 156

** Note that a non-associative algebra does not possess a matrix representation.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Appendix C

ALGEBRAS, SHAPES AND GROUPS

Mathematicians are fond of generalizing concepts. One of the most generalized concepts of all is the concept of *space*. Understanding mathematical definitions and generalizations means learning to think with precision. The appendix of the previous, fourth volume provided a simple introduction to the types of *spaces* that are of importance in physics; this appendix provides an introduction to the *algebras* that are of importance in physics.

ALGEBRAS

The term *algebra* is used in mathematics with three different, but loosely related, meanings. First, it denotes a part of mathematics, as in 'I hated algebra at school'. Secondly, it denotes a set of formal rules that are obeyed by abstract objects, as in the expression 'tensor algebra'. Finally – and this is the only meaning used here – an algebra denotes a *specific* type of mathematical structure.

Intuitively, an algebra is a set of vectors with a vector multiplication defined on it. More precisely, a (unital, associative) algebra is a vector space (over a field K) that is also a (unital) ring. (The concept is due to Benjamin Peirce (b. 1809 Salem, d. 1880 Cambridge), father of Charles Sanders Peirce.) A ring is a set for which an addition and a multiplication is defined – like the integers. Thus, in an algebra, there are (often) *three* types of multiplications:

Vol. IV, page 222

- the (main) algebraic multiplication: the product of two vectors x and y is another vector $z = xy$;
- the scalar multiplication: the c-fold multiple of a vector x is another vector $y = cx$;
- if the vector space is a inner product space, the scalar product: the scalar product of two algebra elements (vectors) x and y is a scalar $c = x \cdot y$;

A precise definition of an algebra thus only needs to define properties of the (main) multiplication and to specify the number field K. An *algebra* is defined by the following axioms

$$x(y+z) = xy + xz \quad , \quad (x+y)z = xz + yz \quad \textit{distributivity of multiplication}$$
$$c(xy) = (cx)y = x(cy) \quad \textit{bilinearity} \tag{139}$$

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Ref. 62 sands of setulae. Again, the van der Waals force in each setula helps the spider to stick on surfaces. Also many insects use small hairs for the same aim. Figure 57 shows a Ref. 63 comparison. Researchers have shown that the hairs – or setae – are finer the more massive the animal is. Eduard Arzt likes to explain that small flies and beetles have simple, spherical setae with a diameter of a few micrometers whereas the considerably bigger and heavier geckos have branched nanohairs with diameters of 200 nm.

Researchers have copied the hairy adhesion mechanism for the first time in 2003, using microlithography on polyimide, and they hope to make durable sticky materials – without using any glue – in the future.

* *

Ref. 64 One of the most fascinating materials in nature are bones. Bones are light, stiff, and can heal after fractures. If you are interested in composite materials, read more about bones: their structure, shown in Figure 58, and their material properties are fascinating and complex, and so are their healing and growth mechanisms. All these aspects are still subject of research.

* *

Challenge 56 s A cereal stalk has a height-to-width ratio of about 300. No human-built tower or mast achieves this. Why?

* *

Millimetre waves or terahertz waves are emitted by all bodies at room temperature. Modern camera systems allow producing images with them. In this way, it is possible to see through clothes, as shown by Figure 59. (Caution is needed; there is the widespread suspicion that the image is a fake produced to receive more development funding.) This ability could be used in future to detect hidden weapons in airports. But the development of a practical and affordable detector which can be handled as easily as a binocular is still under way. The waves can also be used to see through paper, thus making it unnecessary to open letters in order to read them. Secret services are exploiting this technique. A third application of terahertz waves might be in medical diagnostic, for example for the search of tooth decay. Terahertz waves are almost without side effects, and thus superior to X-rays. The lack of low-priced quality sources is still an obstacle to their application.

* *

Ref. 65 Does the melting point of water depend on the magnetic field? This surprising claim was made in 2004 by Inaba Hideaki and colleagues. They found a change of 0.9 mK/T. It is known that the refractive index and the near infrared spectrum of water is affected by magnetic fields. Indeed, not everything about water might be known yet.

* *

Plasmas, or ionized gases, are useful for many applications. A few are shown in Figure 60. Not only can plasmas be used for heating or cooking and generated by chemical means (such plasmas are variously called fire or flames) but they can also be generated electrically and used for lighting or deposition of materials. Electrically generated plasmas are even being studied for the disinfection of dental cavities.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

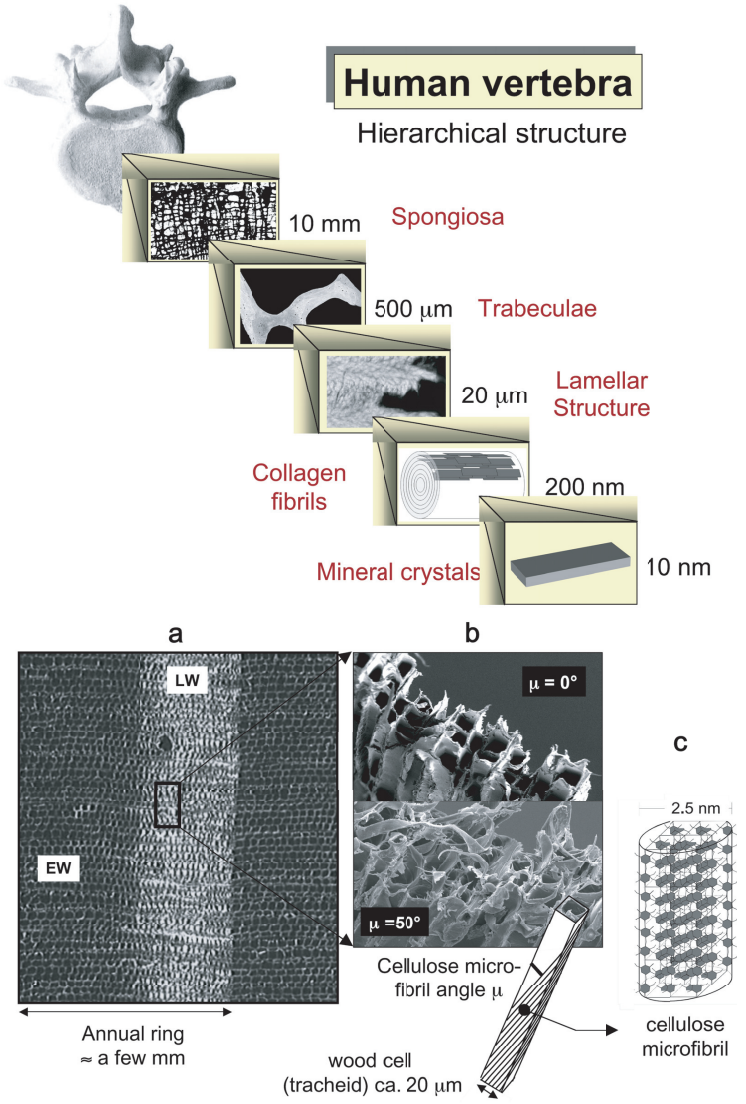


FIGURE 58 The structure of bones, shown for a human vertebra (© Peter Fratzl and Physik Journal).

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

the *longest living* isotope is given; as it is not an average, it is written in brackets, as is customary in this domain.

b. The element is not found on Earth because of its short lifetime.

c. The element has at least one radioactive isotope.

d. The element has no stable isotopes.

e. Strictly speaking, the *atomic radius* does not exist. Because atoms are clouds, they have no boundary. Several approximate definitions of the 'size' of atoms are possible. Usually, the radius is defined in such a way as to be useful for the estimation of distances between atoms. This distance is different for different bond types. In the table, radii for metallic bonds are labelled m, radii for (single) covalent bonds with carbon c, and Van der Waals radii v. Noble gas radii are labelled n. Note that values found in the literature vary by about 10 %; values in brackets lack literature references.

Ref. 299

Ref. 299

The covalent radius can be up to 0.1 nm smaller than the metallic radius for elements on the (lower) left of the periodic table; on the (whole) right side it is essentially equal to the metallic radius. In between, the difference between the two decreases towards the right. Can you explain why? By the way, ionic radii differ considerably from atomic ones, and depend both on the ionic charge and the element itself.

Challenge 195 s

All these values are for atoms in their ground state. Excited atoms can be hundreds of times larger than atoms in the ground state; however, excited atoms do not form solids or chemical compounds.

f. The isotopic composition, and thus the average atomic mass, of the element varies depending on the place where it was mined or on subsequent human treatment, and can lie outside the values given. For example, the atomic mass of commercial lithium ranges between 6.939 and 6.996 u. The masses of isotopes are known in atomic mass units to nine or more significant digits, and usually with one or two fewer digits in kilograms. The errors in the atomic mass are thus mainly due to the variations in isotopic composition.

Ref. 291

Ref. 298

g. The lifetime errors are asymmetric or not well known.

h. Extensive details on element names can be found on elements.vanderkrogt.net.



Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 36 (Continued) The elements, with their atomic number, average mass, atomic radius and main properties.

NAME	SYMBOL	AT. N.	AVER. MASS[a] IN U (ERROR), LONGEST LIFETIME	ATOMIC[e] RADIUS IN PM	MAIN PROPERTIES, (NAMING)[h] DISCOVERY DATE AND USE
Thorium	Th	90	232.038 06(2)[d,f] 14.0(1) Ga	180m	Radioactive (Nordic god Thor, as in 'Thursday') 1828, found in nature, heats Earth, used as oxide in gas mantles for campers, in alloys, as coating, and in nuclear energy.
Thulium	Tm	69	168.934 21(2) stable	175m	Rare Earth metal (Thule, mythical name for Scandinavia) 1879, found in monazite, used in lasers and radiation detectors.
Tin	Sn	50	118.710(7)[f] stable	139c, 210v, 162m	Grey metal that, when bent, allows one to hear the 'tin cry' (Latin *stannum*) antiquity, used in paint, bronze and superconductors.
Titanium	Ti	22	47.867(1) stable	146m	Metal (Greek hero Titanos) 1791, alloys, fake diamonds.
Tungsten	W	74	183.84(1) stable	141m	Heavy, highest-melting metal (Swedish *tung sten* heavy stone, German name *Wolfram*) 1783, lightbulbs.
Uranium	U	92	238.028 91(3)[d,f] $4.468(3) \cdot 10^9$ a	156m	Radioactive and of high density (planet Uranus, after the Greek sky god) 1789, found in pechblende and other minerals, used for nuclear energy.
Vanadium	V	23	50.9415(1) stable	135m	Metal (Vanadis, scandinavian goddess of beauty) 1830, used in steel.
Xenon	Xe	54	131.293(6)[f] stable	(103n) 200v	Noble gas (Greek *xenos* foreign) 1898, used in lamps and lasers.
Ytterbium	Yb	70	173.04(3)[f] stable	174m	Malleable heavy metal (Ytterby, Swedish town) 1878, used in superconductors.
Yttrium	Y	39	88.905 85(2) stable	180m	Malleable light metal (Ytterby, Swedish town) 1794, used in lasers.
Zinc	Zn	30	65.409(4) stable	139m	Heavy metal (German *Zinke* protuberance) antiquity, iron rust protection.
Zirconium	Zr	40	91.224(2)[f] stable	160m	Heavy metal (from the mineral zircon, after Arabic *zargum* golden colour) 1789, chemical and surgical instruments, nuclear industry.

a. The atomic mass unit is defined as $1\,\mathrm{u} = \frac{1}{12}m(^{12}\mathrm{C})$, making $1\,\mathrm{u} = 1.660\,5402(10)\,\mathrm{yg}$. For elements found on Earth, the *average* atomic mass for the naturally occurring isotope mixture is given, with the error in the last digit in brackets. For elements not found on Earth, the mass of

Ref. 298

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 59 An alleged image acquired with terahertz waves. Can you explain why it is a fake? (© Jefferson Lab)

* *

Ref. 66 Challenge 57 s

It is known that the concentration of CO_2 in the atmosphere between 1800 and 2005 has increased from 280 to 380 parts per million, as shown in Figure 61. (In 2016, the value was already 403 ppm. How would you measure this?) It is known without doubt that this increase is due to human burning of fossil fuels, and not to natural sources such as the oceans or volcanoes. There are three arguments. First of all, there was a parallel decline of the $^{14}C/^{12}C$ ratio. Second, there was a parallel decline of the $^{13}C/^{12}C$ ratio. Finally, there was a parallel decline of the oxygen concentration. All three measurements independently imply that the CO_2 increase is due to the burning of fuels, which are low in ^{14}C and in ^{13}C, and at the same time decrease the oxygen ratio. Natural sources do not have these three effects. Since CO_2 is a major greenhouse gas, the data implies that humans are also responsible for a large part of the temperature increase during the same period. Global warming exists and is mainly due to humans. On average, the Earth has cooled over the past 10 million years; since a few thousand years, the temperature has, however, slowly risen; together with the fast rise during the last decades the temperature is now at the same level as 3 million years ago. How do the decade global warming trend, the thousand year warming trend and the million year cooling trend interact? This is a topic of intense research.

Ref. 67

* *

Making crystals can make one rich. The first man who did so, the Frenchman Auguste Verneuil (b. 1856 Dunkerque, d. 1913 Paris), sold rubies grown in his laboratory for many years without telling anybody. Many companies now produce synthetic gems with machines that are kept secret. An example is given in Figure 62.

Synthetic diamonds have now displaced natural diamonds in almost all applications. In the last years, methods to produce large, white, jewel-quality diamonds of ten carats and more are being developed. These advances will lead to a big change in all the domains that depend on these stones, such as the production of the special surgical knives used in eye lens operation.

Ref. 68

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

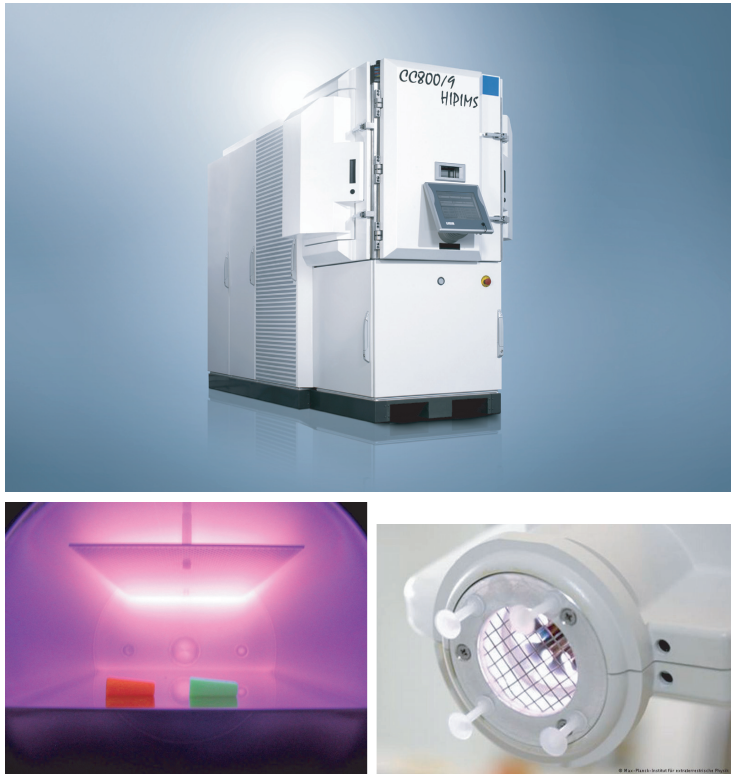


FIGURE 60 Some plasma machines: a machine for coating metal parts, a machine for cleaning polymer parts and a device for healing wounds (© www.cemecon.de, www.diener.de, Max Planck Gesellschaft).

* *

The technologies to produce *perfect* crystals, without grain boundaries or dislocations, are an important part of modern industry. Perfectly regular crystals are at the basis of the integrated circuits used in electronic appliances, are central to many laser and telecommunication systems and are used to produce synthetic jewels.

* *

Challenge 58 s How can a small plant pierce through tarmac?

* *

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 36 (Continued) The elements, with their atomic number, average mass, atomic radius and main properties.

NAME	SYMBOL	AT. N.	AVER. MASS[a] IN U (ERROR), LONGEST LIFETIME	ATOMIC[c] RADIUS IN PM	MAIN PROPERTIES, (NAMING)[h] DISCOVERY DATE AND USE
Silicon	Si	14	28.0855(3)[f] stable	105c, 210v	Grey, shiny semiconductor (Latin *silex* pebble) 1823, Earth's crust, electronics, sand, concrete, bricks, glass, polymers, solar cells, essential for life.
Silver	Ag	47	107.8682(2)[f] stable	145m	White metal with highest thermal and electrical conductivity (Latin *argentum*, Greek *argyros*) antiquity, used in photography, alloys, to make rain.
Sodium	Na	11	22.989 769 28(2) stable	191m	Light, reactive metal (Arabic *souwad* soda, Egyptian and Arabic *natrium*) component of many salts, soap, paper, soda, salpeter, borax, and essential for life.
Strontium	Sr	38	87.62(1)[f] stable	215m	Silvery, spontaneously igniting light metal (Strontian, Scottish town) 1790, used in TV tube glass, in magnets, and in optical materials.
Sulphur	S	16	32.065(5)[f] stable	105c, 180v	Yellow solid (Latin) antiquity, used in gunpowder, in sulphuric acid, rubber vulcanization, as fungicide in wine production, and is essential for life; some bacteria use sulphur instead of oxygen in their chemistry.
Tantalum	Ta	73	180.947 88(2) stable	147m	Heavy metal (Greek Tantalos, a mythical figure) 1802, used for alloys, surgical instruments, capacitors, vacuum furnaces, glasses.
Technetium[b]	Tc	43	(97.9072(1)) 6.6(10) Ma	136m	Radioactive (Greek *technetos* artificial) 1939, used as radioactive tracer and in nuclear technology.
Tellurium	Te	52	127.60(3)[f] stable	139c, 206v	Brittle, garlic-smelling semiconductor (Latin *tellus* Earth) 1783, used in alloys and as glass component.
Tennessine[b]	Ts	117	(294)	78 ms[g]	2010 (Tennessee), no use.
Terbium	Tb	65	158.925 35(2) stable	178m	Malleable rare Earth metal (Ytterby, Swedish town) 1843, used as dopant in optical material.
Thallium	Tl	81	204.3833(2) stable	172m	Soft, poisonous heavy metal (Greek *thallos* branch) 1861, used as poison and for infrared detection.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 36 (Continued) The elements, with their atomic number, average mass, atomic radius and main properties.

Name	Symbol	At. n.	Aver. mass[a] in u (error), longest lifetime	Atomic[e] radius in pm	Main properties, (naming)[h] discovery date and use
Radon	Rn	86	(222.0176(1)) 3.823(4) d	(130n)	Radioactive noble gas (from its old name 'radium emanation') 1900, no use (any more), found in soil, produces lung cancer .
Rhenium	Re	75	186.207(1)[c] stable	138m	TRansition metal (Latin *rhenus* for Rhine river) 1925, used in filaments for mass spectrographs and ion gauges, superconductors, thermocouples, flash lamps, and as catalyst.
Rhodium	Rh	45	102.905 50(2) stable	135m	White metal (Greek *rhodon* rose) 1803, used to harden platinum and palladium alloys, for electroplating, and as catalyst.
Roentgenium[b]	Rg	111	(272.1535(1)) 1.5 ms[g]	n.a.	Made in lab (after Conrad Roentgen) 1994, no use.
Rubidium	Rb	37	85.4678(3)[f] stable	255m	Silvery-white, reactive alkali metal (Latin *rubidus* red) 1861, used in photocells, optical glasses, solid electrolytes.
Ruthenium	Ru	44	101.107(2)[f] stable	134m	White metal (Latin *Rhuthenia* for Russia) 1844, used in platinum and palladium alloys, superconductors, as catalyst; the tetroxide is toxic and explosive.
Rutherfordium[b]	Rf	104	(261.1088(1)) 1.3 min[g]	n.a.	Radioactive transactinide (after Ernest Rutherford) 1964, no use.
Samarium	Sm	62	150.36(2)[c,f] stable	180m	Silver-white rare Earth metal (from the mineral samarskite, after Wassily Samarski) 1879, used in magnets, optical glasses, as laser dopant, in phosphors, in high-power light sources.
Scandium	Sc	21	44.955 912(6) stable	164m	Silver-white metal (from Latin *Scansia* Sweden) 1879, the oxide is used in high-intensity mercury vapour lamps, a radioactive isotope is used as tracer.
Seaborgium[b]	Sg	106	266.1219(1) 21 s[g]	n.a.	Radioactive transurane (after Glenn Seaborg) 1974, no use.
Selenium	Se	34	78.96(3)[f] stable	120c, 190v	Red or black or grey semiconductor (Greek *selene* Moon) 1818, used in xerography, glass production, photographic toners, as enamel dye.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

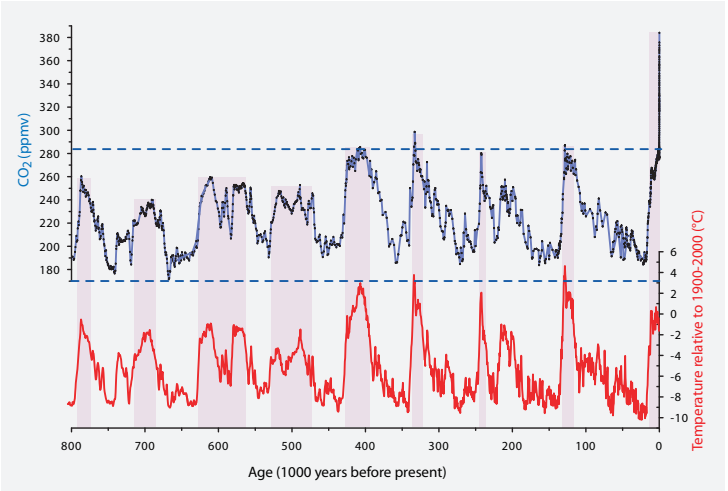


FIGURE 61 The concentration of CO_2 and the change of average atmospheric temperature in the past 0.8 million years (© Dieter Lüthi).

If you like abstract colour images, do not miss looking at liquid crystals through a microscope. You will discover a wonderful world. The best introduction is the text by Ingo Dierking. Ref. 69

* *

The Lorentz force leads to an interesting effect inside materials. If a current flows along a conducting strip that is in a (non-parallel) magnetic field, a voltage builds up between two edges of the conductor, because the charge carriers are deflected in their flow. This effect is called the (classical) *Hall effect* after the US-American physicist Edwin Hall (b. 1855 Great Falls, d. 1938 Cambridge), who discovered it in 1879, during his PhD. The effect, shown in Figure 63, is regularly used, in so-called *Hall probes*, to measure magnetic fields; the effect is also used to read data from magnetic storage media or to measure electric currents (of the order of 1 A or more) in a wire without cutting it. Typical Hall probes have sizes of around 1 cm down to 1 µm and less. The Hall voltage V turns out to be given by

$$V = \frac{IB}{ned} , \tag{10}$$

where n is the electron number density, e the electron charge, and d is the thickness of the probe, as shown in Figure 63. Deducing the equation is a secondary school exercise. Challenge 59 e The Hall effect is a material effect, and the material parameter n determines the Hall voltage. The sign of the voltage also tells whether the material has positive or negative

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

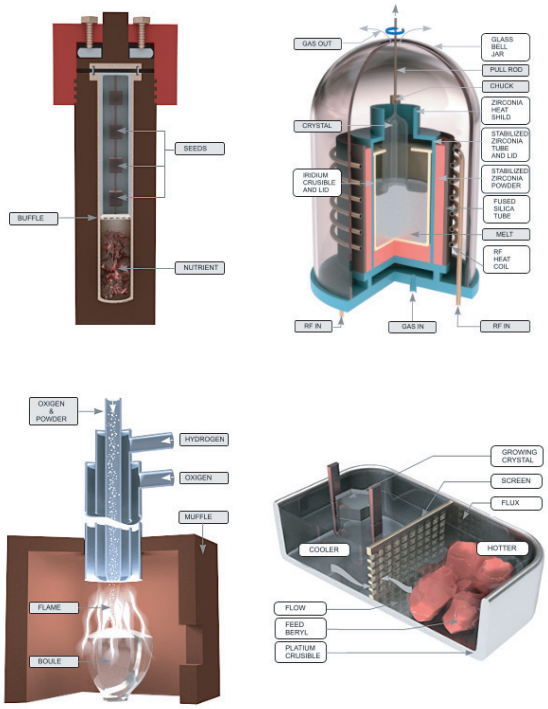


FIGURE 62 Four crystal and synthetic gemstone growing methods. Top: the hydrothermal technique, used to grow emeralds, quartz, rock crystal and amethyst, and Czochralski's pulling technique, used for growing ruby, sapphire, spinel, yttrium-aluminium-garnet, gadolinium-gallium-garnet and alexandrite. Bottom: Verneuil's flame fusion technique, used for growing corundum, sapphire, ruby and spinel boules, and the flux process, used for chrysoberyl (© Ivan Golota).

charge carriers; indeed, for metal strips the voltage polarity is opposite to the one shown in the figure. Challenge 60 e

Many variations of the Hall effect have been studied. For example, the *quantum* Hall effect and the fractional quantum Hall effect will be explored below. Page 107

In 1998, Geert Rikken and his coworkers found that in certain materials photons can also be deflected by a magnetic field; this is the *photonic Hall effect*. Ref. 70

In 2005, again Geert Rikken and his coworkers found a material, a terbium gallium garnet, in which a flow of phonons in a magnetic field leads to temperature difference on

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 36 (Continued) The elements, with their atomic number, average mass, atomic radius and main properties.

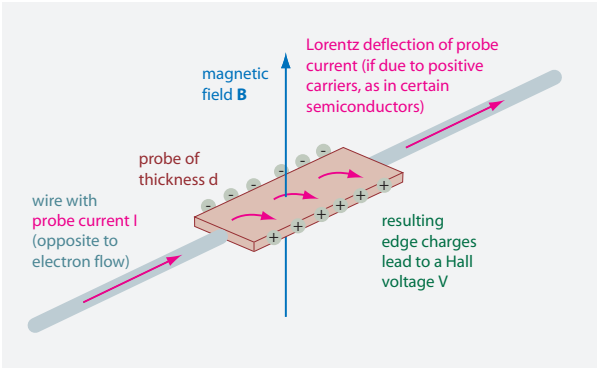
Name	Symbol	At. n.	Aver. mass[a] in u (error), longest lifetime	Atomic[c] radius in pm	Main properties, (naming)[h] discovery date and use
Plutonium	Pu	94	(244.0642(1)) 80.0(9) Ma	n.a.	Extremely toxic alpha-emitting metal (after the planet) synthesized 1940, found in nature 1971, used as nuclear explosive, and to power space equipment, such as satellites and the measurement equipment brought to the Moon by the Apollo missions.
Polonium	Po	84	(208.9824(1)) 102(5) a	(140)	Alpha-emitting, volatile metal (from Poland) 1898, used as thermoelectric power source in space satellites, as neutron source when mixed with beryllium; used in the past to eliminate static charges in factories, and on brushes for removing dust from photographic films.
Potassium	K	19	39.0983(1) stable	238m	Reactive, cuttable light metal (German *Pottasche*, Latin *kalium* from Arabic *quilyi*, a plant used to produce potash) 1807, part of many salts and rocks, essential for life, used in fertilizers, essential to chemical industry.
Praeseodymium	Pr	59	140.907 65(2) stable	183m	White, malleable rare Earth metal (Greek *praesos didymos* green twin) 1885, used in cigarette lighters, material for carbon arcs used by the motion picture industry for studio lighting and projection, glass and enamel dye, darkens welder's goggles.
Promethium[b]	Pm	61	(144.9127(1)) 17.7(4) a	181m	Radioactive rare Earth metal (from the Greek mythical figure of Prometheus) 1945, used as β source and to excite phosphors.
Protactinium	Pa	91	(231.035 88(2)) 32.5(1) ka	n.a.	Radioactive metal (Greek *protos* first, as it decays into actinium) 1917, found in nature, no use.
Radium	Ra	88	(226.0254(1)) 1599(4) a	(223)	Highly radioactive metal (Latin *radius* ray) 1898, no use any more; once used in luminous paints and as radioactive source and in medicine.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 36 (Continued) The elements, with their atomic number, average mass, atomic radius and main properties.

Name	Symbol	At. n.	Aver. mass[a] in u (error), longest lifetime	Atomic[c] radius in pm	Main properties, (naming)[h] discovery date and use
Niobium	Nb	41	92.906 38(2) stable	147m	Ductile metal (Greek Niobe, mythical daughter of Tantalos) 1801, used in arc welding, alloys, jewellery, superconductors.
Nitrogen	N	7	14.0067(2)[f] stable	70c, 155v	Diatomic gas (Greek for nitre-former) 1772, found in air, in living organisms, Viagra, fertilizers, explosives.
Nobelium[b]	No	102	(259.1010(1)) 58(5) min	n.a.	(after Alfred Nobel) 1958, no use.
Oganesson[b]	Og	118	(294)	0.9 ms[g]	False discovery claim in 1999, correct claim from 2006 (after Yuri Oganessian), no use.
Osmium	Os	76	190.23(3)[f] stable	135m	Heavy metal (from Greek *osme* odour) 1804, used for fingerprint detection and in very hard alloys.
Oxygen	O	8	15.9994(3)[f] stable	66c, 152v	Transparent, diatomic gas (formed from Greek to mean 'acid former') 1774, used for combustion, blood regeneration, to make most rocks and stones, in countless compounds, colours auroras red.
Palladium	Pd	46	106.42(1)[f] stable	138m	Heavy metal (from asteroid Pallas, after the Greek goddess) 1802, used in alloys, white gold, catalysts, for hydride storage.
Phosphorus	P	15	30.973 762(2) stable	109c, 180v	Poisonous, waxy, white solid (Greek *phosphoros* light bearer) 1669, fertilizers, glasses, porcelain, steels and alloys, living organisms, bones.
Platinum	Pt	78	195.084(9) stable	139m	Silvery-white, ductile, noble heavy metal (Spanish *platina* little silver) pre-Columbian, again in 1735, used in corrosion-resistant alloys, magnets, furnaces, catalysts, fuel cells, cathodic protection systems for large ships and pipelines; being a catalyst, a fine platinum wire glows red hot when placed in vapour of methyl alcohol, an effect used in hand warmers.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



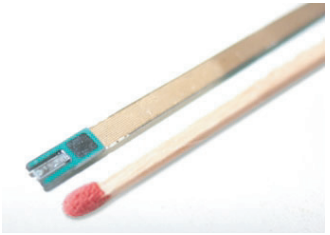


FIGURE 63 Top: the (classical) Hall effect. Bottom: a modern miniature Hall probe using the effect to measure magnetic fields (© Metrolab).

Ref. 71 the two sides. They called this the *phonon Hall effect*.

* *

Ref. 72 Do magnetic fields influence the crystallization of calcium carbonate in water? This issue is topic of intense debates. It might be, or it might not be, that magnetic fields change the crystallization seeds from calcite to aragonite, thus influencing whether water tubes are covered on the inside with carbonates or not. The industrial consequences of reduction in *scaling*, as this process is called, would be enormous. But the issue is still open, as are convincing data sets.

* *

Ref. 73 It has recently become possible to make the thinnest possible sheets of graphite and other materials (such as BN, MoS_2, $NbSe_2$, $Bi_2Sr_2CaCu_2O_x$): these crystal sheets are precisely one atom thick! The production of *graphene* – that is the name of a monoatomic graphite layer – is extremely complicated: you need graphite from a pencil and a roll of adhesive tape. That is probably why it was necessary to wait until 2004 for the development of the technique. (In fact, the stability of monoatomic sheets was questioned for many years before that. Some issues in physics cannot be decided with paper and pencil; sometimes you

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

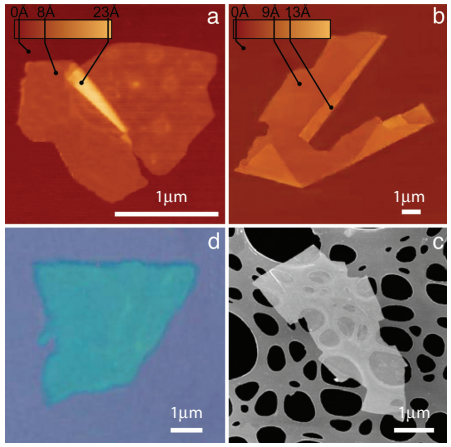


FIGURE 64 Single atom sheets, mapped by atomic force microscopy, of a: $NbSe_2$, b: of graphite or graphene, d: a single atom sheet of MoS_2 imaged by optical microscopy, and c: a single atom sheet of $Bi_2Sr_2CaCu_2O_x$ on a holey carbon film imaged by scanning electron microscopy (from Ref. 73, © 2005 National Academy of Sciences).

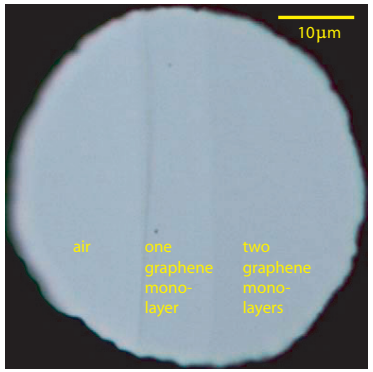


FIGURE 65 A microscope photograph shows the absorption of a single and of a double layer of graphene – and thus provides a way to see the fine structure constant. (© Andre Geim).

need adhesive tape as well.) Graphene and the other so-called *two-dimensional crystals* (this is, of course, a tabloid-style exaggeration) are studied for their electronic and mechanical properties; in the future, they might even have applications in high-performance batteries.

* *

A monolayer of graphene has an astonishing optical property. Its optical absorption over the full optical spectrum is $\pi\alpha$, where α is the fine structure constant. (The exact expres-

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 36 (Continued) The elements, with their atomic number, average mass, atomic radius and main properties.

NAME	SYMBOL	AT. N.	AVER. MASS[a] IN U (ERROR), LONGEST LIFETIME	ATOMIC[c] RADIUS IN PM	MAIN PROPERTIES, (NAMING)[h] DISCOVERY DATE AND USE
Livermorium[b]	Lv	116	(293)	61 ms[g]	False discovery claim from 1999, correct claim from 2000, no use.
Lutetium	Lu	71	174.967(1)[f] stable	173m	Rare-earth metal (Latin *Lutetia* for Paris) 1907, used as catalyst.
Magnesium	Mg	12	24.3050(6) stable	160m	Light common alkaline Earth metal (from Magnesia, a Greek district in Thessalia) 1755, used in alloys, pyrotechnics, chemical synthesis and medicine, found in chlorophyll.
Manganese	Mn	25	54.938 045(5) stable	126m	Brittle metal (Italian *manganese*, a mineral) 1774, used in alloys, colours amethyst and permanganate.
Meitnerium[b]	Mt	109	(268.1388(1)) 0.070 s[g]	n.a.	Appears in nuclear reactions (after Lise Meitner) 1982, no use.
Mendelevium[b]	Md	101	(258.0984(1)) 51.5(3) d	n.a.	Appears in nuclear reactions (after Дмитрии Иванович Менделеев Dmitriy Ivanovich Mendeleyev) 1955, no use.
Mercury	Hg	80	200.59(2) stable	157m	Liquid heavy metal (Latin god Mercurius, Greek *hydrargyrum* liquid silver) antiquity, used in switches, batteries, lamps, amalgam alloys.
Molybdenum	Mo	42	95.94(2)[f] stable	140m	Metal (Greek *molybdos* lead) 1788, used in alloys, as catalyst, in enzymes and lubricants.
Moscovium[b]	Mc	115	(288)	8 ms[g]	2004 (Moscow), no use.
Neodymium	Nd	60	144.242(3)[c,f] stable	182m	(Greek *neos* and *didymos* new twin) 1885, used in magnets.
Neon	Ne	10	20.1797(6)[f] stable	(36n)	Noble gas (Greek *neos* new) 1898, used in lamps, lasers and cryogenics.
Neptunium[b]	Np	93	(237.0482(1)) 2.14(1) Ma	n.a.	Radioactive metal (planet Neptune, after Uranus in the solar system) 1940, appears in nuclear reactors, used in neutron detection and by the military.
Nickel	Ni	28	58.6934(2) stable	125m	Metal (German *Nickel* goblin) 1751, used in coins, stainless steels, batteries, as catalyst.
Nihonium[b]	Nh	113	(284)	0.48 s[g]	2003 (Nihon is Japan in Japanese), no use.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 36 (Continued) The elements, with their atomic number, average mass, atomic radius and main properties.

Name	Symbol	At. n.	Aver. mass[a] in u (error), longest lifetime	Atomic[e] radius in pm	Main properties, (naming)[h] discovery date and use
Germanium	Ge	32	72.64(1) stable	122c, 195v	Semiconductor (from Germania, as opposed to gallium) 1886, used in electronics.
Gold	Au	79	196.966 569(4) stable	144m	Heavy noble metal (Sanskrit *jval* to shine, Latin aurum) antiquity, electronics, jewels.
Hafnium	Hf	72	178.49(2)[c] stable	158m	Metal (Latin for Copenhagen) 1923, alloys, incandescent wire.
Hassium[b]	Hs	108	(277) 16.5 min[g]	n.a.	Radioactive element (Latin form of German state Hessen) 1984, no use .
Helium	He	2	4.002 602(2)[f] stable	(31n)	Noble gas (Greek *helios* Sun) where it was discovered 1895, used in balloons, stars, diver's gas and cryogenics.
Holmium	Ho	67	164.930 32(2) stable	177m	Metal (Stockholm, Swedish capital) 1878, alloys.
Hydrogen	H	1	1.007 94(7)[f] stable	30c	Reactive gas (Greek for water-former) 1766, used in building stars and universe.
Indium	In	49	114.818(3) stable	141c, 166m	Soft metal (Greek *indikon* indigo) 1863, used in solders and photocells.
Iodine	I	53	126.904 47(3) stable	140c, 198v	Blue-black solid (Greek *iodes* violet) 1811, used in photography.
Iridium	Ir	77	192.217(3) stable	136m	Precious metal (Greek *iris* rainbow) 1804, electrical contact layers.
Iron	Fe	26	55.845(2) stable	127m	Metal (Indo-European *ayos* metal, Latin ferrum) antiquity, used in metallurgy.
Krypton	Kr	36	83.798(2)[f] stable	(88n)	Noble gas (Greek *kryptos* hidden) 1898, used in lasers.
Lanthanum	La	57	138.905 47(7)[c,f] stable	188m	Reactive rare Earth metal (Greek *lanthanein* to be hidden) 1839, used in lamps and in special glasses.
Lawrencium[b]	Lr	103	(262.110 97(1)) 3.6(3) h	n.a.	Appears in reactions (after Ernest Lawrence) 1961, no use.
Lead	Pb	82	207.2(1)[c,f] stable	175m	Poisonous, malleable heavy metal (Latin *plumbum*) antiquity, used in car batteries, radioactivity shields, paints.
Lithium	Li	3	6.941(2)[f] stable	156m	Light alkali metal with high specific heat (Greek *lithos* stone) 1817, used in batteries, anti-depressants, alloys, nuclear fusion and many chemicals.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 66 The beauty of materials science: the surface of a lotus leaf leads to almost spherical water droplets; plasma-deposited PTFE, or teflon, on cotton leads to the same effect for the coloured water droplets on it (© tapperboy, Diener Electronics).

sion for the absorption is $A = 1 - (1 + \pi\alpha/2)^{-2}$.) The expression for the absorption is the consequence of the electric conductivity $G = e^2/4\hbar$ for every monolayer of graphene. The numeric value of the absorption is about 2.3 %. This value is visible by the naked eye, as shown in Figure 65. Graphene thus yields a way to 'see' the fine structure constant.

Ref. 74

* *

Gold absorbs light. Therefore it is used, in expensive books, to colour the edges of pages. Apart from protecting the book from dust, it also prevents that sunlight lets the pages turn yellow near the edges.

* *

Like trees, crystals can have *growth rings*. Smoke quartz is known for these so-called *phantoms*, but also fluorite and calcite.

* *

The science and art of surface treatment is still in full swing, as Figure 66 shows. Making hydrophobic surfaces is an important part of modern materials science, that copies what the lotus, *Nelumbo nucifera*, does in nature. Hydrophobic surfaces allow that water droplets bounce on them, like table tennis balls on a table. The lotus surface uses this property to clean itself, hence the name *lotus effect*. This is also the reason that lotus plants have become a symbol of purity.

Vol. I, page 40

* *

Sometimes research produces bizarre materials. An example are the so-called *aerogels*, highly porous solids, shown in Figure 67. Aerogels have a density of a few g/l, thus a few hundred times lower than water and only a few times that of air. Like any porous material, aerogels are good insulators; however, they are easily destroyed and therefore have not found important applications up to now.

* *

Where do the minerals in the Amazonian rainforest come from? The Amazonas river

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 67 A piece of aerogel, a solid that is so porous that it is translucent (courtesy NASA).

washes many nutrient minerals into the Atlantic Ocean. How does the rainforest get its minerals back? It was a long search until it became clear that the largest supply of minerals is airborne: from the Sahara. Winds blow dust from the Sahara desert to the Amazonas basin, across the Atlantic Ocean. It is estimated that 40 million tons of dust are moved from the Sahara to the Amazonas rainforest every year.

* *

Some materials undergo almost unbelievable transformations. What is the final state of *moss*? Large amounts of moss often become peat (turf). Old turf becomes lignite, or brown coal. Old lignite becomes black coal (bituminous coal). Old black coal can become *diamond*. In short, diamonds can be the final state of moss.

* *

In materials science, there is a dream: to make a material that is harder than diamond. It is not clear whether this dream can be realized. The coming years will tell.

QUANTUM TECHNOLOGY

> "I were better to be eaten to death with a rust than to be scoured to nothing with perpetual motion."
>
> William Shakespeare *King Henry IV*.

Quantum effects do not appear only in microscopic systems or in material properties. Also *applied* quantum effects are important in modern life: technologies such as transistors, lasers, superconductivity and other effects and systems have deeply affected our civilisation.

Transistors

Transistors are found in almost all devices that improve health, as well as in almost all devices for telecommunication. A *transistor*, shown in Figure 68 is a device that allows controlling a large electric current with the help of a small one; therefore it can play

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 36 (Continued) The elements, with their atomic number, average mass, atomic radius and main properties.

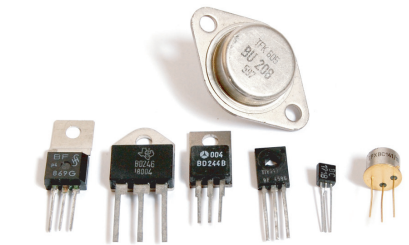
Name	Symbol	At. n.	Aver. mass[a] in u (error), longest lifetime	Atomic[c] radius in pm	Main properties, (naming)[h] discovery date and use
Copper	Cu	29	63.546(3)[f] stable	128m	Red metal (Latin *cuprum* from Cyprus island) antiquity, part of many enzymes, electrical conductors, bronze, brass and other alloys, algicides, etc.
Curium[b]	Cm	96	(247.0704(1)) 15.6(5) Ma	n.a.	Highly radioactive, silver-coloured (after Pierre and Marie Curie) 1944, used as radioactivity source.
Darmstadtium[b]	Ds	110	(271) 1.6 min[g]	n.a.	Made in lab (after the German city) 1994, no use.
Dubnium[b]	Db	105	(262.1141(1)) 34(5) s	n.a.	Made in lab in small quantities, radioactive (Dubna, Russian city) 1967, no use (once known as hahnium).
Dysprosium	Dy	66	162.500(1)[f] stable	177m	Rare Earth metal (Greek *dysprositos* difficult to obtain) 1886, used in laser materials, as infrared source material, and in nuclear industry.
Einsteinium[b]	Es	99	(252.0830(1)) 472(2) d	n.a.	Made in lab, radioactive (after Albert Einstein) 1952, no use.
Erbium	Er	68	167.259(3)[f] stable	176m	Rare Earth metal (Ytterby, Swedish town) 1843, used in metallurgy and optical fibres.
Europium	Eu	63	151.964(1)[f] stable	204m	Rare Earth metal (named after the continent) 1901, used in red screen phosphor for TV tubes.
Fermium[b]	Fm	100	(257.0901(1)) 100.5(2) d	n.a.	Made in lab (after Enrico Fermi) 1952, no use.
Flerovium[b]	Fl	114	(289)	2.7 s[g]	1999, no use.
Fluorine	F	9	18.998 4032(5) stable	62c, 147v	Gaseous halogen (from fluorine, a mineral, from Greek *fluo* flow) 1886, used in polymers and toothpaste.
Francium[b]	Fr	87	(223.0197(1)) 22.0(1) min	(278)	Radioactive metal (from France) 1939, no use.
Gadolinium	Gd	64	157.25(3)[f] stable	180m	Rare-earth metal (after Johan Gadolin) 1880, used in lasers and phosphors.
Gallium	Ga	31	69.723(1) stable	125c, 141m	Almost liquid metal (Latin for both the discoverer's name and his nation, France) 1875, used in optoelectronics.

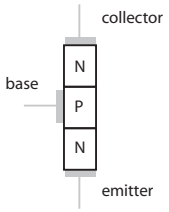
Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

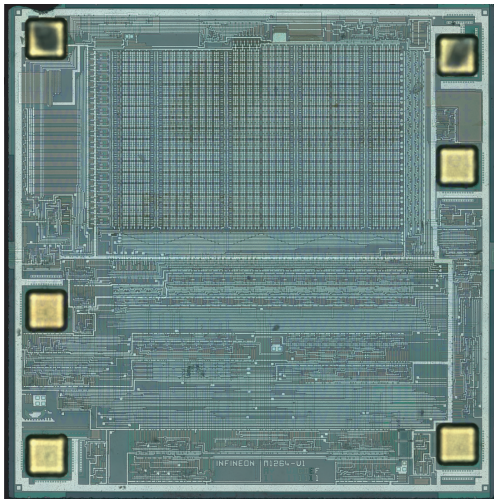
TABLE 36 (Continued) The elements, with their atomic number, average mass, atomic radius and main properties.

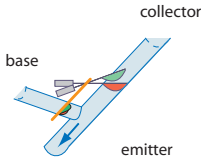
Name	Symbol	At. n.	Aver. mass[a] in u (error), longest lifetime	Atomic[c] radius in pm	Main properties, (naming)[h] discovery date and use
Cadmium	Cd	48	112.411(8)[f] stable	157m	Heavy metal, cuttable and screaming (Greek *kadmeia*, a zinc carbonate mineral where it was discovered) 1817, electroplating, solder, batteries, TV phosphors, dyes.
Caesium	Cs	55	132.905 4519(2) stable	273m	Alkali metal (Latin *caesius* sky blue) 1860, getter in vacuum tubes, photoelectric cells, ion propulsion, atomic clocks.
Calcium	Ca	20	40.078(4)[f] stable	197m	Earth-alkali metal (Latin *calcis* chalk) antiquity, pure in 1880, found in stones and bones, reducing agent, alloying.
Californium[b]	Cf	98	(251.0796(1)) 0.90(5) ka	n.a.	Made in lab, probably metallic, strong neutron emitter (Latin *calor* heat and *fornicare* have sex, the land of hot sex :-) 1950, used as neutron source, for well logging.
Carbon	C	6	12.0107(8)[f] stable	77c	Makes up coal and diamond (Latin *carbo* coal) antiquity, used to build most life forms.
Cerium	Ce	58	140.116(1)[f] stable	183m	Rare Earth metal (after asteroid Ceres, Roman goddess) 1803, cigarette lighters, incandescent gas mantles, glass manufacturing, self-cleaning ovens, carbon-arc lighting in the motion picture industry, catalyst, metallurgy.
Chlorine	Cl	17	35.453(2)[f] stable	102c, 175v	Green gas (Greek *chloros* yellow-green) 1774, drinking water, polymers, paper, dyes, textiles, medicines, insecticides, solvents, paints, rubber.
Chromium	Cr	24	51.9961(6) stable	128m	Transition metal (Greek *chromos* colour) 1797, hardens steel, makes steel stainless, alloys, electroplating, green glass dye, catalyst.
Cobalt	Co	27	58.933 195(5) stable	125m	Ferromagnetic transition metal (German *Kobold* goblin) 1694, part of vitamin B_{12}, magnetic alloys, heavy-duty alloys, enamel dyes, ink, animal nutrition.
Copernicium[b]	Cn	112	(285) 34 s[g]	n.a.	Made in lab, 1996, no use.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net









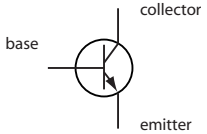


FIGURE 68 Top: examples of packaged single transistors. Right: the basic semiconductor structure, the equivalent water structure, and the technical drawing of an NPN transistor. Bottom: a typical integrated circuit for smart cards incorporating a large number of transistors. (© Benedikt Seidl, blog.ioactive.com)

the role of an electrically controlled switch or of an amplifier. Transistors are made from silicon and can be as small as a 2 by 2 µm and as large as 10 by 10 cm. Transistors are used to control the signals in pacemakers for the heart and the current of electric train engines. Amplifying transistors are central to the transmitter in mobile phones and switching transistors are central to computers and their displays.

Transistors are (almost exclusively) based on *semiconductors*, i.e., on materials where the electrons that are responsible for electric conductivity are *almost* free. The devices

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

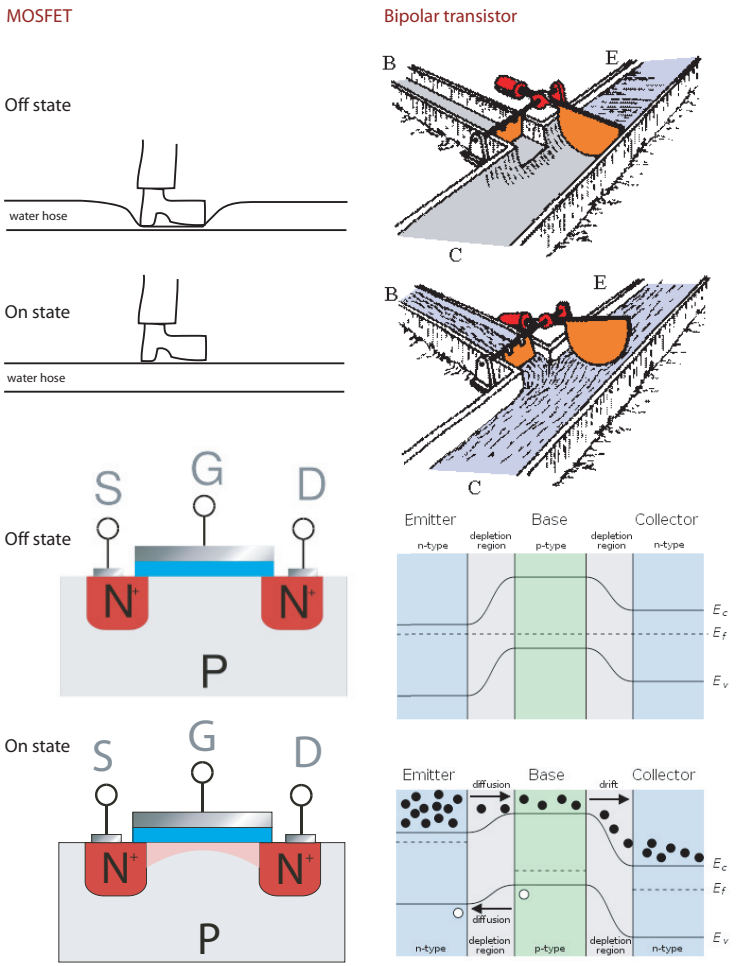


FIGURE 69 The working and construction of a metal-oxide silicon field effect transistor (left) and of a bipolar transistor (right). The 'off' and 'on' states are shown (© Leifi Physik, Wikimedia).

are built in such a way that applying an electric signal changes the conductivity. Every explanation of a transistor makes use of potentials and tunnelling; transistors are applied quantum devices.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 36 (Continued) The elements, with their atomic number, average mass, atomic radius and main properties.

NAME	SYMBOL	AT. N.	AVER. MASS[a] IN U (ERROR), LONGEST LIFETIME	ATOMIC[c] RADIUS IN PM	MAIN PROPERTIES, (NAMING)[h] DISCOVERY DATE AND USE
Antimony	Sb	51	121.760(1)[f] stable	137c, 159m, 205v	Toxic semimetal (via Arabic from Latin *stibium*, itself from Greek, Egyptian for one of its minerals) antiquity, colours rubber, used in medicines, constituent of enzymes.
Argon	Ar	18	39.948(1)[f] stable	(71n)	Noble gas (Greek *argos* inactive, from *an-ergos* without energy) 1894, third component of air, used for welding and in lasers.
Arsenic	As	33	74.921 60(2) stable	120c, 185v	Poisonous semimetal (Greek *arsenikon* tamer of males) antiquity, for poisoning pigeons and doping semiconductors.
Astatine[b]	At	85	(209.9871(1)) 8.1(4) h	(140)	Radioactive halogen (Greek *astatos* unstable) 1940, no use.
Barium	Ba	56	137.327(7) stable	224m	Earth-alkali metal (Greek *bary* heavy) 1808, used in vacuum tubes, paint, oil industry, pyrotechnics and X-ray diagnosis.
Berkelium[b]	Bk	97	(247.0703(1)) 1.4(3) ka	n.a.	Made in lab, probably metallic (Berkeley, US town) 1949, no use because rare.
Beryllium	Be	4	9.012 182(3) stable	106c, 113m	Toxic Earth-alkali metal (Greek *beryllos*, a mineral) 1797, used in light alloys, in nuclear industry as moderator.
Bismuth	Bi	83	208.980 40(1) stable	170m, 215v	Diamagnetic metal (Latin via German *weisse Masse* white mass) 1753, used in magnets, alloys, fire safety, cosmetics, as catalyst, nuclear industry.
Bohrium[b]	Bh	107	(264.12(1)) 0.44 s[g]	n.a.	Made in lab, probably metallic (after Niels Bohr) 1981, found in nuclear reactions, no use.
Boron	B	5	10.811(7)[f] stable	83c	Semimetal, semiconductor (Latin *borax*, from Arabic and Persian for brilliant) 1808, used in glass, bleach, pyrotechnics, rocket fuel, medicine.
Bromine	Br	35	79.904(1) stable	120c, 185v	Red-brown liquid (Greek *bromos* strong odour) 1826, fumigants, photography, water purification, dyes, medicines.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

the number of protons (and electrons) found in an atom of a given element. This number determines the chemical behaviour of an element. Most – but not all – elements up to 92 are found on Earth; the others can be produced in laboratories. The highest element discovered is element 118. In a famous case of research fraud, a scientist in the 1990s tricked two whole research groups into claiming to have made and observed elements 116 and 118. Both elements were independently made and observed later on.

Ref. 297 Nowadays, extensive physical and chemical data are available for every element. Photographs of the pure elements are shown in Figure 19. Elements in the same *group* behave similarly in chemical reactions. The *periods* define the repetition of these similarities.

Page 61

The elements of group 1 are the *alkali metals* (though the exceptional hydrogen is a gas), those of group 2 are the alkaline earth metals. Also *actinoids*, *lanthanoids* are metals, as are the elements of groups 3 to 12, which are called *transition* or *heavy metals*. The elements of group 16 are called *chalkogens*, i.e., ore-formers; group 17 are the *halogens*, i.e., the salt-formers, and group 18 are the inert *noble gases*, which form (almost) no chemical compounds. The groups 13, 14 and 15 contain metals, semimetals, the only room-temperature liquid – bromine – and a few gases and non-metals; these groups have no special name. Groups 1 and 13 to 17 are central for the chemistry of life; in fact, 96 % of living matter is made of C, O, N, H;* almost 4 % of P, S, Ca, K, Na, Cl; trace elements such as Mg, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Cd, Pb, Sn, Li, Mo, Se, Si, I, F, As, B form the rest. Over 30 elements are known to be essential for animal life. The full list is not yet known; candidate elements to extend this list are Al, Br, Ge and W.

Many elements exist in versions with different numbers of neutrons in their nucleus, and thus with different mass; these various *isotopes* – so called because they are found at the *same place* in the periodic table – behave identically in chemical reactions. There are

Ref. 291, Ref. 298 over 2000 of them.

TABLE 36 The elements, with their atomic number, average mass, atomic radius and main properties.

Name	Symbol	At. n.	Aver. mass[a] in u (error), longest lifetime	Atomic[c] radius in pm	Main properties, (naming)[h] discovery date and use
Actinium[b]	Ac	89	(227.0277(1)) 21.77(2) a	(188)	Highly radioactive metallic rare Earth (Greek *aktis* ray) 1899, used as alpha-emitting source.
Aluminium	Al	13	26.981 538 (8) stable	118c, 143m	Light metal (Latin *alumen* alum) 1827, used in machine construction and living beings.
Americium[b]	Am	95	(243.0614(1)) 7.37(2) ka	(184)	Radioactive metal (Italian *America* from Amerigo) 1945, used in smoke detectors.

* The 'average formula' of life is approximately $C_5H_{40}O_{18}N$.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

The transistor is just one of a family of semiconductor devices that includes the field-effect transistor (FET), the metal-oxide-silicon field-effect transistor (MOSFET), the junction gate field-effect transistor (JFET), the insulated gate bipolar transistor (IGBT) and the unijunction transistor (UJT), but also the memristors, diode, the PIN diode, the Zener diode, the avalanche diode, the light-emitting diode (LED), the photodiode, the photovoltaic cell, the diac, the triac, the thyristor and finally, the integrated circuit (IC). These are important in industrial applications: the semiconductor industry has at least 300 thousand million Euro sales every year (2010 value) and employ millions of people across the world.

Motion without friction – superconductivity and superfluidity

We are used to thinking that friction is inevitable. We even learned that friction was an inevitable result of the particle structure of matter. It should come to the surprise of every physicist that motion *without* friction is indeed possible.

In 1911 Gilles Holst and Heike Kamerlingh Onnes discovered that at low temperatures, electric currents can flow with no resistance, i.e., with no friction, through lead. The observation is called *superconductivity*. In the century after that, many metals, alloys and ceramics have been found to show the same behaviour.

The condition for the observation of motion without friction is that quantum effects play an essential role. To ensure this, low temperature is usually needed. Despite a large amount of data, it took over 40 years to reach a full understanding of superconductivity.

Ref. 75 This happened in 1957, when Bardeen, Cooper and Schrieffer published their results. At low temperatures, electron behaviour in certain materials is dominated by an *attractive* interaction that makes them form pairs. These so-called *Cooper pairs* are effective bosons. And bosons can all be in the same state, and can thus effectively move without friction.

In superconductivity, the attractive interaction between electrons is due to the deformation of the lattice. At low temperature, two electrons attract each other in the same way as two masses attract each other due to deformation of the space-time mattress. However, in the case of solids, these deformations are quantized. With this approach, Bardeen, Cooper and Schrieffer explained the lack of electric resistance of superconducting materials, their complete diamagnetism ($\mu_r = 0$), the existence of an energy gap, the second-order transition to normal conductivity at a specific temperature, and the dependence of this temperature on the mass of the isotopes. As a result, they received the Nobel Prize in 1972.*

Another type of motion without friction is *superfluidity*. In 1937, Pyotr Kapitsa had understood that usual liquid helium, i.e., ^{4}He, below a transition observed at the temperature of 2.17 K, is a *superfluid*: the liquid effectively moves without friction through

* For John Bardeen (b. 1908 Madison, d. 1991 Boston), this was his second, after he had got the first Nobel Prize in Physics in 1956, shared with William Shockley and Walter Brattain, for the discovery of the transistor. The first Nobel Prize was a problem for Bardeen, as he needed time to work on superconductivity. In an example to many, he reduced the tam-tam around himself to a minimum, so that he could work as much as possible on the problem of superconductivity. By the way, Bardeen is topped by Frederick Sanger and by Marie Curie. Sanger first won a Nobel Prize in Chemistry in 1958 by himself and then won a second one shared with Walter Gilbert in 1980; Marie Curie first won one with her husband and a second one by herself, though in two different fields.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

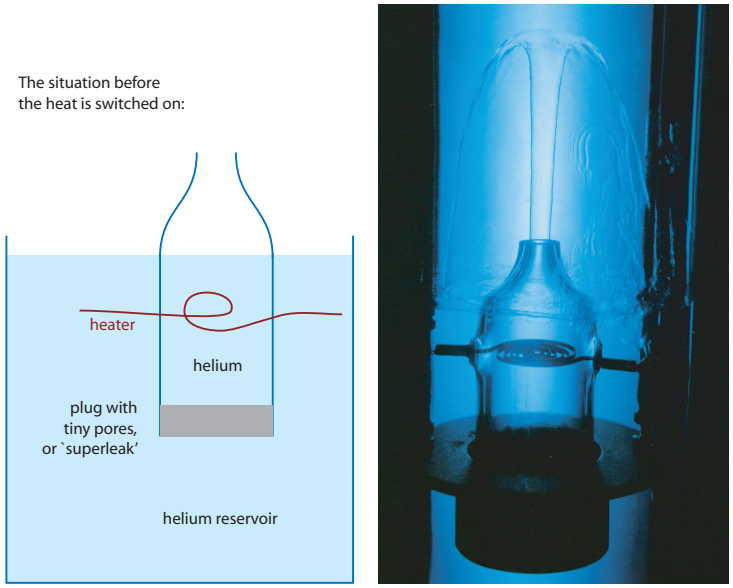


FIGURE 70 The superfluidity of helium 4 can be used to produce the fountain effect above a disc with very small pores, through which superfluid helium can pass, but normal fluid cannot. Superfluid helium 4 has a large thermal conductivity and flows towards a heated region trying to cool it down again, whereas the normal liquid cannot return back through the pores. This thermomechanical effect leads to the fountain (© Pacific Institute of Theoretical Physics).

devices, tubes, etc. More precisely, liquid helium remains a mixture of a superfluid component and a normal component; only the superfluid component moves without friction. Superfluid helium is even able, after an initial kick, to flow over obstacles, such as glass walls, or to flow out of bottles. A well-known effect of superfluidity is shown in Figure 70. Superfluidity occurs because the ^{4}He atom is a boson. Therefore no pairing is necessary for it to move without friction. This research earned Kapitsa a Nobel Prize in 1978.

In 1972, Richardson, Lee and Osheroff found that even ^{3}He is superfluid, provided that the temperature is lowered below 2.7 mK. ^{3}He is a fermion, and requires *pairing* to become superfluid. In fact, below 2.2 mK, ^{3}He is even superfluid in two different ways; one speaks of phase A and phase B. They received the Nobel Prize in 1996 for this discovery.

In the case of ^{3}He, the theoreticians had been faster than the experimentalists. The theory for superconductivity through pairing had been adapted to superfluids already in 1958 – before any data were available – by Bohr, Mottelson and Pines. This theory was then adapted and expanded by Anthony Leggett.* The attractive interaction between

* Aage Bohr, son of Niels Bohr, and Ben Mottelson received the Nobel Prize in 1975, Anthony Leggett in

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

to form aggregates.

Comparable to the periodic table of the atoms, there are tables for the mesons (made of two quarks) and the baryons (made of three quarks). Neither the meson nor the baryon table is included here; they can both be found in the *Review of Particle Physics* at pdg.web.cern.ch. In fact, the baryon table still has a number of vacant spots. The missing baryons are extremely heavy and short-lived (which means expensive to make and detect), and their discovery is not expected to yield deep new insights.

TABLE 35 The periodic table of the elements, with their atomic numbers. Light blue: nonmetals, orange: alkali metals, green: alkaline earth metals, grey: transition metals, dark blue: basic metals, light orange: semimetals, yellow: halogens, brown: noble gases, red: lanthanoids, dark red: actinoids, black: no data.

Group	1 I	2 II	3 IIIa	4 IVa	5 Va	6 VIa	7 VIIa	8	9 VIIIa	10	11 Ia	12 IIa	13 III	14 IV	15 V	16 VI	17 VII	18 VIII
Period 1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

Lanthanoids	*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinoids	**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

More elaborate periodic tables can be found on the chemlab.pc.maricopa.edu/periodic website. The most beautiful of them all can be found on page 60. The *atomic number* gives

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 34 (Continued) Properties of selected composites.

COMPOSITE	MASS m, QUANTUM NUMBERS[a]	LIFETIME τ, MAIN DECAY MODES	SIZE (DIAM.)
Other composites			
Blue whale nerve cell	~ 1 kg	~ 50 a	20 m
Cell (red blood)	0.1 ng	7 plus 120 days	~ 10 µm
Cell (sperm)	10 pg	not fecundated: ~ 5 d	length 60 µm, head 3 µm × 5 µm
Cell (ovule)	1 µg	fecundated: over 4000 million years	~ 120 µm
Cell (*E. coli*)	1 pg	4000 million years	body: 2 µm
Apple	0.1 kg	4 weeks	0.1 m
Adult human	35 kg < m < 350 kg	$\tau \approx 2.5 \cdot 10^9$ s Ref. 294 ≈ 600 million breaths ≈ 2 500 million heartbeats < 122 a, 60 % H_2O and 40 % dust	~ 1.7 m
Heaviest living thing: colony of aspen trees	$6.6 \cdot 10^6$ kg	> 130 a	> 4 km
Larger composites	See the table on page 259 in volume I.		

Page 263 Notes (see also the notes of Table 9):
a. The charge parity C is defined only for certain neutral particles, namely those that are different from their antiparticles. For neutral mesons, the charge parity is given by $C = (-1)^{L+S}$, where L is the orbital angular momentum.
P is the parity under space inversion $\boldsymbol{r} \to -\boldsymbol{r}$. For mesons, it is related to the orbital angular momentum L through $P = (-1)^{L+1}$.
The electric polarizability, defined on page 71 in volume III, is predicted to vanish for all elementary particles.
G-parity is defined only for mesons and given by $G = (-1)^{L+S+I} = (-1)^I C$.
b. Neutrons bound in nuclei have a lifetime of at least 10^{20} years.
c. The first *anti-atoms*, made of antielectrons and antiprotons, were made in January 1996 at CERN Ref. 296 in Geneva. All properties of antimatter checked so far are consistent with theoretical predictions.
d. The number of existing molecules is several orders of magnitude larger than the number of molecules that have been analysed and named.

The most important matter composites are the *atoms*. Their size, structure and interactions determine the properties and colour of everyday objects. Atom types, also called *elements* in chemistry, are most usefully set out in the so-called *periodic table*, which groups together atoms with similar properties in rows and columns. It is given in Table 35 and results from the various ways in which protons, neutrons and electrons can combine

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

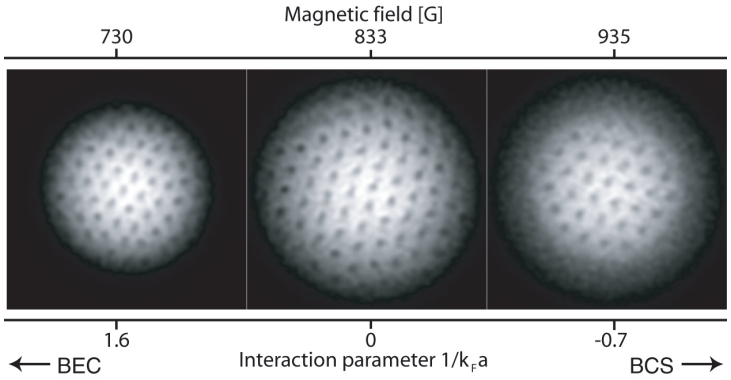


FIGURE 71 A vortex lattice in cold lithium gas, showing their quantized structure (© Andre Schirotzek).

^{3}He atoms, the basic mechanism that leads to superfluidity, turns out to be the spin-spin interaction.

Superfluidity has also been observed in a number of *gases*, though at much lower temperatures. Studying the behaviour of gases at lowest temperatures has become popular in recent years. When the temperature is so low that the de Broglie wavelength is comparable to the atom-atom distance, bosonic gases form a Bose–Einstein condensate. The first such states were realized in 1995 by several groups; the group around Eric Cornell and Carl Wieman used ^{87}Rb, Rand Hulet and his group used ^{7}Li and Wolfgang Ketterle and his group used ^{23}Na. For fermionic gases, the first degenerate gas, ^{40}K, was observed in 1999 by the group around Deborah Jin. In 2004, the same group observed the first gaseous Fermi condensate, after the potassium atoms paired up. All these condensates show superfluidity.

Superfluids are fascinating substances. Vortices also exist in them. But in superfluids, be they gases or liquids, vortices have properties that do not appear in normal fluids. In the superfluid ^{3}He-B phase, vortices are *quantized*: vortices only exist in integer multiples of the elementary circulation $h/2m_{^3\mathrm{He}}$. (This is also the case in superconductors.) Vortices in superfluids have quantized angular momentum. An effect of the quantization can be seen in Figure 71. In superfluids, these quantized vortices flow forever! Like in ordinary fluids, also in superfluids one can distinguish between laminar and turbulent flow. The transition between the two regimes is mediated by the behaviour the *vortices* Ref. 76 in the fluid. Present research is studying how these vortices behave and how they induce the transition.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

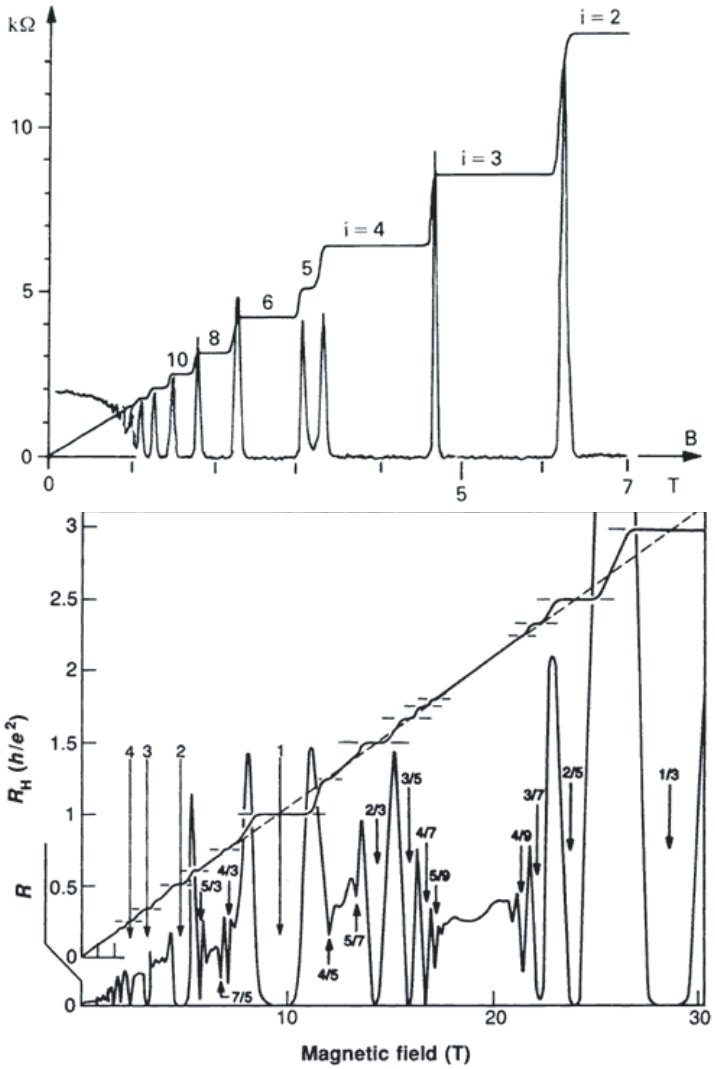


FIGURE 72 The quantum Hall effect (above) and the fractional quantum Hall effect (below): each graph yielded a Nobel prize. The graphs show how the Hall resistance and the Ohmic resistance vary with the applied magnetic field at very low temperature. The step height is quantized in integer or simple fractions of $h/e^2 = 25.812\,807\,557(18)\,\mathrm{k\Omega}$. Quantum Hall experiments allow the most precise determination known to date of this constant of nature.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 34 (Continued) Properties of selected composites.

Composite	Mass m, quantum numbers[a]	Lifetime τ, main decay modes	Size (diam.)
	electric polarizability $\alpha_e = 12.1(0.9) \cdot 10^{-4}\,\mathrm{fm}^3$ magnetic polarizability $\alpha_m = 2.1(0.9) \cdot 10^{-4}\,\mathrm{fm}^3$		
Neutron[b] n or N^0 (udd)	1.674 927 16(13) yg = 1.008 664 915 78(55) u = 939.565 330(38) MeV/c^2 $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$, $S = 0$ gyromagnetic ratio $\mu_n/\mu_N = -1.913\,042\,72(45)$ electric dipole moment $d_n = (-3.3 \pm 4.3) \cdot 10^{-28}\,e\,\mathrm{m}$ electric polarizability $\alpha = 0.98(23) \cdot 10^{-3}\,\mathrm{fm}^3$	887.0(2.0) s, $pe^-\bar{\nu}_e$ 100 %	~ 1 fm
Omega Ω^- (sss)	1672.43(32) MeV/c^2 gyromagnetic ratio $\mu_\Omega/\mu_N = -1.94(22)$	82.2(1.2) ps, ΛK^- 67.8(7) %, $\Xi^0\pi^-$ 23.6(7) %	~ 1 fm
composite radiation: glueballs			
glueball candidate $f_0(1500)$, status unclear	1503(11) MeV $I^G(J^{PC}) = 0^+(0^{++})$	full width 120(19) MeV	~ 1 fm
Atoms (selected from 114 known elements with over 2000 known nuclides) Ref. 291			
Hydrogen (^{1}H) [lightest]	1.007 825 032(1) u = 1.6735 yg		2 · 53 pm
Antihydrogen[c]	1.007 u = 1.67 yg		2 · 53 pm
Helium (^{4}He) [smallest]	4.002 603250(1) u = 6.6465 yg		2 · 31 pm
Carbon (^{12}C)	12 u = 19.926 482(12) yg		2 · 77 pm
Bismuth (^{209}Bi*) [shortest living and rarest]	209 u	0.1 ps Ref. 292	
Tantalum (^{180m}Ta) [second longest living radioactive]	180 u	> 10^{15} a Ref. 293	
Bismuth (^{209}Bi) [longest living radioactive]	209 u	1.9(2)10^{19} a Ref. 292	
Francium (^{223}Fr) [largest]	223 u	22 min	2 · 0.28 nm
Oganesson (^{289}Og) [heaviest]	294 u	0.9 ms	
Molecules[d] (selected from over 10^7 known types)			
Hydrogen (H_2)	~ 2 u	> 10^{25} a	
Water (H_2O)	~ 18 u	> 10^{25} a	
ATP (adenosinetriphosphate)	507 u	> 10^{10} a	*c.* 3 nm
Human Y chromosome	70 · 10^6 base pairs	> 10^6 a	*c.* 50 mm (uncoiled)

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Appendix B

COMPOSITE PARTICLE PROPERTIES

The following table lists the most important composite particles. he list has not changed much recently, mainly because of the vast progress hat was achieved already in the middle of the twentieth century. In principle, Page 261 using the standard model of particle physics, *all* properties of composite matter and radiation can be deduced. In particular, all properties of objects encountered in everyday life follow. (Can you explain how the size of an apple follows from the standard model?) Challenge 194 s The most important examples of composites are grouped in the following table.

TABLE 34 Properties of selected composites.

Composite	Mass m, quantum numbers[a]	Lifetime τ, main decay modes	Size (diam.)
Mesons (hadrons, bosons) (selected from over 130 known types)			
Pion $\pi^0(u\bar{u} - d\bar{d})/\sqrt{2}$	134.976 4(6) MeV/c^2 $I^G(J^{PC}) = 1^-(0^{-+})$, $S = C = B = 0$	84(6) as, 2γ 98.798(32) %	~ 1 fm
Pion $\pi^+(u\bar{d})$	139.569 95(35) MeV/c^2 $I^G(J^P) = 1^-(0^-)$, $S = C = B = 0$	26.030(5) ns, $\mu^+\nu_\mu$ 99.987 7(4) %	~ 1 fm
Kaon K^0_S	$m_{K^0_S}$	89.27(9) ps	~ 1 fm
Kaon K^0_L	$m_{K^0_S}$ + 3.491(9) μeV/c^2	51.7(4) ns	~ 1 fm
Kaon K^+ ($u\bar{s}, \bar{u}s$)	493.677(16) MeV/c^2	12.386(24) ns, $\mu^+\nu_\mu$ 63.51(18) % $\pi^+\pi^0$ 21.16(14) %	~ 1 fm
Kaon K^0 ($d\bar{s}$) (50 % K_S, 50 % K_L)	497.672(31) MeV/c^2	n.a.	~ 1 fm
All kaons $K^\pm, K^0, K^0_S, K^0_L$:	$I(J^P) = \frac{1}{2}(0^-)$, $S = \pm 1$, $B = C = 0$		
Baryons (hadrons, fermions) (selected from over 100 known types)			
Proton p or N^+ (uud)	1.672 621 58(13) yg = 1.007 276 466 88(13) u = 938.271 998(38) MeV/c^2 $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$, $S = 0$ gyromagnetic ratio $\mu_p/\mu_N = 2.792\,847\,337(29)$ electric dipole moment $d = (-4 \pm 6) \cdot 10^{-26} e$ m	$\tau_{\text{total}} > 1.6 \cdot 10^{25}$ a, $\tau(p \to e^+\pi^0) > 5.5 \cdot 10^{32}$ a Ref. 290	0.89(1) fm

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

The fractional quantum Hall effect

The fractional quantum Hall effect is one of the most intriguing discoveries of materials science, and possibly, of physics as a whole. The effect concerns the flow of electrons in Ref. 77 a two-dimensional surface. In 1982, Robert Laughlin predicted that in this system one should be able to observe objects with electrical charge $e/3$. This strange and fascinating Ref. 78 prediction was indeed verified in 1997.

Page 97 We encountered the (classical) Hall effect above. The story continues with the discovery by Klaus von Klitzing of the *quantum* Hall effect. In 1980, Klitzing and his Ref. 79 collaborators found that in two-dimensional systems at low temperatures – about 1 K – the electrical conductance S, also called the Hall conductance, is quantized in multiples of the quantum of conductance

$$S = n \frac{e^2}{h} \,. \tag{11}$$

The explanation is straightforward: it is the quantum analogue of the classical Hall effect, which describes how conductance varies with applied magnetic field. The corresponding resistance values are

$$R = \frac{1}{n}\frac{h}{e^2} = \frac{1}{n}\, 25,812\,807\,557(18)\,\text{k}\Omega \,. \tag{12}$$

The values are independent of material, temperature, or magnetic field. They are constants of nature. Von Klitzing received the Nobel Prize in Physics for the discovery, because the effect was unexpected, allows a highly precise measurement of the fine structure constant, and also allows one to build detectors for the smallest voltage variations measurable so far. His discovery started a large wave of subsequent research.

Only two years later, in 1982, it was found that in extremely strong magnetic fields and at extremely low temperatures, the conductance could vary in steps *one third* that Ref. 80 size. Shortly afterwards, even stranger numerical fractions were also found. In fact, all fractions of the form $m/(2m+1)$ or of the form $(m+1)/(2m+1)$, m being an integer, are possible. This is the *fractional quantum Hall effect*. In a landmark paper, Robert Laughlin Ref. 77 explained all these results by assuming that the electron gas could form collective states showing quasiparticle excitations with a charge $e/3$. This was confirmed experimentally 15 years later and earned him a Nobel Prize as well. We have seen in several occasions that quantization is best discovered through noise measurements; also in this case, the clearest confirmation came from electrical current noise measurements.

Subsequent experiments confirmed Laughlin's deduction. He had predicted the appearance of a new form of a *composite* quasi-particle, built of electrons and of one or several magnetic flux quanta. If an electron bonds with an *even* number of quanta, the composite is a fermion, and leads to Klitzing's *integral* quantum Hall effect. If the electron bonds with an *odd* number of quanta, the composite is a boson, and the *fractional* quantum Hall effect appears. The experimental and theoretical details of these quasiparticles might well be the most complex and fascinating aspects of physics, but exploring them would lead us too far from the aim of our adventure.

Ref. 81 In 2007, a new chapter in the story was opened by Andre Geim and his team, and a

2003.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 8 Matter at lowest temperatures.

PHASE	TYPE	LOW TEMPERATURE BEHAVIOUR	EXAMPLE
Solid	conductor	superconductivity	lead, MgB_2 (40 K)
		antiferromagnet	chromium, MnO
		ferromagnet	iron
	insulator	diamagnet	
Liquid	bosonic	Bose–Einstein condensation, i.e., superfluidity	^{4}He
	fermionic	pairing, then BEC, i.e., superfluidity	^{3}He
Gas	bosonic	Bose–Einstein condensation	^{87}Rb, ^{7}Li, ^{23}Na, H, ^{4}He, ^{41}K
	fermionic	pairing, then Bose–Einstein condensation	^{40}K, ^{6}Li

second team, when they discovered a new type of quantum Hall effect at room temperature. They used graphene, i.e., single-atom layers of graphite, and found a relativistic analogue of the quantum Hall effect. This effect was even more unexpected than the previous ones, is equally interesting, and can be performed on a table top. The groups are good candidates for a trip to Stockholm.*

Page 98

What do we learn from these results? Systems in two dimensions have states which follow different rules than systems in three dimensions. The fractional charges in superconductors have no relation to quarks. Quarks, the constituents of protons and neutrons, have charges $e/3$ and $2e/3$. Might the quarks have something to do with a mechanism similar to superconductivity? At this point we need to stand the suspense, as no answer is possible; we come back to this issue in the last part of this adventure.

How does matter behave at the lowest temperatures?

The low-temperature behaviour of matter has numerous experimental and theoretical aspects. The first issue is whether matter is always solid at low temperatures. The answer is no: all phases exist at low temperatures, as shown in Table 8.

Concerning the electric properties of matter at lowest temperatures, the present status is that matter is either insulating or superconducting. Finally, one can ask about the magnetic properties of matter at low temperatures. We know already that matter can not be paramagnetic at lowest temperatures. It seems that matter is either ferromagnetic, diamagnetic or antiferromagnetic at lowest temperatures.

Lasers and other spin-one vector boson launchers

Photons are vector bosons; a lamp is thus a vector boson launcher. All existing lamps fall into one of three classes. *Incandescent lamps* use emission from a hot solid, *gas discharge lamps* use excitation of atoms, ions or molecules through collision, and *recombination lamps* generate (cold) light through recombination of charges in semiconductors or li-

Ref. 82

* This prediction from the December 2008 edition became reality in December 2010.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 33 (Continued) Cosmological constants.

QUANTITY	SYMBOL	VALUE
Baryon mass	m_b	$1.67 \cdot 10^{-27}$ kg
Baryon number density		0.25(1) /m^3
Luminous matter density		$3.8(2) \cdot 10^{-28}$ kg/m^3
Stars in the universe	n_s	$10^{22\pm1}$
Baryons in the universe	n_b	$10^{81\pm1}$
Microwave background temperature [b]	T_0	2.725(1) K
Photons in the universe	n_γ	10^{89}
Photon energy density	$\rho_\gamma = \pi^2 k^4 / 15 T_0^4$	$4.6 \cdot 10^{-31}$ kg/m^3
Photon number density		410.89 /cm^3 or 400 /cm^3 $(T_0/2.7\,\mathrm{K})^3$
Density perturbation amplitude	$\sqrt{S}$	$5.6(1.5) \cdot 10^{-6}$
Gravity wave amplitude	$\sqrt{T}$	$< 0.71\sqrt{S}$
Mass fluctuations on 8 Mpc	σ_8	0.84(4)
Scalar index	n	0.93(3)
Running of scalar index	$\mathrm{d}n/\mathrm{d}\ln k$	−0.03(2)
Planck length	$l_{Pl} = \sqrt{\hbar G/c^3}$	$1.62 \cdot 10^{-35}$ m
Planck time	$t_{Pl} = \sqrt{\hbar G/c^5}$	$5.39 \cdot 10^{-44}$ s
Planck mass	$m_{Pl} = \sqrt{\hbar c/G}$	21.8 µg
Instants in history [a]	t_0/t_{Pl}	$8.7(2.8) \cdot 10^{60}$
Space-time points inside the horizon [a]	$N_0 = (R_0/l_{Pl})^3 \cdot (t_0/t_{Pl})$	$10^{244\pm1}$
Mass inside horizon	M	$10^{54\pm1}$ kg

a. The index 0 indicates present-day values.

b. The radiation originated when the universe was 380 000 years old and had a temperature of about 3000 K; the fluctuations ΔT_0 which led to galaxy formation are today about 16 ± 4 µK = $6(2) \cdot 10^{-6}\, T_0$.

Vol. II, page 231

Useful numbers

π	3.14159 26535 89793 23846 26433 83279 50288 41971 69399 37510$_5$
e	2.71828 18284 59045 23536 02874 71352 66249 77572 47093 69995$_9$
γ	0.57721 56649 01532 86060 65120 90082 40243 10421 59335 93992$_3$
ln 2	0.69314 71805 59945 30941 72321 21458 17656 80755 00134 36025$_5$
ln 10	2.30258 50929 94045 68401 79914 54684 36420 76011 01488 62877$_2$
$\sqrt{10}$	3.16227 76601 68379 33199 88935 44432 71853 37195 55139 32521$_6$

Ref. 289



Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

formula for the change of the length of the year over time.
b. The truly amazing precision in the average distance Earth–Sun of only 30 m results from time averages of signals sent from Viking orbiters and Mars landers taken over a period of over twenty years. Note that the International Astronomical Union distinguishes the average distance Earth–Sun from the *astronomical unit* itself; the latter is defined as a fixed and exact length. Also the *light year* is a unit defined as an exact number by the IAU. For more details, see www.iau.org/public/measuring.
c. The shape of the Earth is described most precisely with the World Geodetic System. The last edition dates from 1984. For an extensive presentation of its background and its details, see the www.wgs84.com website. The International Geodesic Union refined the data in 2000. The radii and the flattening given here are those for the 'mean tide system'. They differ from those of the 'zero tide system' and other systems by about 0.7 m. The details constitute a science in itself.
d. Measured centre to centre. To find the precise position of the Moon at a given date, see the www.fourmilab.ch/earthview/moon_ap_per.html page. For the planets, see the page www.fourmilab.ch/solar/solar.html and the other pages on the same site.
e. Angles are defined as follows: 1 degree = $1^\circ = \pi/180$ rad, 1 (first) minute = $1' = 1°/60$, 1 second (minute) = $1'' = 1'/60$. The ancient units 'third minute' and 'fourth minute', each 1/60th of the preceding, are not in use any more. ('Minute' originally means 'very small', as it still does in modern English.)

Some properties of nature at large are listed in the following table. (If you want a challenge, can you determine whether any property of the universe itself is listed?)

TABLE 33 Cosmological constants.

Quantity	Symbol	Value
Cosmological constant	Λ	*c*. $1 \cdot 10^{-52}\,\mathrm{m}^{-2}$
Age of the universe [a]	t_0	$4.333(53) \cdot 10^{17}\,\mathrm{s} = 13.8(0.1) \cdot 10^9\,\mathrm{a}$
(determined from space-time, via expansion, using general relativity)		
Age of the universe [a]	t_0	over $3.5(4) \cdot 10^{17}\,\mathrm{s} = 11.5(1.5) \cdot 10^9\,\mathrm{a}$
(determined from matter, via galaxies and stars, using quantum theory)		
Hubble parameter [a]	H_0	$2.3(2) \cdot 10^{-18}\,\mathrm{s}^{-1} = 0.73(4) \cdot 10^{-10}\,\mathrm{a}^{-1}$
	$= h_0 \cdot 100\,\mathrm{km/s\,Mpc} = h_0 \cdot 1.0227 \cdot 10^{-10}\,\mathrm{a}^{-1}$	
Reduced Hubble parameter [a]	h_0	0.71(4)
Deceleration parameter [a]	$q_0 = -(\ddot{a}/a)_0/H_0^2$	−0.66(10)
Universe's horizon distance [a]	$d_0 = 3ct_0$	$40.0(6) \cdot 10^{26}\,\mathrm{m} = 13.0(2)\,\mathrm{Gpc}$
Universe's topology		trivial up to 10^{26} m
Number of space dimensions		3, for distances up to 10^{26} m
Critical density	$\rho_c = 3H_0^2/8\pi G$	$h_0^2 \cdot 1.878\,82(24) \cdot 10^{-26}\,\mathrm{kg/m}^3$
of the universe		$= 0.95(12) \cdot 10^{-26}\,\mathrm{kg/m}^3$
(Total) density parameter [a]	$\Omega_0 = \rho_0/\rho_c$	1.02(2)
Baryon density parameter [a]	$\Omega_{B0} = \rho_{B0}/\rho_c$	0.044(4)
Cold dark matter density parameter [a]	$\Omega_{CDM0} = \rho_{CDM0}/\rho_c$	0.23(4)
Neutrino density parameter [a]	$\Omega_{\nu 0} = \rho_{\nu 0}/\rho_c$	0.001 to 0.05
Dark energy density parameter [a]	$\Omega_{X0} = \rho_{X0}/\rho_c$	0.73(4)
Dark energy state parameter	$w = p_X/\rho_X$	−1.0(2)

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

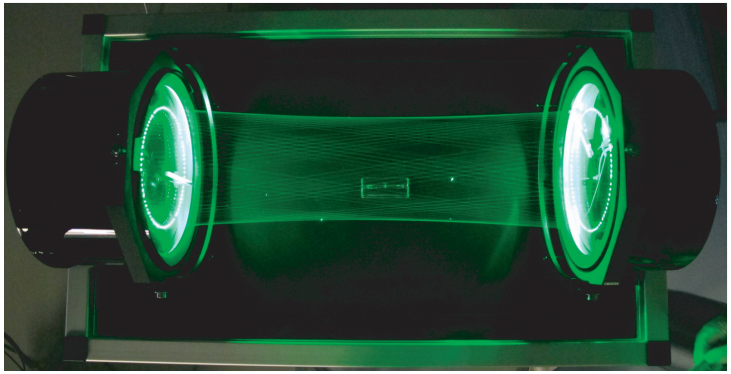


FIGURE 73 The beauty of lasers: the fine mesh created by a green laser delay line (© Laser Zentrum Hannover).

quids. The latter are the only lamp types found in living systems. The other main sources of light are *lasers*. All light sources are based on quantum effects, but for lasers the connection is especially obvious. The following table gives an overview of the main types and their uses.

TABLE 9 A selection of lamps and lasers.

Lamp type, application	Wavelength	Brightness or power	Cost	Lifetime
Incandescent lamps				
Oil lamps, candles, for illumination	white	up to 500 lm	1 cent/lm	5 h
Tungsten wire light bulbs, halogen lamps, for illumination	300 to 800 nm	5 to 25 lm/W	0.1 cent/lm	700 h
Stars, for production of heavy elements	full spectrum	up to 10^{44} W	free	up to thousands of millions of years
Gas discharge lamps				
Neon lamps, for advertising	red			up to 30 kh
Mercury lamps, for illumination	UV plus spectrum	45 to 110 lm/W	0.05 cent/lm	3000 to 24 000 h
Metal halogenide lamps (ScI_3 or 'xenon light', NaI, DyI_3, HoI_3, TmI_5) for car headlights and illumination	white	110 lm/W	1 cent/lm	up to 20 kh
Sodium low pressure lamps for street illumination	589 nm yellow	200 lm/W	0.2 cent/lm	up to 18 kh

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 9 A selection of lamps and lasers (continued).

Lamp type, application	Wavelength	Brightness or power	Cost	Lifetime
Sodium high pressure lamps for street illumination	broad yellow	120 lm/W	0.2 cent/lm	up to 24 kh
Xenon arc lamps, for cinemas	white	30 to 150 lm/W, up to 15 kW		100 to 2500 h
Stars, for production of heavy elements	many lines	up to 10^{20} W	free	up to thousands of millions of years
Recombination lamps				
Foxfire in forests, e.g. due to *Armillaria mellea*, *Neonothopanus gardneri* or other bioluminescent fungi	green	just visible	free	years
Firefly, to attract mates	green-yellow		free	*c.* 10 h
Large deep sea squid, *Taningia danae*, producing light flashes, to confuse prey	red	*c.* 1 W	free	years
Deep-sea fish, such as *angler fish*, to attract prey or find mates	white	*c.* 1 μW	free	years
Deep-sea medusae, to produce attention so that predators of predators are attracted	blue and all other colours		free	years
Light emitting diodes, for measurement, illumination and communication	red, green, blue, UV	up to 150 lm/W, up to 5 W	10 cent/lm	15k to 100 kh
Synchrotron radiation sources				
Electron synchroton source	X-rays to radio waves	pulsed	many MEuro	years
Maybe some stars	broad spectrum		free	thousands of years
Ideal white lamp or laser	visible	*c.* 300 lm/W	0	∞
Ideal coloured lamp or laser	green	683 lm/W	0	∞
Gas lasers				
He-Ne laser (obsolete), for school experiments	632.8 nm	550 lm/W	2000 cent/lm	300 h
Argon laser, for pumping and laser shows, now obsolete	several blue and green lines	up to 100 W	10 kEuro	

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 32 (Continued) Astronomical constants.

Quantity	Symbol	Value
Moon's distance at apogee [d]		typically 404 Mm, historical maximum 406 720 km
Moon's angular size [e]		average 0.5181° = 31.08′, minimum 0.49°, maximum 0.55°
Moon's average density	$\rho_{☾}$	3.3 Mg/m^3
Moon's surface gravity	$g_{☾}$	1.62 m/s^2
Moon's atmospheric pressure	$p_{☾}$	from 10^{-10} Pa (night) to 10^{-7} Pa (day)
Jupiter's mass	$M_{♃}$	$1.90 \cdot 10^{27}$ kg
Jupiter's radius, equatorial	$R_{♃}$	71.398 Mm
Jupiter's radius, polar	$R_{♃}$	67.1(1) Mm
Jupiter's average distance from Sun	$D_{♃}$	778 412 020 km
Jupiter's surface gravity	$g_{♃}$	24.9 m/s^2
Jupiter's atmospheric pressure	$p_{♃}$	from 20 kPa to 200 kPa
Sun's mass	$M_{\odot}$	$1.988\,43(3) \cdot 10^{30}$ kg
Sun's gravitational length	$2GM_{\odot}/c^2$	2.953 250 08(5) km
Heliocentric gravitational constant	$GM_{\odot}$	$132.712\,440\,018(8) \cdot 10^{18}$ m^3/s^2
Sun's luminosity	$L_{\odot}$	384.6 YW
Solar equatorial radius	$R_{\odot}$	695.98(7) Mm
Sun's angular size		0.53° average; minimum on fourth of July (aphelion) 1888″, maximum on fourth of January (perihelion) 1952″
Sun's average density	$\rho_{\odot}$	1.4 Mg/m^3
Sun's average distance	AU	149 597 870.691(30) km
Sun's age	$T_{\odot}$	4.6 Ga
Solar velocity around centre of galaxy	$v_{\odot g}$	220(20) km/s
Solar velocity against cosmic background	$v_{\odot b}$	370.6(5) km/s
Sun's surface gravity	$g_{\odot}$	274 m/s^2
Sun's lower photospheric pressure	$p_{\odot}$	15 kPa
Distance to Milky Way's centre		8.0(5) kpc = 26.1(1.6) kal
Milky Way's age		13.6 Ga
Milky Way's size		*c.* 10^{21} m or 100 kal
Milky Way's mass		10^{12} solar masses, *c.* $2 \cdot 10^{42}$ kg
Most distant galaxy cluster known	SXDF-XCLJ 0218-0510	$9.6 \cdot 10^9$ al

a. Defining constant, from vernal equinox to vernal equinox; it was once used to define the second. (Remember: π seconds is about a nanocentury.) The value for 1990 is about 0.7 s less, corresponding to a slowdown of roughly 0.2 ms/a. (Watch out: why?) There is even an empirical

Challenge 192 s

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 31 (Continued) Derived physical constants.

Quantity	Symbol	Value in SI units	Uncert.
Neutron magnetic moment	μ_n	$-0.966\,236\,47(23) \cdot 10^{-26}$ J/T	$2.4 \cdot 10^{-7}$
	μ_n/μ_B	$-1.041\,875\,63(25) \cdot 10^{-3}$	$2.4 \cdot 10^{-7}$
	μ_n/μ_N	$-1.913\,042\,72(45)$	$2.4 \cdot 10^{-7}$
Stefan–Boltzmann constant	$\sigma = \pi^2 k^4/60\hbar^3 c^2$	56.703 73(21) nW/m^{2}K^4	$3.6 \cdot 10^{-6}$
Wien's displacement constant	$b = \lambda_{max} T$	2.897 7721(26) mmK	$9.1 \cdot 10^{-7}$
		58.789 254(53) GHz/K	$9.1 \cdot 10^{-7}$
Electron volt	eV	$1.602\,176\,565(35) \cdot 10^{-19}$ J	$2.2 \cdot 10^{-8}$
Bits to entropy conversion const.	$k \ln 2$	10^{23} bit = 0.956 994 5(9) J/K	$9.1 \cdot 10^{-7}$
TNT energy content		3.7 to 4.0 MJ/kg	$4 \cdot 10^{-2}$

a. For infinite mass of the nucleus.

Some useful properties of our local environment are given in the following table.

TABLE 32 Astronomical constants.

Quantity	Symbol	Value
Tropical year 1900 [a]	a	31 556 925.974 7 s
Tropical year 1994	a	31 556 925.2 s
Mean sidereal day	d	$23^h56'4.090\,53''$
Average distance Earth–Sun [b]		149 597 870.691(30) km
Astronomical unit [b]	AU	149 597 870 691 m
Light year, based on Julian year [b]	al	9.460 730 472 5808 Pm
Parsec	pc	30.856 775 806 Pm = 3.261 634 al
Earth's mass	$M_{\oplus}$	$5.973(1) \cdot 10^{24}$ kg
Geocentric gravitational constant	GM	$3.986\,004\,418(8) \cdot 10^{14}$ m^3/s^2
Earth's gravitational length	$l_{\oplus} = 2GM/c^2$	8.870 056 078(16) mm
Earth's equatorial radius [c]	$R_{\oplus eq}$	6378.1366(1) km
Earth's polar radius [c]	$R_{\oplus p}$	6356.752(1) km
Equator–pole distance [c]		10 001.966 km (average)
Earth's flattening [c]	$e_{\oplus}$	1/298.25642(1)
Earth's av. density	$\rho_{\oplus}$	5.5 Mg/m^3
Earth's age	$T_{\oplus}$	4.54(5) Ga = 143(2) Ps
Earth's normal gravity	g	9.806 65 m/s^2
Earth's standard atmospher. pressure	p_0	101 325 Pa
Moon's radius	$R_{\leftmoon v}$	1738 km in direction of Earth
Moon's radius	$R_{\leftmoon h}$	1737.4 km in other two directions
Moon's mass	$M_{\leftmoon}$	$7.35 \cdot 10^{22}$ kg
Moon's mean distance [d]	$d_{\leftmoon}$	384 401 km
Moon's distance at perigee [d]		typically 363 Mm, historical minimum 359 861 km

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 9 A selection of lamps and lasers (continued).

Lamp type, application	Wavelength	Brightness or power	Cost	Lifetime
Krypton laser, for pumping and laser shows, now obsolete	several blue, green, red lines	50 W		
Xenon laser	many lines in the IR, visible and near UV	20 W		
Nitrogen (or 'air') laser, for pumping of other lasers, for hobbyists	337.1 nm	pulsed up to 1 MW	down to a few hundred Euro	limited by metal electrode lifetime
Water vapour laser, for research, now obsolete	many lines between 7 and 220 µm, often 118 µm	CW 0.5 W, pulsed much higher	a few kEuro	
CO_2 laser, for cutting, welding, glass welding and surgery	10.6 µm	CW up to 100 kW, pulsed up to 10 TW	*c.* 100 Euro/W	1500 h
Excimer laser, for lithography in silicon chip manufacturing, eye surgery, laser pumping, psoriasis treatment, laser deposition	193 nm (ArF), 248 nm (KrF), 308 nm (XeCl), 353 nm (XeF)	100 W	10 to 500 kEuro	years
Metal vapour lasers (Cu, Cd, Se, Ca, Ag, Au, Mn, Tl, In, Hg)				
Copper vapour laser, for pumping, photography, dermatology, laser cutting, hobby constructions and explorative research	248 nm, 511 nm and 578 nm	pulses up to 5 MW	10 kEuro	1 khour
Cadmium vapour laser, for printing, typesetting and recognition of forged US dollar notes	325 nm and 442 nm	up to 200 mW	12 kEuro	10 kh
Gold vapour laser, for explorative research, dermatology	627 nm	pulses up to 1 MW	from a few hundred Euro upwards	
Chemical gas lasers				
HF, DF and oxygen-iodine laser, used as weapons, pumped by chemical reactions, all obsolete	1.3 to 4.2 µm	up to MW in CW mode	over 10 MEuro	unknown
Liquid dye lasers				

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 9 A selection of lamps and lasers (continued).

Lamp type, application	Wavelength	Brightness or power	Cost	Lifetime
Rhodamine, stilbene, coumarin etc. lasers, for spectroscopy and medical uses	tunable, range depends on dye in 300 to 1100 nm range	up to 10 W	10 kEuro	dye-dependent
Beer, vodka, whiskey, diluted marmelade and many other liquids work as laser material	IR, visible	usually mW	1 kEuro	a few minutes
Solid state lasers				
Ruby laser (obsolete), for holography and tattoo removal	694 nm		1 kEuro	
Nd:YAG (neodymium:yttrium aluminium granate) laser, for material processing, surgery, pumping, range finding, velocimetry, also used with doubled frequency (532 nm), with tripled frequency (355 nm) and with quadrupled frequency (266 nm), also used as slab laser	1064 nm	CW 10 kW, pulsed 300 MW	50 to 500 kEuro	1000 h
Er:YAG laser, for dermatology	2940 nm			
Ti:sapphire laser, for ultrashort pulses for spectroscopy, LIDAR, and research	650 to 1200 nm	CW 1 W, pulsed 300 TW	from 5 kEuro upwards	
Alexandrite laser, for laser machining, dermatology, LIDAR	700 to 840 nm			
Cr:LiSAF laser		pulsed 10 TW, down to 30 fs		
Cr:YAG laser	1.35 to 1.6 µm	pulsed, down to 100 fs		
Cr:Forsterite laser, optical tomography	1200 to 1300 nm	pulsed, below 100 fs		
Erbium doped glass fibre laser, used in optical communications (undersea cables) and optical amplifiers	1.53 to 1.56 µm			years
Perovskite laser, such as Co:$KZnF_3$, for research	NIR tunable, 1650 to 2070 nm	100 mW	2 kEuro	
F-centre laser, for spectroscopy (NaCl:OH-, KI:Li, LiF)	tuning ranges between 1.2 and 6 µm	100 mW	20 kEuro	

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 31 (Continued) Derived physical constants.

Quantity	Symbol	Value in SI units	Uncert.
Loschmidt's number at 273.15 K and 101 325 Pa	N_L	$2.686\,7805(24) \cdot 10^{23}$	$9.1 \cdot 10^{-7}$
Faraday's constant	$F = N_A e$	96 485.3365(21) C/mol	$2.2 \cdot 10^{-8}$
Universal gas constant	$R = N_A k$	8.314 4621(75) J/mol K	$9.1 \cdot 10^{-7}$
Molar volume of an ideal gas at 273.15 K and 101 325 Pa	$V = RT/p$	22.413 968(20) l/mol	$9.1 \cdot 10^{-7}$
Rydberg constant [a]	$R_\infty = m_e c\alpha^2/2h$	10 973 731.568 539(55) m^{-1}	$5 \cdot 10^{-12}$
Conductance quantum	$G_0 = 2e^2/h$	77.480 917 346(25) µS	$3.2 \cdot 10^{-10}$
Magnetic flux quantum	$\varphi_0 = h/2e$	2.067 833 758(46) pWb	$2.2 \cdot 10^{-8}$
Josephson frequency ratio	$2e/h$	483.597 870(11) THz/V	$2.2 \cdot 10^{-8}$
Von Klitzing constant	$h/e^2 = \mu_0 c/2\alpha$	25 812.807 4434(84) Ω	$3.2 \cdot 10^{-10}$
Bohr magneton	$\mu_B = e\hbar/2m_e$	9.274 009 68(20) yJ/T	$2.2 \cdot 10^{-8}$
Classical electron radius	$r_e = e^2/4\pi\varepsilon_0 m_e c^2$	2.817 940 3267(27) fm	$9.7 \cdot 10^{-10}$
Compton wavelength of the electron	$\lambda_C = h/m_e c$	2.426 310 2389(16) pm	$6.5 \cdot 10^{-10}$
	$\lambda\!\!\!^{-}_c = \hbar/m_e c = r_e/\alpha$	0.386 159 268 00(25) pm	$6.5 \cdot 10^{-10}$
Bohr radius [a]	$a_\infty = r_e/\alpha^2$	52.917 721 092(17) pm	$3.2 \cdot 10^{-10}$
Quantum of circulation	$h/2m_e$	$3.636\,947\,5520(24) \cdot 10^{-4}$ m^2/s	$6.5 \cdot 10^{-10}$
Specific positron charge	e/m_e	$1.758\,820\,088(39) \cdot 10^{11}$ C/kg	$2.2 \cdot 10^{-8}$
Cyclotron frequency of the electron	$f_c/B = e/2\pi m_e$	27.992 491 10(62) GHz/T	$2.2 \cdot 10^{-8}$
Electron magnetic moment	μ_e	$-9.284\,764\,30(21) \cdot 10^{-24}$ J/T	$2.2 \cdot 10^{-8}$
	μ_e/μ_B	−1.001 159 652 180 76(27)	$2.6 \cdot 10^{-13}$
	μ_e/μ_N	$-1.838\,281\,970\,90(75) \cdot 10^3$	$4.1 \cdot 10^{-10}$
Electron g-factor	g_e	−2.002 319 304 361 53(53)	$2.6 \cdot 10^{-13}$
Muon–electron mass ratio	m_μ/m_e	206.768 2843(52)	$2.5 \cdot 10^{-8}$
Muon magnetic moment	μ_μ	$-4.490\,448\,07(15) \cdot 10^{-26}$ J/T	$3.4 \cdot 10^{-8}$
muon g-factor	g_μ	−2.002 331 8418(13)	$6.3 \cdot 10^{-10}$
Proton–electron mass ratio	m_p/m_e	1 836.152 672 45(75)	$4.1 \cdot 10^{-10}$
Specific proton charge	e/m_p	$9.578\,833\,58(21) \cdot 10^7$ C/kg	$2.2 \cdot 10^{-8}$
Proton Compton wavelength	$\lambda_{C,p} = h/m_p c$	1.321 409 856 23(94) fm	$7.1 \cdot 10^{-10}$
Nuclear magneton	$\mu_N = e\hbar/2m_p$	$5.050\,783\,53(11) \cdot 10^{-27}$ J/T	$2.2 \cdot 10^{-8}$
Proton magnetic moment	μ_p	$1.410\,606\,743(33) \cdot 10^{-26}$ J/T	$2.4 \cdot 10^{-8}$
	μ_p/μ_B	$1.521\,032\,210(12) \cdot 10^{-3}$	$8.1 \cdot 10^{-9}$
	μ_p/μ_N	2.792 847 356(23)	$8.2 \cdot 10^{-9}$
Proton gyromagnetic ratio	$\gamma_p = 2\mu_p/\hbar$	$2.675\,222\,005(63) \cdot 10^8$ Hz/T	$2.4 \cdot 10^{-8}$
Proton g factor	g_p	5.585 694 713(46)	$8.2 \cdot 10^{-9}$
Neutron–electron mass ratio	m_n/m_e	1 838.683 6605(11)	$5.8 \cdot 10^{-10}$
Neutron–proton mass ratio	m_n/m_p	1.001 378 419 17(45)	$4.5 \cdot 10^{-10}$
Neutron Compton wavelength	$\lambda_{C,n} = h/m_n c$	1.319 590 9068(11) fm	$8.2 \cdot 10^{-10}$

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 30 (Continued) Basic physical constants.

Quantity	Symbol	Value in SI units	Uncert.[a]
Z boson mass	Z^0	91.1876(21) GeV/c^2	
Higgs mass	H	126(1) GeV/c^2	
Gluon mass	$g_{1...8}$	*c.* 0 MeV/c^2	
Composite particle masses			
Proton mass	m_p	$1.672\,621\,777(74) \cdot 10^{-27}$ kg	$4.4 \cdot 10^{-8}$
		1.007 276 466 812(90) u	$8.9 \cdot 10^{-11}$
		938.272 046(21) MeV	$2.2 \cdot 10^{-8}$
Neutron mass	m_n	$1.674\,927\,351(74) \cdot 10^{-27}$ kg	$4.4 \cdot 10^{-8}$
		1.008 664 916 00(43) u	$4.2 \cdot 10^{-10}$
		939.565 379(21) MeV	$2.2 \cdot 10^{-8}$
Atomic mass unit	$m_u = m_{^{12}C}/12 = 1$ u	1.660 538 921(73) yg	$4.4 \cdot 10^{-8}$

a. Uncertainty: standard deviation of measurement errors.
b. Only measured from to 10^{-19} m to 10^{26} m.
c. Defining constant.
d. All coupling constants depend on the 4-momentum transfer, as explained in the section on renormalization. *Fine-structure constant* is the traditional name for the electromagnetic coupling constant g_{em} in the case of a 4-momentum transfer of $Q^2 = m_e^2c^2$, which is the smallest one possible. At higher momentum transfers it has larger values, e.g., $g_{em}(Q^2 = M_W^2c^2) \approx 1/128$. In contrast, the strong coupling constant has lover values at higher momentum transfers; e.g., $\alpha_s(34\,\text{GeV}) = 0.14(2)$.

Page 131

Why do all these constants have the values they have? For any constant *with a dimension*, such as the quantum of action $\hbar$, the numerical value has only historical meaning. It is $1.054 \cdot 10^{-34}$ Js because of the SI definition of the joule and the second. The question why the value of a dimensional constant is not larger or smaller therefore always requires one to understand the origin of some dimensionless number giving the ratio between the constant and the corresponding *natural unit* that is defined with c, G, $\hbar$ and α. More details and the values of the natural units were given earlier on. Understanding the sizes of atoms, people, trees and stars, the duration of molecular and atomic processes, or the mass of nuclei and mountains, implies understanding the ratios between these values and the corresponding natural units. The key to understanding nature is thus the understanding of all ratios, and thus of all dimensionless constants. The quest of understanding all ratios, including the fine structure constant α itself, is completed only in the final volume of our adventure.

Page 328

The basic constants yield the following useful high-precision observations.

TABLE 31 Derived physical constants.

Quantity	Symbol	Value in SI units	Uncert.
Vacuum wave resistance	$Z_0 = \sqrt{\mu_0/\varepsilon_0}$	376.730 313 461 77... Ω	0
Avogadro's number	N_A	$6.022\,141\,29(27) \cdot 10^{23}$	$4.4 \cdot 10^{-8}$

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 9 A selection of lamps and lasers (continued).

Lamp type, application	Wavelength	Brightness or power	Cost	Lifetime
Semiconductor lasers				
GaN laser diode, for optical recording	355 to 500 nm, depending on doping	up to 150 mW	a few Euro to 5 kEuro	*c.* 10 000 h
AlGaAs laser diode, for optical recording, pointers, data communication, laser fences, bar code readers (normal or vertical cavity)	620 to 900 nm, depending on doping	up to 1 W	below 1 Euro to 100 Euro	*c.* 10 000 h
InGaAsP laser diode, for fiberoptic communication, laser pumping, material processing, medial uses (normal and vertical cavity or VCSEL)	1 to 2.5 µm	up to 100 W	below 1 Euro up to a few k Euro	up to 20 000 h
Lead salt (PbS/PbSe) laser diode, for spectroscopy and gas detection	3 to 25 µm	0.1 W	a few 100 Euro	
Quantum cascade laser, for research and spectroscopy	2.7 to 350 µm	up to 4 W	*c.* 10 kEuro	*c.* 1 000 h
Hybrid silicon lasers, for research	IR	nW	0.1 MEuro	
Free electron lasers				
Used for materials science	5 nm to 1 mm	CW 20 kW, pulsed in GW range	10 MEuro	years
Nuclear-reaction pumped lasers				
Have uses only in science fiction and for getting money from gullible military				

From lamps to lasers

Most solid state lamps are light emitting diodes. The large progress in brightness of light emitting diodes could lead to a drastic reduction in future energy consumption, if their cost is lowered sufficiently. Many engineers are working on this task. Since the cost is a good estimate for the energy needed for production, can you estimate which lamp is the most friendly to the environment?

Challenge 61 s

Nobody thought much about lamps, until Albert Einstein and a few other great physicists came along, such as Theodore Maiman and Hermann Haken. Many other researchers later received Nobel Prizes by building on their work. In 1916, Einstein showed that there are two types of sources of light – or of electromagnetic radiation in general – both of which actually 'create' light. He showed that every lamp whose brightness is turned up high enough will change behaviour when a certain intensity threshold is passed. The

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

main mechanism of light emission then changes from spontaneous emission to *stimulated emission*. Nowadays such a special lamp is called a *laser*. (The letters 'se' in laser are an abbreviation of 'stimulated emission'.) After a passionate worldwide research race, in 1960 Maiman was the first to build a laser emitting visible light. (So-called *masers* emitting microwaves were already known for several decades.) In summary, Einstein and the other physicists showed that whenever a lamp is sufficiently turned up, it becomes a laser. Lasers consist of some light producing and amplifying material together with a mechanism to pump energy into it. The material can be a gas, a liquid or a solid; the pumping process can use electrical current or light. Usually, the material is put between two mirrors, in order to improve the efficiency of the light production. Common lasers are semiconductor lasers (essentially strongly pumped LEDs or light emitting diodes), He–Ne lasers (strongly pumped neon lamps), liquid lasers (essentially strongly pumped fire flies) and ruby lasers (strongly pumped luminescent crystals). Most materials can be used to make lasers for fun, including water, beer and vodka.

Lasers produce radiation in the range from microwaves and extreme ultraviolet. They have the special property of emitting *coherent* light, usually in a collimated beam. Therefore lasers achieve much higher light intensities than lamps, allowing their use as tools. In modern lasers, the coherence length, i.e., the length over which interference can be observed, can be thousands of kilometres. Such high quality light is used e.g. in gravitational wave detectors.

People have become pretty good at building lasers. Lasers are used to cut metal sheets up to 10 cm thickness, others are used instead of knives in surgery, others increase surface hardness of metals or clean stones from car exhaust pollution. Other lasers drill holes in teeth, measure distances, image biological tissue or grab living cells.

Some materials amplify light so much that end mirrors are not necessary. This is the case for nitrogen lasers, in which nitrogen, or simply air, is used to produce a UV beam. Even a laser made of a single atom (and two mirrors) has been built; in this example, only
Ref. 83 eleven photons on average were moving between the two mirrors. Quite a small lamp. Also lasers emitting light in two dimensions have been built. They produce a light plane instead of a light beam.

The three lightbulb scams

In the 1990s, all major light bulb producers in the world were fined large sums because they had agreed to keep the lifetimes of light bulbs constant. It is no technical problem to make light bulbs that last 2000 hours; however, the producers agreed not to increase the lifetime above 700 hours, thus effectively making every lightbulb three times as expensive as it should. This was the first world-wide light bulb scam.

Despite the fines, the crooks in the light bulb industry did not give up. In 2012, a large German light bulb maker explained in its advertising that its new light sources were much longer living than its conventional light bulbs, which, they explained on their ads, lasted only 500 hours. In other words, not only did the fines not help, the light bulb industry even *reduced* the lifetimes of the light bulbs from the 1990s to 2012. This was the second light bulb scam.

Parallel to the second scam, in the years around 2000, the light bulb industry started lobbying politics with the false statement that light bulbs were expensive and would

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 30 (Continued) Basic physical constants.

Quantity	Symbol	Value in SI units	Uncert.[a]
Gravitational constant	G	$6.673\,84(80)\cdot10^{-11}\,\mathrm{Nm^2/kg^2}$	$1.2\cdot10^{-4}$
Gravitational coupling constant	$\kappa = 8\pi G/c^4$	$2.076\,50(25)\cdot10^{-43}\,\mathrm{s^2/kg\,m}$	$1.2\cdot10^{-4}$
Fundamental constants (of unknown origin)			
Number of space-time dimensions		3 + 1	0[b]
Fine-structure constant[d] or	$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c}$	1/137.035 999 074(44)	$3.2\cdot10^{-10}$
e.m. coupling constant	$= g_{\mathrm{em}}(m_e^2c^2)$	= 0.007 297 352 5698(24)	$3.2\cdot10^{-10}$
Fermi coupling constant[d] or	$G_F/(\hbar c)^3$	$1.166\,364(5)\cdot10^{-5}\,\mathrm{GeV^{-2}}$	$4.3\cdot10^{-6}$
weak coupling constant	$\alpha_w(M_Z) = g_w^2/4\pi$	1/30.1(3)	$1\cdot10^{-2}$
Weak mixing angle	$\sin^2\theta_W(\overline{MS})$	0.231 24(24)	$1.0\cdot10^{-3}$
	$\sin^2\theta_W$ (on shell) $= 1-(m_W/m_Z)^2$	0.2224(19)	$8.7\cdot10^{-3}$
Strong coupling constant[d]	$\alpha_s(M_Z) = g_s^2/4\pi$	0.118(3)	$25\cdot10^{-3}$
CKM quark mixing matrix	$\lvert V\rvert$	$\begin{pmatrix} 0.97428(15) & 0.2253(7) & 0.00347(16) \\ 0.2252(7) & 0.97345(16) & 0.0410(11) \\ 0.00862(26) & 0.0403(11) & 0.999152(45) \end{pmatrix}$	
Jarlskog invariant	J	$2.96(20)\cdot10^{-5}$	
PMNS neutrino mixing m.	P	$\begin{pmatrix} 0.82 & 0.55 & -0.15+0.038i \\ -0.36+0.020i & 0.70+0.013i & 0.61 \\ 0.44+0.026i & -0.45+0.017i & 0.77 \end{pmatrix}$	
Elementary particle masses (of unknown origin)			
Electron mass	m_e	$9.109\,382\,91(40)\cdot10^{-31}\,\mathrm{kg}$	$4.4\cdot10^{-8}$
		$5.485\,799\,0946(22)\cdot10^{-4}\,\mathrm{u}$	$4.0\cdot10^{-10}$
		0.510 998 928(11) MeV	$2.2\cdot10^{-8}$
Muon mass	m_μ	$1.883\,531\,475(96)\cdot10^{-28}\,\mathrm{kg}$	$5.1\cdot10^{-8}$
		0.113 428 9267(29) u	$2.5\cdot10^{-8}$
		105.658 3715(35) MeV	$3.4\cdot10^{-8}$
Tau mass	m_τ	$1.776\,82(16)\,\mathrm{GeV/c^2}$	
El. neutrino mass	m_{ν_e}	$< 2\,\mathrm{eV/c^2}$	
Muon neutrino mass	m_{ν_e}	$< 2\,\mathrm{eV/c^2}$	
Tau neutrino mass	m_{ν_e}	$< 2\,\mathrm{eV/c^2}$	
Up quark mass	u	1.8 to 3.0 MeV/c^2	
Down quark mass	d	4.5 to 5.5 MeV/c^2	
Strange quark mass	s	95(5) MeV/c^2	
Charm quark mass	c	1.275(25) GeV/c^2	
Bottom quark mass	b	4.18(17) GeV/c^2	
Top quark mass	t	173.5(1.4) GeV/c^2	
Photon mass	γ	$< 2\cdot10^{-54}\,\mathrm{kg}$	
W boson mass	$W^\pm$	80.385(15) GeV/c^2	

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Limits to precision

What are the limits to accuracy and precision? There is no way, even in principle, to measure a length x to a *precision* higher than about 61 digits, because in nature, the ratio between the largest and the smallest measurable length is $\Delta x/x > l_{\mathrm{Pl}}/d_{\mathrm{horizon}} = 10^{-61}$. (Is this ratio valid also for force or for volume?) In the final volume of our text, studies of clocks and metre bars strengthen this theoretical limit.

Challenge 191 e

Vol. VI, page 93

But it is not difficult to deduce more stringent practical limits. No imaginable machine can measure quantities with a higher precision than measuring the diameter of the Earth within the smallest length ever measured, about 10^{-19} m; that is about 26 digits of precision. Using a more realistic limit of a 1000 m sized machine implies a limit of 22 digits. If, as predicted above, time measurements really achieve 17 digits of precision, then they are nearing the practical limit, because apart from size, there is an additional practical restriction: cost. Indeed, an additional digit in measurement precision often means an additional digit in equipment cost.

Physical constants

In physics, general observations are deduced from more fundamental ones. As a consequence, many measurements can be deduced from more fundamental ones. The most fundamental measurements are those of the physical constants.

The following tables give the world's best values of the most important physical constants and particle properties – in SI units and in a few other common units – as published in the standard references. The values are the world averages of the best measurements made up to the present. As usual, experimental errors, including both random and estimated systematic errors, are expressed by giving the standard deviation in the last digits. In fact, behind each of the numbers in the following tables there is a long story which is worth telling, but for which there is not enough room here.

Ref. 286

Ref. 287

In principle, all quantitative properties of matter can be calculated with quantum theory and the values of certain physical constants. For example, colour, density and elastic properties can be predicted using the equations of the standard model of particle physics and the values of the following basic constants.

Ref. 286

Page 261

TABLE 30 Basic physical constants.

Quantity	Symbol	Value in SI units	Uncert.[a]
Constants that define the SI measurement units			
Vacuum speed of light[c]	c	299 792 458 m/s	0
Vacuum permeability[c]	μ_0	$4\pi \cdot 10^{-7}$ H/m	0
		= 1.256 637 061 435 ... μH/m	0
Vacuum permittivity[c]	$\varepsilon_0 = 1/\mu_0 c^2$	8.854 187 817 620 ... pF/m	0
Original Planck constant	h	$6.626\,069\,57(52) \cdot 10^{-34}$ Js	$4.4 \cdot 10^{-8}$
Reduced Planck constant, quantum of action	$\hbar$	$1.054\,571\,726(47) \cdot 10^{-34}$ Js	$4.4 \cdot 10^{-8}$
Positron charge	e	0.160 217 656 5(35) aC	$2.2 \cdot 10^{-8}$
Boltzmann constant	k	$1.380\,6488(13) \cdot 10^{-23}$ J/K	$9.1 \cdot 10^{-7}$

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

waste energy. As a result of the false data provided from the other two scams, light bulbs were forbidden in Europe, with the result that consumers in Europe are now forced to buy other, much more expensive means of illumination. On top of this, many of these more expensive light sources are bad for the eyes. Indeed, flickering mercury or flickering LED lamps, together with their reduced colour spectrum, force the human visual system in overload mode, a situation that does not occur with the constantly glowing light bulbs. In other words, with this third scam, the light bulb industry increased their profits even more, while ruining the health of consumers at the same time. One day, maybe, parliaments will be less corrupt and more sensible. The situation will then again improve.

Applications of lasers

As shown in Figure 74, lasers can be used to make beautiful parts – including good violins and personalized bicycle parts – via sintering of polymer or metal powders. Lasers are used in rapid prototyping machines and to build architectural models. Lasers can cut paper, metal, plastics and flesh.

Lasers are used to read out data from compact discs (CDs) and digital versatile discs (DVDs), are used in the production of silicon integrated circuits and for the transport telephone signals through optical fibres. In our adventure, we already encountered lasers that work as loudspeakers. Important advances in recent years came from the applications of *femtosecond laser* pulses. Femtosecond pulses generate high-temperature plasmas in the materials they propagate through; this happens even in air, if the pulses are focused. The effect has been used to create luminous three-dimensional displays floating in mid-air, as shown in Figure 74, or in liquids. Such short pulses can also be used to cut material without heating it, for example to cut bones in skull operations. The lack of heating is so complete that femtosecond lasers can be used to engrave matches and even dynamite without triggering a reaction. Femtosecond lasers have been used to make high resolution holograms of human heads within a single flash. Recently such lasers have been used to guide lightning along a predetermined path; they seem promising candidates for laser ligtning rods. A curious demonstration application of femtosecond lasers is the storage of information in fingernails (up to 5 Mbit for a few months), in a way not unlike that used in recordable compact discs (CD-R).

Vol. I, page 406

Ref. 84

Ref. 85

Lasers are used in ophthalmology, with a technique called *optical coherence tomography*, to diagnose eye and heart illnesses. Around 2025, there will finally be laser-based breast screening devices that use laser light to search for cancer without any danger to the patient. The race to produce the first working system is already ongoing since the 1990s. Additional medical laser applications will appear in the coming years.

Lasers have been used in recent demonstrations, together with image processing software, to kill mosquitos in flight; other lasers are burning weeds while the laser is moved over a field of crops. One day, such combined laser and vision systems will be used to evaporate falling rain drops one by one; as soon as the first such *laser umbrella* will be available, it will be presented here. The feat should be possible before the year 2022.

Ref. 86

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

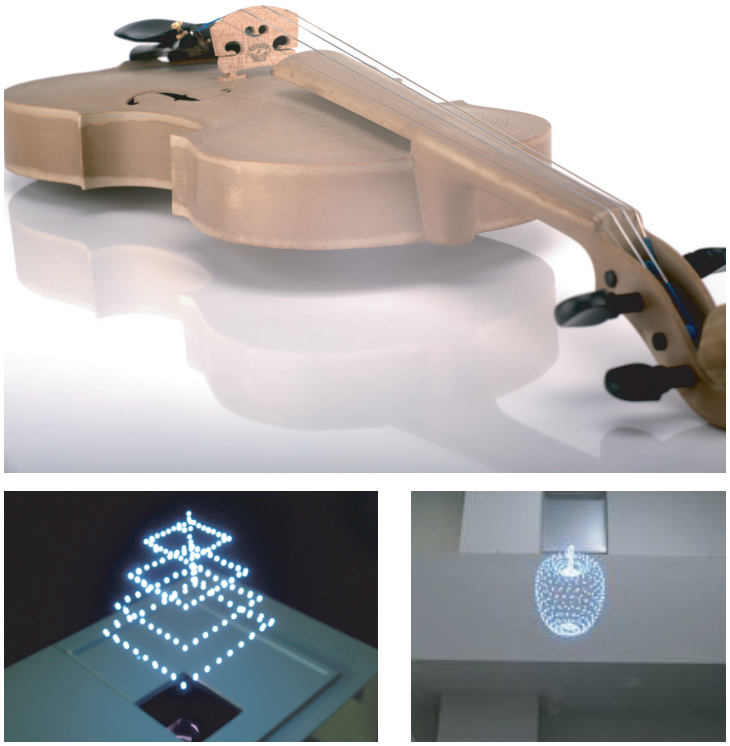


FIGURE 74 Some laser applications. Top: a violin, with excellent sound quality, made of a single piece of polymer (except for the chords and the black parts) through laser sintering of PEEK by EOS from Krailling, in Germany. Bottom: a display floating in mid-air produced with a galvanometer scanner and a fast focus shifter (© Franz Aichinger, Burton).

Challenges, dreams and curiosities about quantum technology

Nowadays, we carry many electronic devices in our jacket or trousers. Almost all use batteries. In the future, there is a high chance that some of these devices will extract energy from the human body. There are several options. One can extract thermal energy with thermoelements, or one can extract vibrational energy with piezoelectric, electrostatic or electromagnetic transducers. The challenge is to make these elements small and cheap. It will be interesting to find out which technology will arrive to the market first.

* *

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

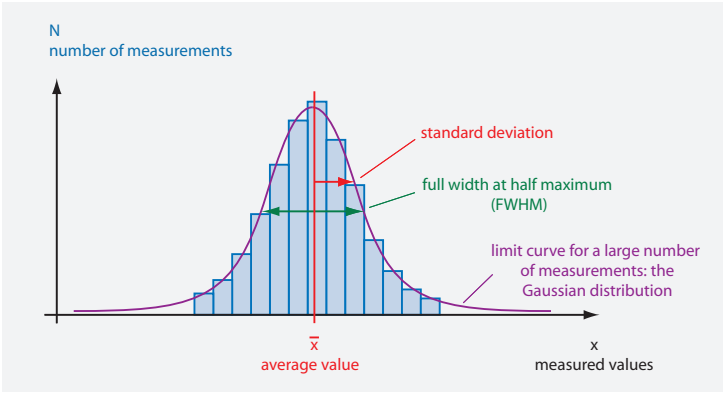


FIGURE 182 A precision experiment and its measurement distribution. The precision is high if the width of the distribution is narrow; the accuracy is high if the centre of the distribution agrees with the actual value.

Lack of accuracy is due to *systematic errors*; usually these can only be estimated. This estimate is often added to the random errors to produce a *total experimental error*, sometimes also called *total uncertainty*. The *relative* error or uncertainty is the ratio between the error and the measured value.

Ref. 285

For example, a professional measurement will give a result such as 0.312(6) m. The number between the parentheses is the standard deviation σ, in units of the last digits. As above, a Gaussian distribution for the measurement results is assumed. Therefore, a value of 0.312(6) m implies that the actual value is expected to lie

Challenge 190 e

- within 1σ with 68.3 % probability, thus in this example within 0.312 ± 0.006 m;
- within 2σ with 95.4 % probability, thus in this example within 0.312 ± 0.012 m;
- within 3σ with 99.73 % probability, thus in this example within 0.312 ± 0.018 m;
- within 4σ with 99.9937 % probability, thus in this example within 0.312 ± 0.024 m;
- within 5σ with 99.999 943 % probability, thus in this example within 0.312 ± 0.030 m;
- within 6σ with 99.999 999 80 % probability, thus within 0.312 ± 0.036 m;
- within 7σ with 99.999 999 999 74 % probability, thus within 0.312 ± 0.041 m.

However, these numbers are much too precise and should be taken with a grain of salt.

Note that standard deviations have one digit; you must be a world expert to use two, and a fool to use more. If no standard deviation is given, a (1) is assumed. As a result, among professionals, 1 km and 1000 m are *not* the same length!

What happens to the errors when two measured values A and B are added or subtracted? If the all measurements are independent – or uncorrelated – the standard deviation of the sum *and* that of difference is given by $\sigma = \sqrt{\sigma_A^2 + \sigma_B^2}$. For both the product or ratio of two measured and uncorrelated values C and D, the result is $\rho = \sqrt{\rho_C^2 + \rho_D^2}$, where the ρ terms are the *relative* standard deviations.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

between 1 ms for optical clocks and 5000 s for masers. Pulsars are the only type of clock for which this region is not known yet; it certainly lies at more than 20 years, the time elapsed at the time of writing since their discovery.

* *

The shortest times measured are the lifetimes of certain 'elementary' particles. In particular, the lifetime of certain D mesons have been measured at less than 10^{-23} s. Such times are measured using a bubble chamber, where the track is photographed. Can you estimate how long the track is? (This is a trick question – if your length cannot be observed with an optical microscope, you have made a mistake in your calculation.)

Ref. 283

Challenge 187 s

* *

The longest times encountered in nature are the lifetimes of certain radioisotopes, over 10^{15} years, and the lower limit of certain proton decays, over 10^{32} years. These times are thus much larger than the age of the universe, estimated to be fourteen thousand million years.

Ref. 284

* *

There is a unit for the spicy heat of chili peppers, officially called the *pungency*. The pungency is due to an organic compound called *capsaicin*. If you multiply by 16 the capsaicin concentration in parts per million, you get the *Scoville heat unit* for chili peppers. A few extreme chili varieties exceed the value of 2 million Scoville units.

Precision and accuracy of measurements

Measurements are the basis of physics. Every measurement has an *error*. Errors are due to lack of precision or to lack of accuracy. *Precision* means how well a result is reproduced when the measurement is repeated; *accuracy* is the degree to which a measurement corresponds to the actual value.

Lack of precision is due to accidental or *random errors*; they are best measured by the *standard deviation*, usually abbreviated σ; it is defined through

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2 \,, \tag{137}$$

where $\bar{x}$ is the average of the measurements x_i. (Can you imagine why $n-1$ is used in the formula instead of n?)

Challenge 188 s

For most experiments, the distribution of measurement values tends towards a normal distribution, also called *Gaussian distribution*, whenever the number of measurements is increased. The distribution, shown in Figure 182, is described by the expression

$$N(x) \approx \mathrm{e}^{-\frac{(x-\bar{x})^2}{2\sigma^2}} \,. \tag{138}$$

The square σ^2 of the standard deviation is also called the *variance*. For a Gaussian distribution of measurement values, 2.35σ is the full width at half maximum.

Challenge 189 e

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

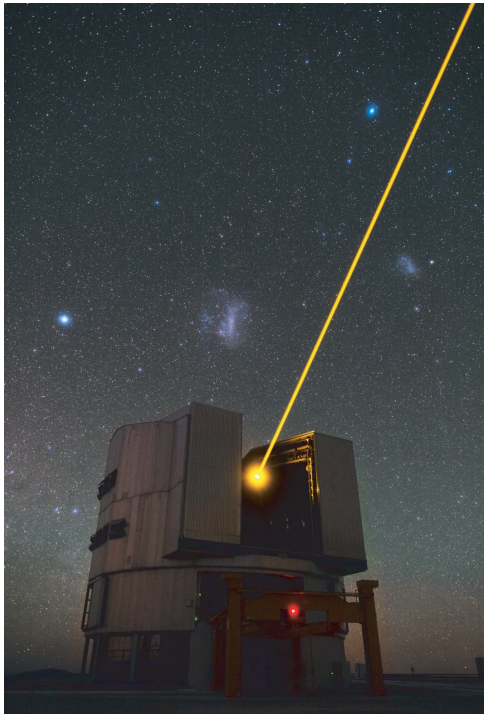


FIGURE 75 The most expensive laser pointer: a yellow 10 W laser that is frequency-stabilized at the wavelength of sodium lamps allows astronomers to improve the image quality of terrestrial telescopes. By exciting sodium atoms found at a height of 80 to 90 km, the laser provides an artificial guide star that is used to compensate for atmospheric turbulence, using the adaptive optics built into the telescope. (© ESO/Babak Tafreshi).

In 2007, Humphrey Maris and his student Wei Guo performed an astonishing experiment: they filmed *single electrons* with a video camera. Actually the truth is a bit more complicated, but it is not a lie to summarize it in this way.

Ref. 87

Maris is an expert on superfluid helium. For many years he knew that free electrons in superfluid helium repel helium atoms, and can move, surrounded by a small vacuum bubble, about 2 nm across, through the fluid. He also discovered that under negative pressure, these bubbles can grow and finally explode. When they explode, they are able to scatter light. With his student Wei Guo, he then injected electrons into superfluid helium through a tungsten needle under negative voltage, produced negative pressure by focussing waves from two piezoelectric transducers in the bulk of the helium, and

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

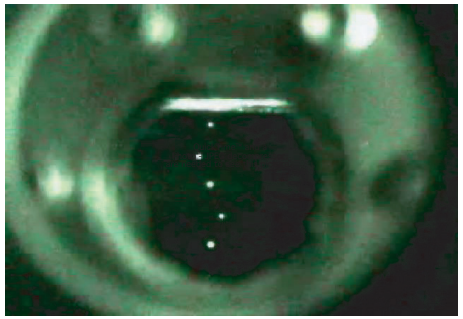


FIGURE 76 How to image single electrons with a video camera: isolated electrons surrounded by bubbles that explode in liquid helium under negative pressure produce white spots (mpg film © Humphrey Maris).

shone light through the helium. When the pressure became negative enough they saw the explosions of the bubbles. Figure 76 shows the video. The experiment is one of the highlights of experimental physics in the last decade.

* *

Challenge 62 d Is it possible to make A4-size flexible colour displays for an affordable price and with print-like quality?

* *

Will there ever be rechargeable batteries with an energy content per mass that is comparable to diesel oil? How long will it take, from 2014 onwards, until the last company producing electric cars powered by batteries stops production?

* *

How many companies promising free energy, engineers promising cars powered by water, politicians promising fusion energy or quacks promising food additives or sugar pills that cure cancer will we see every year?

* *

Challenge 63 r Will there ever be room-temperature superconductivity?

* *

Challenge 64 r Will there ever be desktop laser engravers for 1000 euro?

* *

Challenge 65 s Will there ever be teleportation of everyday objects?

* *

One process that quantum physics does not allow is telephathy. An unnamed space

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

would be a better name). Therefore one has $1\,\mathrm{eV} = 1.6 \cdot 10^{-19}\,\mathrm{J}$, or roughly

$$1\,\mathrm{eV} \approx \tfrac{1}{6}\,\mathrm{aJ} \tag{136}$$

which is easily remembered. The simplification $c = \hbar = 1$ yields $G = 6.9 \cdot 10^{-57}\,\mathrm{eV}^{-2}$ and allows one to use the unit eV also for mass, momentum, temperature, frequency, time and length, with the respective correspondences $1\,\mathrm{eV} \equiv 1.8 \cdot 10^{-36}\,\mathrm{kg} \equiv 5.4 \cdot 10^{-28}\,\mathrm{Ns} \equiv 242\,\mathrm{THz} \equiv 11.6\,\mathrm{kK}$ and $1\,\mathrm{eV}^{-1} \equiv 4.1\,\mathrm{fs} \equiv 1.2\,\mu\mathrm{m}$.

Challenge 186 e

To get some feeling for the unit eV, the following relations are useful. Room temperature, usually taken as 20 °C or 293 K, corresponds to a kinetic energy per particle of 0.025 eV or 4.0 zJ. The highest particle energy measured so far belongs to a cosmic ray with an energy of $3 \cdot 10^{20}$ eV or 48 J. Down here on the Earth, an accelerator able to produce an energy of about 105 GeV or 17 nJ for electrons and antielectrons has been built, and one able to produce an energy of 14 TeV or 2.2 μJ for protons will be finished soon. Both are owned by CERN in Geneva and have a circumference of 27 km.

Ref. 277

The lowest temperature measured up to now is 280 pK, in a system of rhodium nuclei held inside a special cooling system. The interior of that cryostat may even be the coolest point in the whole universe. The kinetic energy per particle corresponding to that temperature is also the smallest ever measured: it corresponds to 24 feV or $3.8\,\mathrm{vJ} = 3.8 \cdot 10^{-33}$ J. For isolated particles, the record seems to be for neutrons: kinetic energies as low as 10^{-7} eV have been achieved, corresponding to de Broglie wavelengths of 60 nm.

Ref. 278

Curiosities and fun challenges about units

The Planck length is roughly the de Broglie wavelength $\lambda_B = h/mv$ of a man walking comfortably ($m = 80\,\mathrm{kg}$, $v = 0.5\,\mathrm{m/s}$); this motion is therefore aptly called the 'Planck stroll.'

Ref. 279

* *

The Planck mass is equal to the mass of about 10^{19} protons. This is roughly the mass of a human embryo at about ten days of age.

* *

The most precisely measured quantities in nature are the frequencies of certain millisecond pulsars, the frequency of certain narrow atomic transitions, and the Rydberg constant of *atomic* hydrogen, which can all be measured as precisely as the second is defined. The caesium transition that defines the second has a finite line width that limits the achievable precision: the limit is about 14 digits.

Ref. 280

* *

The most precise clock ever built, using microwaves, had a stability of 10^{-16} during a running time of 500 s. For longer time periods, the record in 1997 was about 10^{-15}; but values around 10^{-17} seem within technological reach. The precision of clocks is limited for short measuring times by noise, and for long measuring times by drifts, i.e., by systematic effects. The region of highest stability depends on the clock type; it usually lies

Ref. 281

Ref. 282

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

The natural units are important for another reason: whenever a quantity is sloppily called 'infinitely small (or large)', the correct expression is 'as small (or as large) as the corresponding corrected Planck unit'. As explained throughout the text, and especially in the final part, this substitution is possible because almost all Planck units provide, within a correction factor of order 1, the extremal value for the corresponding observable – some an upper and some a lower limit. Unfortunately, these correction factors are not yet widely known. The exact extremal value for each observable in nature is obtained when G is substituted by $4G$ and $4\pi\varepsilon_0$ by $4\pi\varepsilon_0\alpha$ in all Planck quantities. These extremal values, or *corrected Planck units*, are the *true natural units*. To exceed the extremal values is possible only for some extensive quantities. (Can you find out which ones?)

Vol. VI, page 36

Challenge 185 s

Other unit systems

A central aim of research in high-energy physics is the calculation of the strengths of all interactions; therefore it is not practical to set the gravitational constant G to unity, as in the Planck system of units. For this reason, high-energy physicists often only set $c = \hbar = k = 1$ and $\mu_0 = 1/\varepsilon_0 = 4\pi$,* leaving only the gravitational constant G in the equations.

In this system, only one fundamental unit exists, but its choice is free. Often a standard length is chosen as the fundamental unit, length being the archetype of a measured quantity. The most important physical observables are then related by

$$\begin{aligned} 1/[l^2] &= [E]^2 = [F] = [B] = [E_{\text{electric}}]\,, \\ 1/[l] &= [E] = [m] = [p] = [a] = [f] = [I] = [U] = [T]\,, \\ 1 &= [v] = [q] = [e] = [R] = [S_{\text{action}}] = [S_{\text{entropy}}] = \hbar = c = k = [\alpha]\,, \\ [l] &= 1/[E] = [t] = [C] = [L] \quad \text{and} \\ [l]^2 &= 1/[E]^2 = [G] = [P] \end{aligned} \tag{135}$$

where we write $[x]$ for the unit of quantity x. Using the same unit for time, capacitance and inductance is not to everybody's taste, however, and therefore electricians do not use this system.**

Often, in order to get an impression of the energies needed to observe an effect under study, a standard energy is chosen as fundamental unit. In particle physics the most common energy unit is the *electronvolt* (eV), defined as the kinetic energy acquired by an electron when accelerated by an electrical potential difference of 1 volt ('protonvolt'

* Other definitions for the proportionality constants in electrodynamics lead to the Gaussian unit system often used in theoretical calculations, the Heaviside–Lorentz unit system, the electrostatic unit system, and the electromagnetic unit system, among others.

Ref. 276

** In the list, l is length, E energy, F force, E_{electric} the electric and B the magnetic field, m mass, p momentum, a acceleration, f frequency, I electric current, U voltage, T temperature, v speed, q charge, R resistance, P power, G the gravitational constant.

The web page www.chemie.fu-berlin.de/chemistry/general/units_en.html provides a tool to convert various units into each other.

Researchers in general relativity often use another system, in which the *Schwarzschild radius* $r_S = 2Gm/c^2$ is used to measure masses, by setting $c = G = 1$. In this case, mass and length have the *same* dimension, and $\hbar$ has the dimension of an area.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 77 The interior of a gyroscope that uses superfluid helium (© Eric Varoquaux).

agency found this out during the Apollo 14 mission, when, during the flight to the moon, cosmonaut Edgar Mitchell tested telepathy as communication means. Unsurprisingly, he found that telepathy was useless. It is unclear why the space agency spent so much money for a useless experiment – an experiment that could have been performed, at a cost of a phone call, also down here on earth.

Ref. 88

* *

Will there ever be applied quantum cryptology?

Challenge 66 d

* *

Will there ever be printable polymer electronic circuits, instead of lithographically patterned silicon electronics as is common now?

Challenge 67 d

* *

Will there ever be radio-controlled flying toys in the size of insects?

Challenge 68 r

* *

By shining an invisible and harmless laser onto cars driving by, it is now possible to

Ref. 107

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 78 These colours were produced on steel using just an infrared laser shining on it. (© Trotec Laser at www.troteclaser.com)

detect whether the persons inside have drunk alcohol. Will this method ever become widespread? Challenge 69 s

* *

In 1997, Eric Varoquaux and his group built a quantum version of the Foucault pendulum, using the superfluidity of helium. In this beautiful piece of research, they cooled a small ring of fluid helium below the temperature of 0.28 K, below which the helium moves without friction. In such situations helium can behave like a Foucault pendulum. With a clever arrangement, shown in Figure 77, they were able to measure the rotation of the helium in the ring using phonon signals, and, finally, to detect the rotation of the Earth. Ref. 108

* *

Lasers are quantum devices that can be used for many applications. Figure 78 shows a way to produce colours on steel by scanning a focused infrared laser beam over the surface. Why and how do the colours appear? Challenge 70 e

Summary on changing the world with quantum effects

Atoms form bonds. Quantum effects thus produce molecules, gases, liquids and solids, as well as all effects and properties of all materials. In the past, quantum effects have been used to develop numerous materials with desired properties, such as new steel types, new carbon fibre composites, new colourants, new magnetic materials and new polymers.

Quantum effects have been used to develop modern electronics, lasers, light detectors, data storage devices, superconducting magnets, new measurement systems and new production machines. Magnetic resonance imaging, computers, polymers, telecommunication and the internet resulted from applying quantum effects to technology.

Quantum effects will continue to be used to design new materials and systems: new nanoparticles to deliver drugs inside the body, new polymers, new crystals, new environmentally friendly production processes and new medical devices, among others.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

of fundamental constants; those corresponding to the fundamental SI units are given in Table 29.* The table is also useful for converting equations written in natural units back to SI units: just substitute every quantity X by X/X_{Pl}. Challenge 184 e

TABLE 29 Planck's (uncorrected) natural units.

Name	Definition				Value
Basic units					
the Planck length	l_{Pl}	=	$\sqrt{\hbar G/c^3}$	=	$1.616\,0(12) \cdot 10^{-35}$ m
the Planck time	t_{Pl}	=	$\sqrt{\hbar G/c^5}$	=	$5.390\,6(40) \cdot 10^{-44}$ s
the Planck mass	m_{Pl}	=	$\sqrt{\hbar c/G}$	=	21.767(16) µg
the Planck current	I_{Pl}	=	$\sqrt{4\pi\varepsilon_0 c^6/G}$	=	$3.479\,3(22) \cdot 10^{25}$ A
the Planck temperature	T_{Pl}	=	$\sqrt{\hbar c^5/Gk^2}$	=	$1.417\,1(91) \cdot 10^{32}$ K
Trivial units					
the Planck velocity	v_{Pl}	=	c	=	0.3 Gm/s
the Planck angular momentum	L_{Pl}	=	$\hbar$	=	$1.1 \cdot 10^{-34}$ Js
the Planck action	S_{aPl}	=	$\hbar$	=	$1.1 \cdot 10^{-34}$ Js
the Planck entropy	S_{ePl}	=	k	=	13.8 yJ/K
Composed units					
the Planck mass density	ρ_{Pl}	=	$c^5/G^2\hbar$	=	$5.2 \cdot 10^{96}$ kg/m^3
the Planck energy	E_{Pl}	=	$\sqrt{\hbar c^5/G}$	=	2.0 GJ = $1.2 \cdot 10^{28}$ eV
the Planck momentum	p_{Pl}	=	$\sqrt{\hbar c^3/G}$	=	6.5 Ns
the Planck power	P_{Pl}	=	c^5/G	=	$3.6 \cdot 10^{52}$ W
the Planck force	F_{Pl}	=	c^4/G	=	$1.2 \cdot 10^{44}$ N
the Planck pressure	p_{Pl}	=	$c^7/G\hbar$	=	$4.6 \cdot 10^{113}$ Pa
the Planck acceleration	a_{Pl}	=	$\sqrt{c^7/\hbar G}$	=	$5.6 \cdot 10^{51}$ m/s^2
the Planck frequency	f_{Pl}	=	$\sqrt{c^5/\hbar G}$	=	$1.9 \cdot 10^{43}$ Hz
the Planck electric charge	q_{Pl}	=	$\sqrt{4\pi\varepsilon_0 c\hbar}$	=	1.9 aC = 11.7 e
the Planck voltage	U_{Pl}	=	$\sqrt{c^4/4\pi\varepsilon_0 G}$	=	$1.0 \cdot 10^{27}$ V
the Planck resistance	R_{Pl}	=	$1/4\pi\varepsilon_0 c$	=	30.0 Ω
the Planck capacitance	C_{Pl}	=	$4\pi\varepsilon_0\sqrt{\hbar G/c^3}$	=	$1.8 \cdot 10^{-45}$ F
the Planck inductance	L_{Pl}	=	$(1/4\pi\varepsilon_0)\sqrt{\hbar G/c^7}$	=	$1.6 \cdot 10^{-42}$ H
the Planck electric field	E_{Pl}	=	$\sqrt{c^7/4\pi\varepsilon_0\hbar G^2}$	=	$6.5 \cdot 10^{61}$ V/m
the Planck magnetic flux density	B_{Pl}	=	$\sqrt{c^5/4\pi\varepsilon_0\hbar G^2}$	=	$2.2 \cdot 10^{53}$ T

* The natural units x_{Pl} given here are those commonly used today, i.e., those defined using the constant $\hbar$, and not, as Planck originally did, by using the constant $h = 2\pi\hbar$. The electromagnetic units can also be defined with other factors than $4\pi\varepsilon_0$ in the expressions: for example, using $4\pi\varepsilon_0\alpha$, with the *fine-structure constant* α, gives $q_{\mathrm{Pl}} = e$. For the explanation of the numbers between brackets, see below. Vol. IV, page 195

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

at home, in education and in research. They could even be used by extraterrestrial civilizations, if they existed.

- SI units form a *self-consistent* system: the product or quotient of two SI units is also an SI unit. This means that in principle, the same abbreviation, e.g. 'SI', could be used for every unit.

The SI units are not the only possible set that could fulfil all these requirements, but they are the only existing system that does so.* In the near future, the BIPM plans to redefine the SI units using the physics cube diagram shown in Figure 1. This will be realized by fixing, in addition to the values of c and K_{cd}, also the values of $\hbar$, e, k and N_A. The proposed values are $h = 6.626\,069\,57 \cdot 10^{-34}$ Js, $e = 1.602\,176\,565 \cdot 10^{-19}$ C, $k = 1.380\,648\,8 \cdot 10^{-23}$ J/K and $N_A = 6.022\,141\,29 \cdot 10^{23}$ 1/mol. The definition of the second will be retained, in order to avoid the low precision of all known measurements of G. The details of this future, new SI are presented on www.bipm.org/en/measurement-units/new-si/ and www.bipm.org/utils/common/pdf/si-brochure-draft-2016.pdf.

Page 8

The meaning of measurement

Every measurement is a comparison with a standard. Therefore, any measurement requires *matter* to realize the standard (even for a speed standard), and *radiation* to achieve the comparison. The concept of measurement thus assumes that matter and radiation exist and can be clearly separated from each other.

Challenge 183 e

Every measurement is a comparison. Measuring thus implies that space and time exist, and that they differ from each other.

Every measurement produces a measurement result. Therefore, every measurement implies the *storage* of the result. The process of measurement thus implies that the situation before and after the measurement can be distinguished. In other terms, every measurement is an *irreversible* process.

Every measurement is a process. Thus every measurement takes a certain amount of time and a certain amount of space.

All these properties of measurements are simple but important. Beware of anybody who denies them.

Planck's natural units

Since the exact form of many equations depends on the system of units used, theoretical physicists often use unit systems optimized for producing simple equations. The chosen units and the values of the constants of nature are related. In microscopic physics, the system of *Planck's natural units* is frequently used. They are defined by setting $c = 1$, $\hbar = 1$, $G = 1$, $k = 1$, $\varepsilon_0 = 1/4\pi$ and $\mu_0 = 4\pi$. Planck units are thus defined from combinations

* Apart from international units, there are also *provincial* units. Most provincial units still in use are of Roman origin. The mile comes from *milia passum*, which used to be one thousand (double) strides of about 1480 mm each; today a nautical mile, once defined as minute of arc on the Earth's surface, is defined as exactly 1852 m. The inch comes from *uncia*/*onzia* (a twelfth – now of a foot). The pound (from *pondere* 'to weigh') is used as a translation of *libra* – balance – which is the origin of its abbreviation lb. Even the habit of counting in dozens instead of tens is Roman in origin. These and all other similarly funny units – like the system in which all units start with 'f', and which uses furlong/fortnight as its unit of velocity – are now officially defined as multiples of SI units.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Chapter 3

QUANTUM ELECTRODYNAMICS – THE ORIGIN OF VIRTUAL REALITY

The central concept that quantum field theory adds to the description of nature is the idea of *virtual particles*. Virtual particles are short-lived particles; they owe their existence exclusively to the quantum of action. Because of the quantum of action, they do not need to follow the energy-mass relation that special relativity requires of usual, *real* particles. Virtual particles can move faster than light and can move backward in time. Despite these strange properties, they have many observable effects. We explore the most spectacular ones.

Ships, mirrors and the Casimir effect

When two parallel ships roll in a big swell, *without* even the slightest wind blowing, they will attract each other. The situation is illustrated in Figure 79. It might be that this effect was known before the nineteenth century, when many places still lacked harbours.**

Waves induce oscillations of ships because a ship absorbs energy from the waves. When oscillating, the ship also emits waves. This happens mainly towards the two sides of the ship. As a result, for a single ship, the wave emission has no net effect on its position. Now imagine that two parallel ships oscillate in a long swell, with a wavelength much larger than the distance between the ships. Due to the long wavelength, the two ships will oscillate in phase. The ships will thus not be able to absorb energy from each other. As a result, the energy they radiate towards the outside will push them towards each other.

The effect is not difficult to calculate. The energy of a rolling ship is

$$E = mgh\,\alpha^2/2 \tag{13}$$

where α is the roll angle amplitude, m the mass of the ship and $g = 9,8\,\mathrm{m/s^2}$ the acceleration due to gravity. The *metacentric height* h is the main parameter characterizing a ship, especially a sailing ship; it tells with what torque the ship returns to the vertical when inclined by an angle α. Typically, one has h =1.5 m.

When a ship is inclined, it will return to the vertical by a damped oscillation. A damped oscillation is characterized by a period T and a quality factor Q. The *quality factor* is the number of oscillations the system takes to reduce its amplitude by a factor

** Sipko Boersma published a paper in which he gave his reading of shipping manuals, advising captains to let the ships be pulled apart using a well-manned rowing boat. This reading has been put into question by subsequent research, however.

Ref. 89 Ref. 90

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Name	Abbreviation
hertz	Hz = 1/s
pascal	Pa = N/m^2 = kg/m s^2
watt	W = kg m^2/s^3
volt	V = kg m^2/As^3
ohm	Ω = V/A = kg m^2/A^{2}s^3
weber	Wb = Vs = kg m^2/As^2
henry	H = Vs/A = kg m^2/A^{2}s^2
lumen	lm = cd sr
becquerel	Bq = 1/s
sievert	Sv = J/kg = m^2/s^2

Name	Abbreviation
newton	N = kg m/s^2
joule	J = Nm = kg m^2/s^2
coulomb	C = As
farad	F = As/V = A^{2}s^4/kg m^2
siemens	S = 1/Ω
tesla	T = Wb/m^2 = kg/As^2 = kg/Cs
degree Celsius	°C (see definition of kelvin)
lux	lx = lm/m^2 = cd sr/m^2
gray	Gy = J/kg = m^2/s^2
katal	kat = mol/s

The *admitted* non-SI units are *minute*, *hour*, *day* (for time), *degree* $1° = \pi/180$ rad, *minute* $1' = \pi/10\,800$ rad, *second* $1'' = \pi/648\,000$ rad (for angles), *litre*, and *tonne*. All other units are to be avoided.

All SI units are made more practical by the introduction of standard names and abbreviations for the powers of ten, the so-called *prefixes*:*

Power	Name	
10^{1}	deca	da
10^{2}	hecto	h
10^{3}	kilo	k
10^{6}	Mega	M
10^{9}	Giga	G
10^{12}	Tera	T
10^{15}	Peta	P

Power	Name	
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f

Power	Name	
10^{18}	Exa	E
10^{21}	Zetta	Z
10^{24}	Yotta	Y
unofficial:		
10^{27}	Xenta	X
10^{30}	Wekta	W
10^{33}	Vendekta	V
10^{36}	Udekta	U

Power	Name	
10^{-18}	atto	a
10^{-21}	zepto	z
10^{-24}	yocto	y
Ref. 275		
10^{-27}	xenno	x
10^{-30}	weko	w
10^{-33}	vendeko	v
10^{-36}	udeko	u

- SI units form a *complete* system: they cover in a systematic way the full set of observables of physics. Moreover, they fix the units of measurement for all other sciences as well.
- SI units form a *universal* system: they can be used in trade, in industry, in commerce,

* Some of these names are invented (yocto to sound similar to Latin *octo* 'eight', zepto to sound similar to Latin *septem*, yotta and zetta to resemble them, exa and peta to sound like the Greek words ἑξάκις and πεντάκις for 'six times' and 'five times', the unofficial ones to sound similar to the Greek words for nine, ten, eleven and twelve); some are from Danish/Norwegian (atto from *atten* 'eighteen', femto from *femten* 'fifteen'); some are from Latin (from *mille* 'thousand', from *centum* 'hundred', from *decem* 'ten', from *nanus* 'dwarf'); some are from Italian (from *piccolo* 'small'); some are Greek (micro is from μικρός 'small', deca/deka from δέκα 'ten', hecto from ἑκατόν 'hundred', kilo from χίλιοι 'thousand', mega from μέγας 'large', giga from γίγας 'giant', tera from τέρας 'monster').

Translate: I was caught in such a traffic jam that I needed a microcentury for a picoparsec and that my car's fuel consumption was two tenths of a square millimetre.

Challenge 182 e

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

- 'The *candela* is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency $540 \cdot 10^{12}$ hertz and has a radiant intensity in that direction of (1/683) watt per steradian.' (1979)*

We note that both time and length units are defined as certain properties of a standard example of motion, namely light. In other words, also the Conférence Générale des Poids et Mesures makes the point that the observation of motion is a *prerequisite* for the definition and construction of time and space. *Motion is the fundament of every observation and of all measurement.* By the way, the use of light in the definitions had been proposed already in 1827 by Jacques Babinet.**

From these basic units, all other units are defined by multiplication and division. Thus, all SI units have the following properties:

- SI units form a system with *state-of-the-art precision*: all units are defined with a precision that is higher than the precision of commonly used measurements. Moreover, the precision of the definitions is regularly being improved. The present relative uncertainty of the definition of the second is around 10^{-14}, for the metre about 10^{-10}, for the kilogram about 10^{-9}, for the ampere 10^{-7}, for the mole less than 10^{-6}, for the kelvin 10^{-6} and for the candela 10^{-3}.
- SI units form an *absolute* system: all units are defined in such a way that they can be reproduced in every suitably equipped laboratory, independently, and with high precision. This avoids as much as possible any misuse by the standard-setting organization. (The kilogram, still defined with the help of an artefact, is the last exception to this requirement; extensive research is under way to eliminate this artefact from the definition – an international race that will take a few more years. There are two approaches: counting particles, or fixing $\hbar$. The former can be achieved in crystals, e.g., crystals made of pure silicon, the latter using any formula where $\hbar$ appears, such as the formula for the de Broglie wavelength or that of the Josephson effect.)
- SI units form a *practical* system: the base units are quantities of everyday magnitude. Frequently used units have standard names and abbreviations. The complete list includes the seven base units just given, the supplementary units, the derived units and the admitted units.

The *supplementary* SI units are two: the unit for (plane) angle, defined as the ratio of arc length to radius, is the *radian* (rad). For solid angle, defined as the ratio of the subtended area to the square of the radius, the unit is the *steradian* (sr).

The *derived* units with special names, in their official English spelling, i.e., without capital letters and accents, are:

Vol. I, page 100
Ref. 274

* The respective symbols are s, m, kg, A, K, mol and cd. The international prototype of the kilogram is a platinum–iridium cylinder kept at the BIPM in Sèvres, in France. For more details on the levels of the caesium atom, consult a book on atomic physics. The Celsius scale of temperature θ is defined as: $\theta/°C = T/K - 273.15$; note the small difference with the number appearing in the definition of the kelvin. SI also states: 'When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.' In the definition of the mole, it is understood that the carbon 12 atoms are unbound, at rest and in their ground state. In the definition of the candela, the frequency of the light corresponds to 555.5 nm, i.e., green colour, around the wavelength to which the eye is most sensitive.

** Jacques Babinet (b. 1794 Lusignan, d. 1874 Paris), physicist, published important work in optics.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

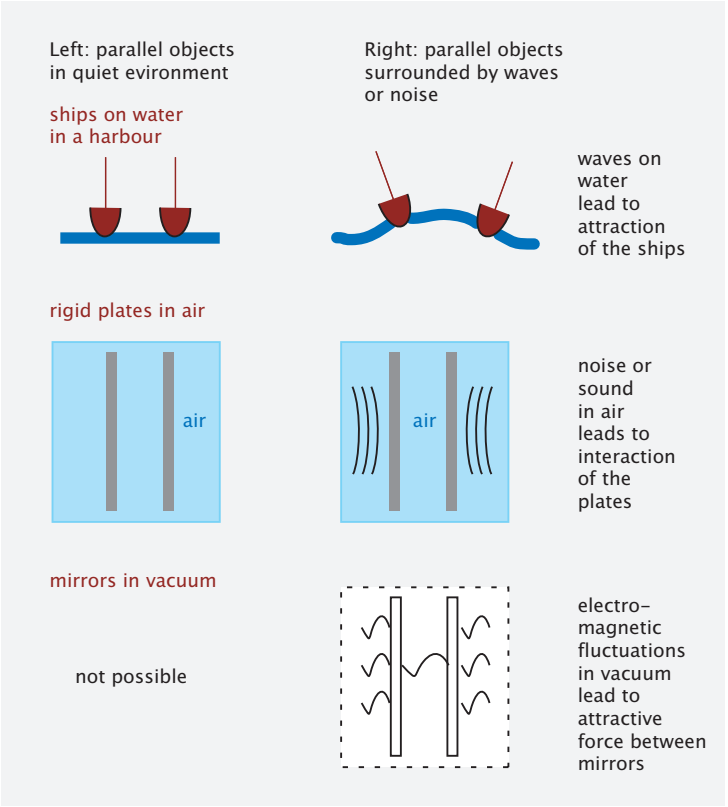


FIGURE 79 The analogy between ships in a harbour, metal plates in air and metal mirrors in vacuum.

$e = 2.718$. If the quality factor Q of an oscillating ship and its oscillation period T are given, the radiated power W is

$$W = 2\pi \frac{E}{QT} \,. \tag{14}$$

Vol. III, page 118
Vol. III, page 294

We saw above that radiation force (radiation pressure times area) is W/c, where c is the wave propagation velocity. For gravity water waves in deep water, we have the well-known relation

$$c = \frac{gT}{2\pi} \,. \tag{15}$$

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Assuming that for two nearby ships each one completely absorbs the power emitted from the other, we find that the two ships are attracted towards each other following

$$ma = m2\pi^2 \frac{h\alpha^2}{QT^2} \,. \tag{16}$$

Inserting typical values such as $Q = 2.5$, $T = 10\,\mathrm{s}$, $\alpha = 0.14\,\mathrm{rad}$ and a ship mass of 700 tons, we get about 1.9 kN. Long swells thus make ships attract each other. The strength of the attraction is comparatively small and could be overcome with a rowing boat. On the other hand, even the slightest wind will damp the oscillation amplitude and have other effects that will hide or overshadow this attraction.

Sound waves or noise in air show the same effect. It is sufficient to suspend two metal plates in air and surround them by loudspeakers. The sound will induce attraction (or repulsion) of the plates, depending on whether the sound wavelength cannot (or can) be taken up by the other plate. Ref. 91

In 1948, the Dutch physicist Hendrik Casimir made one of the most spectacular predictions of quantum theory: he predicted a similar effect for metal plates in vacuum. Casimir, who worked at the Dutch Electronics company Philips, wanted to understand why it was so difficult to build television tubes. The light-emitting surface in a cathode ray tube – or today, in a plasma display – of a television, the phosphor, is made by deposing small neutral, but conductive particles on glass. Casimir observed that the particles somehow attracted each other. Casimir got interested in understanding how neutral particles interact. During these theoretical studies he discovered that two neutral metal plates (or metal mirrors) would attract each other even in complete vacuum. This is the famous *Casimir effect*. Casimir also determined the attraction strength between a sphere and a plate, and between two spheres. In fact, all *conducting* neutral bodies attract each other in vacuum, with a force depending on their geometry. Ref. 92, Ref. 93

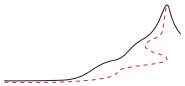
In all these situations, the role of the sea is taken by the zero-point fluctuations of the electromagnetic field, the role of the ships by the conducting bodies. Casimir understood that the space between two parallel conducting mirrors, due to the geometrical constraints, had different zero-point fluctuations than the free vacuum. Like in the case of two ships, the result would be the attraction of the two mirrors.

Casimir predicted that the attraction for two mirrors of mass m and surface Aat distance d is given by

$$\frac{ma}{A} = \frac{\pi^3}{120} \frac{\hbar c}{d^4} \,. \tag{17}$$

The effect is a pure quantum effect; in classical electrodynamics, two neutral bodies do not attract. The effect is small; it takes some dexterity to detect it. The first experimental confirmation was by Derjaguin, Abrikosova and Lifshitz in 1956; the second experimental confirmation was by Marcus Sparnaay, Casimir's colleague at Philips, in 1958. Two beautiful high-precision measurements of the Casimir effect were performed in 1997 by Lamoreaux and in 1998 by Mohideen and Roy; they confirmed Casimir's prediction with a precision of 5 % and 1 % respectively. (Note that at very small distances, the dependence is not $1/d^4$, but $1/d^3$.) In summary, uncharged bodies attract through electromagnetic field fluctuations. Ref. 94 Ref. 95 Ref. 96 Ref. 97

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



Appendix A

UNITS, MEASUREMENTS AND CONSTANTS

Measurements are comparisons with standards. Standards are based on *units*. many different systems of units have been used throughout the world. ost of these standards confer power to the organization in charge of them. Such power can be misused; this is the case today, for example in the computer industry, and was so in the distant past. The solution is the same in both cases: organize an independent and global standard. For measurement units, this happened in the eighteenth century: in order to avoid misuse by authoritarian institutions, to eliminate problems with differing, changing and irreproducible standards, and – this is not a joke – to simplify tax collection and to make it more just, a group of scientists, politicians and economists agreed on a set of units. It is called the *Système International d'Unités*, abbreviated *SI*, and is defined by an international treaty, the 'Convention du Mètre'. The units are maintained by an international organization, the 'Conférence Générale des Poids et Mesures', and its daughter organizations, the 'Commission Internationale des Poids et Mesures' and the 'Bureau International des Poids et Mesures' (BIPM). All originated in the times just before the French revolution. Ref. 273

SI units

All SI units are built from seven *base units*, whose official definitions, translated from French into English, are given below, together with the dates of their formulation:

- 'The *second* is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom.' (1967)*
- 'The *metre* is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second.' (1983)*
- 'The *kilogram* is the unit of mass; it is equal to the mass of the international prototype of the kilogram.' (1901)*
- 'The *ampere* is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to $2 \cdot 10^{-7}$ newton per metre of length.' (1948)*
- 'The *kelvin*, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.' (1967)*
- 'The *mole* is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12.' (1971)*

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

particles in the universe by

$$N = n\,v\,d\,p\,f \tag{133}$$

where n is the number of particles, v is the number of variables (position, momentum, spin), d is the number of different values each of them can take (limited by the maximum of 61 decimal digits), p is the number of visible space-time points (about 10^{183}) and f is a factor expressing how many of all these initial conditions are actually independent of each other. We thus get the following number of possible states of all particles in the universe:

$$N = 10^{92} \cdot 8 \cdot 10^{61} \cdot 10^{183} \cdot f = 10^{336} \cdot f \tag{134}$$

from which the 10^{93} initial conditions have to be explained. But no explanation is known. Worse, there is also the additional problem that we know nothing whatsoever about f. Its value could be 0, if all data were interdependent, or 1, if none were. Even worse, above
Vol. IV, page 168 we noted that initial conditions cannot be defined for the universe at all; thus f should be undefined and not be a number at all! Whatever the case, we need to understand how all the visible particles acquire their present 10^{93} states.

Vol. I, page 435 5 – Were our efforts up to this point *in vain*? Quite at the beginning of our walk we noted that in classical physics, space and time are defined using matter, whereas matter is defined using space-time. Hundred years of general relativity and of quantum theory, including dozens of geniuses, have not solved this oldest paradox of all. The issue is still
Challenge 181 e open at this point of our walk, as you might want to check by yourself.

The answers to these five challenges define the goal of our adventure: the top of Motion Mountain. Answering the five challenges means to know *everything* about motion. It means to find, finally, the answer to the question that drove us here:

▷ What is motion?

In short, our quest for the unravelling of the essence of motion gets really interesting from this point onwards!

> That is why Leucippus and Democritus, who say that the atoms move always in the void and the unlimited, must say what movement is, and in what their natural motion consists.
>
> Aristotle, *Treaty of the Heaven*
Ref. 272



Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

The Casimir effect thus confirms the existence of the zero-point fluctuations of the electromagnetic field. It confirms that quantum theory is valid also for electromagnetism.

The Casimir effect between two spheres is proportional to $1/r^7$ and thus is much weaker than between two parallel plates. Despite this strange dependence, the fascination of the Casimir effect led many amateur scientists to speculate that a mechanism similar to the Casimir effect might explain gravitational attraction. Can you give at least three arguments why this is impossible, even if the effect had the correct distance de-
Challenge 71 s pendence?

Like the case of sound, the Casimir effect can also produce repulsion instead of attraction. It is sufficient that one of the two materials be perfectly permeable, the other a perfect conductor. Such combinations repel each other, as Timothy Boyer discovered in
Ref. 98 1974.

In a cavity, spontaneous emission is suppressed, if it is smaller than the wavelength of the emitted light! This effect has also been observed. It confirms that spontaneous emission is emission stimulated by the zero point fluctuations.

Ref. 99 The Casimir effect bears another surprise: between two metal plates, the speed of light changes and can be larger than c. Can you imagine what exactly is meant by 'speed of
Challenge 72 s light' in this context?

In 2006, the Casimir effect provided another surprise. The ship story just presented is beautiful, interesting and helps understanding the effect; but it seems that the story is based on a misunderstanding. Alas, the interpretation of the old naval text given by
Ref. 90 Sipko Boersma seems to be wishful thinking. There might be such an effect for ships, but it has never been observed nor put into writing by seamen, as Fabrizio Pinto has pointed out after carefully researching naval sources. As an analogy however, it remains valid.

The Lamb shift

In the old days, it was common that a person receives the Nobel Prize in Physics for observing the colour of a lamp – if the observation was sufficiently careful. In 1947, Willis Lamb (b. 1913 Los Angeles, d. 2008 Tucson) performed such a careful measurement of the spectrum of hydrogen. He found that the $2S_{1/2}$ energy level in atomic hydrogen lies slightly above the $2P_{1/2}$ level. This observation is in contrast to the calculation performed
Vol. IV, page 187 earlier on, where the two levels are predicted to have the same energy. In contrast, the measured energy difference is 1057.864 MHz, or 4.3 μeV. This discovery had important consequences for the description of quantum theory and yielded Lamb a share of the 1955 Nobel Prize in Physics. Why?

The reason for contrast between calculation and observation is an approximation performed in the relativistic calculation of the hydrogen levels that took over twenty years to clarify. There are two equivalent explanations. One explanation is to say that the relativistic calculation neglects the coupling terms between the Dirac equation and the Maxwell equations. This explanation lead to the first calculations of the Lamb shift, around the year 1950. The other, equivalent explanation is to say that the calculation *neglects virtual particles*. In particular, the calculation neglects the virtual photons emitted and absorbed during the motion of the electron around the nucleus. This second explanation is in line with the modern vocabulary of quantum electrodynamics. Quantum electrodynamics, or QED, is the (perturbative) approach to solve the coupled Dirac and Maxwell equations.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

In short, Lamb discovered the first effect due to virtual particles. In fact, Lamb used microwaves for his experiments; only in the 1970 it became possible to see the Lamb shift with optical means. For this and similar feats Arthur Schawlow received the Nobel Prize in Physics in 1981.

The QED Lagrangian and its symmetries

In simplified terms, *quantum electrodynamics* is the description of electron motion. This implies that the description is fixed by the effects of mass and charge, and by the quantum of action. The QED Lagrangian density is given by:

$$\begin{aligned} \mathcal{L}_{\text{QED}} = \; & \overline{\psi}(i\hbar c\partial\!\!\!/ - c^2 m_k)\psi \quad \} \text{ the matter term} \\ & - \frac{1}{4\mu_0} F_{\mu\nu}F^{\mu\nu} \quad \} \text{ the electromagnetic field term} \\ & + e\hbar c A_\mu \overline{\psi}\gamma^\mu \psi \; . \quad \} \text{ the electromagnetic interaction term} \end{aligned} \tag{18}$$

We know the matter term from the Dirac equation for free particles; it describes the kinetic energy of free electrons. We know the term of the electromagnetic field from the Maxwell's equations; it describes the kinetic energy of photons. The interaction term is the term that encodes the gauge symmetry of electromagnetism, also called 'minimal coupling'; it encodes the potential energy. In other words, the Lagrangian describes the motion of electrons and photons.

All experiments ever performed agree with the prediction by this Lagrangian. In other words, this Lagrangian is the final and correct description of the motion of electrons and photons. In particular, the Lagrangian describes the size, shape and colour of atoms, the size, shape and colour of molecules, as well as all interactions of molecules. In short, the Lagrangian describes all of materials science, all of chemistry and all of biology. Exaggerating a bit, this is the Lagrangian that describes life. (In fact, the description of atomic nuclei must be added; we will explore it below.)

Page 162

All electromagnetic effects, including the growth of the coloured spots on butterfly wings, the functioning of the transistor or the cutting of paper with scissors, are completely described by the QED Lagrangian. In fact, the Lagrangian also describes the motion of muons, tau leptons and all other charged particles. Since the Lagrangian is part of the final description of motion, it is worth thinking about it in more detail.

Which requirements are necessary to deduce the QED Lagrangian? This issue has been explored in great detail. The answer is given by the following list:

- compliance with the observer-invariant quantum of action for the motion of electrons and photons,
- symmetry under the permutation group among many electrons, i.e., fermion behaviour of electrons,
- compliance with the invariance of the speed of light, i.e., symmetry under transformations of special relativity,
- symmetry under U(1) gauge transformations for the motion of photons and of charged electrons,
- symmetry under renormalization group,

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

size and due to all the connections with our environment, any imagined tiny change would make us disappear, like a water droplet is swept away by large wave. Our walk has repeatedly reminded us of this smallness and dependence, and overwhelmingly does so again at this point.

In our adventure, accepting the powerful message of Table 27 is one of the most awe-inspiring, touching and motivating moments. It shows clearly how vast the universe is. It also shows how much we are dependent on many different and distant aspects of nature. Having faced this powerful experience, everybody has to make up his or her own mind on whether to proceed with the adventure or not. Of course, there is no obligation to do so.

Challenge 180 s

What awaits us?

Assuming that you have decided to continue the adventure, it is natural to ask what awaits you. The shortness of the millennium list of unexplained aspects of nature, given in Table 26, means that *no additional experimental data* are available as check of the final description of nature. Everything we need to arrive at the final description of motion will be deduced from the experimental data given in the millennium list, and from nothing else. In other words, future experiments will *not* help us – except if they change something in the millennium list. Accelerator experiments might do this with the particle list or astronomical experiments with the topology issue. Fantasy provides no limits; fortunately, nature does.

Page 316

The lack of new experimental data means that to continue the walk is a *conceptual* adventure only. Nevertheless, storms rage near the top of Motion Mountain. We have to walk keeping our eyes open, without any other guidance except our reason. This is not an adventure of action, but an adventure of the mind. And it is a fascinating one, as we shall soon find out. To provide an impression of what awaits us, we rephrase the remaining issues in five simple challenges.

1 – What determines *colours*? In other words, what relations of nature fix the famous fine structure constant? Like the hero of Douglas Adams' books, physicists know the answer to the greatest of questions: it is 137.036. But they do not know the question.

2 – What fixes the contents of a *teapot*? It is given by its size to the third power. But why are there only three dimensions? Why is the tea content limited in this way?

3 – Was Democritus *right*? Our adventure has confirmed his statement up to this point: nature is indeed well described by the concepts of *particle* and of *vacuum*. At large scales, relativity has added a horizon, and at small scales, quantum field theory added vacuum energy and pair creation. Nevertheless, both theories *assume* the existence of particles and the existence of space-time, and neither *predicts* them. Even worse, both theories completely fail to predict the existence of *any* of the properties either of space-time – such as its dimensionality – or of particles – such as their masses and other quantum numbers. A lot is missing.

4 – Was Democritus *wrong*? It is often said that the standard model has only about twenty unknown parameters; this common mistake negates about 10^{93} initial conditions! To get an idea of the problem, we simply estimate the number N of possible states of all

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 27 (Continued) A selection of the consequences of changing the properties of nature.

Observable	Change	Result
topology	other:	Unknown; possibly correlated γ ray bursts or star images at the antipodes.

Note. Some researchers speculate that the whole of Table 27 can be condensed into a single sentence: if any parameter in nature is changed, the universe would either have too many or too few black holes. However, the proof of this condensed summary is not complete yet. But it is a beautiful hypothesis.

Ref. 271
Challenge 179 r

The effects of changing nature that are listed in Table 27 lead us to a profound experience: even the tiniest changes in the properties of nature are incompatible with our existence. What does this experience mean? Answering this question too rapidly is dangerous. Many have fallen into one of several traps:

— The first trap is to deduce, incorrectly, that the unexplained numbers and other properties from the millennium list do not need to or even cannot be explained, i.e., deduced from more general principles.
— The second trap is to deduce, incorrectly, that the universe has been *created* or *designed*.
— The third trap is to deduce, incorrectly, that the universe is *designed for people*.
— The fourth trap is to deduce, incorrectly, that the universe is *one of many*.

All these traps are irrational and incorrect beliefs. All these beliefs have in common that they have no factual basis, that they discourage further search and that they sell many books.

The first trap is due to a combination of pessimism and envy; it is a type of wishful thinking. But wishful thinking has no place in the study of motion. The second trap works because many physicists incorrectly speak of *fine tuning* in nature. Many researchers succumb to the belief in 'creation' and are unable to steer clear from the logical errors contained in it. We discussed them earlier on. The third trap, is often, again incorrectly, called the *anthropic principle*. The name is a mistake, because we saw that the anthropic principle is indistinguishable both from the simian principle and from the simple request that statements be based on observations. Around 2000, the third trap has even become fashionable among frustrated particle theorists. The fourth trap, the belief in *multiple universes*, is a minority view, but sells many books. Most people that hold this view are found in institutions. And that is indeed where they belong.

Vol. VI, page 370
Vol. III, page 326
Vol. III, page 333

Stopping our adventure, our mountain ascent, with an incorrect belief at the present stage is not different from doing so directly at the beginning. Such a choice has been taken in various societies that lacked the passion for rational investigation, and still is taken in circles that discourage the use of reason among their members. Looking for beliefs instead of looking for answers means to give up our ascent while pretending to have reached the top. Every such case is a tragedy, sometimes a small one, sometimes a larger one.

In fact, Table 27 purveys only one message: all evidence implies that we are only a *tiny part* of the universe, but that we are *linked* with all other aspects of it. Due to our small

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

— low-energy interaction strength described by the *fine structure constant*, the electromagnetic coupling constant, $\alpha \approx 1/137.036$.

The last two points require some comments. As in all cases of motion, the action is the time-volume integral of the Lagrangian density. All fields, be they matter and radiation, move in such a way that this action remains minimal. In fact there are no known differences between the prediction of the least action principle based on the QED Lagrangian density and observations. Even though the Lagrangian density is known since 1926, it took another twenty years to learn how to calculate with it. Only in the years around 1947 it became clear, through the method of *renormalization*, that the Lagrangian density of QED is the *final* description of all motion of matter due to electromagnetic interaction in flat space-time. The details were developed independently by Julian Schwinger, Freeman Dyson, Richard Feynman and Tomonaga Shin'ichiro, four among the smartest physicists ever. *

The QED Lagrangian density contains the strength of the electromagnetic interaction in the form of the fine structure constant $\alpha = e^2/(4\pi\varepsilon_0\hbar c) \approx 1/137.036(1)$. This number is part of the Lagrangian; no explanation for its value is given, and the explanation was still unknown in the year 2016. It is one of the hardest puzzles of physics. Also the U(1) gauge group is specific to electromagnetism. All others requirements are valid for every type of interaction. Indeed, the search for the Lagrangians of the two nuclear interactions became really focused and finally successful only when the necessary requirements were clearly spelled out, as we will discover in the rest of this volume.

Vol. I, page 432
Challenge 73 e

The Lagrangian density retains all symmetries that we know from classical physics. Motion is continuous, it conserves energy–momentum and angular momentum, it is relative, it is right–left symmetric, it is reversible, i.e., symmetric under change of velocity sign, and it is lazy, i.e., it minimizes action. In short, within the limits given by the quantum of action, also motion due to QED remains predictable.

Interactions and virtual particles

The electromagnetic interaction is exchange of virtual photons. So how can the interaction be attractive? At first sight, any exchange of virtual photons should drive the electrons from each other. However, this is not correct. The momentum of virtual photons does not have to be in the direction of its energy flow; it can also be in opposite direction.** Obviously, this is only possible within the limits provided by the indeterminacy relation.

But virtual particles have also other surprising properties: virtual photons for example, cannot be counted.

* Tomonaga Shin'ichiro (b. 1906 Tokio, d. 1979 Tokio) developed quantum electrodynamics and won the 1965 Nobel Prize in Physics together with Feynman and Schwinger. Later he became an important figure of science politics; together with his class mate from secondary school and fellow physics Nobel Prize winner, Yukawa Hidei, he was an example to many scientists in Japan.

** One of the most beautiful booklets on quantum electrodynamics which makes this point remains the text by Richard Feynman, *QED: the Strange Theory of Light and Matter*, Penguin Books, 1990.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Vacuum energy: infinite or zero?

The strangest result of quantum field theory is the energy density of the vacuum. On one side, the vacuum has, to an excellent approximation, no mass and no energy content. The vacuum energy of vacuum is thus measured and expected to be *zero* (or at least extremely small).*

On the other side, the energy density of the zero-point fluctuations of the electromagnetic field is given by

$$\frac{E}{V} = \frac{4\pi h}{c^3} \int_0^\infty \nu^3 \mathrm{d}\nu \,. \tag{19}$$

The result of this integration is infinite. Quantum field theory thus predicts an *infinite* energy density of the vacuum.

We can try to moderate the problem in the following way. As we will discover in the last part of our adventure, there are good arguments that a smallest measurable distance exists in nature; this smallest length appears when gravity is taken into account. The minimal distance is of the order of the *Planck length*

Vol. VI, page 39

$$l_{\mathrm{Pl}} = \sqrt{\hbar G/c^3} \approx 1.6 \cdot 10^{-35}\,\mathrm{m} \,. \tag{20}$$

A minimal distance leads to a maximum cut-off frequency. But even in this case the vacuum density that follows is still a huge number, and is much larger than observed by over 100 orders of magnitude. In other words, QED seems to predict an infinite, or, when gravity is taken into account, a huge vacuum energy. But measurements show a tiny value. What exactly is wrong in this simple calculation? The answer cannot be given at this point; it will become clear in the last volume of our adventure.

Vol. VI, page 39

Moving mirrors

Mirrors also work when they or the light source is in motion. In contrast, walls, i.e., sound mirrors, do *not* produce echoes for every sound source or for every wall speed. For example, experiments show that walls do not produce echoes if the wall or the sound source moves faster than sound. Walls do not produce echoes even if the sound source moves with them, if both objects move faster than sound. On the other hand, light mirrors *always* produce an image, whatever the involved speed of the light source or the mirror may be. These observations confirm that the speed of light is the same for all observers: it is *invariant* and a limit speed. (Can you detail the argument?) In contrast, the speed of sound in air depends on the observer; it is *not* invariant.

Challenge 74 s

Light mirrors also differ from tennis rackets. (Rackets are tennis ball mirrors, to continue the previous analogy.) We have seen that light mirrors cannot be used to change the speed of the light they hit, in contrast to what tennis rackets can do with balls. This observation shows that the speed of light is a *limit* speed. In short, the simple existence of mirrors and of their properties are sufficient to derive special relativity.

Vol. II, page 22

* In 1998, this side of the issue was confused even further. Astrophysical measurements, confirmed in the subsequent years, have found that the vacuum energy has a small, but non-zero value, of the order of 0.5 nJ/m^3. The reason for this value is not yet understood, and is one of the open issues of modern physics.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 27 (Continued) A selection of the consequences of changing the properties of nature.

Observable	Change	Result
e-p mass ratio	much different:	No molecules.
	much smaller:	No solids.
3 generations	6-8:	Only helium in nature.
	>8:	No asymptotic freedom and confinement.
Global quantities, from general relativity		
horizon size	much smaller:	No people.
baryon number	very different:	No smoothness .
	much higher:	No solar system.
Initial condition changes:		
Moon mass	smaller:	Small Earth magnetic field; too much cosmic radiation; widespread child skin cancer.
Moon mass	larger:	Large Earth magnetic field; too little cosmic radiation; no evolution into humans.
Sun's mass	smaller:	Too cold for the evolution of life.
Sun's mass	larger:	Sun too short lived for the evolution of life.
Jupiter mass	smaller:	Too many comet impacts on Earth; extinction of animal life.
Jupiter mass	larger:	Too little comet impacts on Earth; no Moon; no dinosaur extinction.
Oort cloud object number	smaller:	No comets; no irregular asteroids; no Moon; still dinosaurs.
galaxy centre distance	smaller:	Irregular planet motion; supernova dangers.
initial cosmic speed	+0.1 %:	1000 times faster universe expansion.
	−0.0001 %:	Universe recollapses after 10 000 years.
vacuum energy density	change by 10^{-55}:	No flatness.
3 + 1 dimensions	different:	No atoms, no planetary systems.
Local structures, from quantum theory		
permutation symmetry	none:	No matter.
Lorentz symmetry	none:	No communication possible.
U(1)	different:	No Huygens principle, no way to *see* anything.
SU(2)	different:	No radioactivity, no Sun, no life.
SU(3)	different:	No stable quarks and nuclei.
Global structures, from general relativity		

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

The intense emotions due to quantum field theory and general relativity

It is sometimes deemed chic to pretend that the adventure is over at the stage we have just reached,* the third level of Figure 181. The reasoning given is as follows. If we change the values of the unexplained constants in the millennium list of Table 26 only ever so slightly, nature would look completely different from what it does. Indeed, these consequences have been studied in great detail; an overview of the connections is given in the following table.

Page 316
Ref. 270

TABLE 27 A selection of the consequences of changing the properties of nature.

Observable	Change	Result
Local quantities, from quantum theory		
α_{em}	smaller:	Only short lived, smaller and hotter stars; no Sun.
	larger:	Darker Sun, animals die of electromagnetic radiation, too much proton decay, no planets, no stellar explosions, no star formation, no galaxy formation.
	+60 %:	Quarks decay into leptons.
	+200 %:	Proton-proton repulsion makes nuclei impossible.
α_w	−50 %:	Carbon nucleus unstable.
	very weak:	No hydrogen, no p-p cycle in stars, no C-N-O cycle.
	+2 %:	No protons from quarks.
	$G_F m_e^2 \neq \sqrt{G m_e^2}$:	Either no or only helium in the universe.
	much larger:	No stellar explosions, faster stellar burning.
α_s	−9 %:	No deuteron, stars far less bright.
	−1 %:	No C resonance, no life.
	+3.4 %:	Diproton stable, faster star burning.
	much larger:	Carbon unstable, heavy nuclei unstable, widespread leukaemia.
n-p mass difference	larger:	Neutron decays in proton inside nuclei; no elements.
	smaller:	Free neutron not unstable, all protons into neutrons during big bang; no elements.
	smaller than m_e:	Protons would capture electrons, no hydrogen atoms, star life much shorter.
m_l changes:		

* Actually this attitude is not new. Only the arguments have changed. Maybe the greatest physicist ever, James Clerk Maxwell, already fought against this attitude over a hundred years ago: 'The opinion seems to have got abroad that, in a few years, all great physical constants will have been approximately estimated, and that the only occupation which will be left to men of science will be to carry these measurements to another place of decimals. [...] The history of science shows that even during that phase of her progress in which she devotes herself to improving the accuracy of the numerical measurement of quantities with which she has long been familiar, she is preparing the materials for the subjugation of new regions, which would have remained unknown if she had been contented with the rough methods of her early pioneers.'

Ref. 269

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

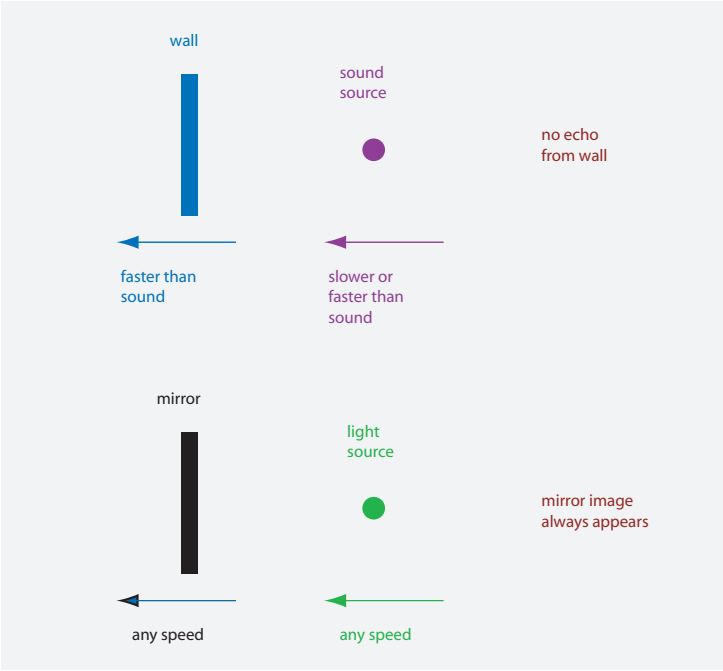


FIGURE 80 A fast wall does not produce an echo; a fast mirror does.

But there are more interesting things to be learned from mirrors. We only have to ask whether mirrors work when they undergo *accelerated* motion. This issue yields a surprising result.

In the 1970s, quite a number of researchers independently found that there is no vacuum for accelerated observers. This effect is called *Fulling–Davies–Unruh effect*. (The incorrect and rarely used term *dynamical Casimir effect* has been abandoned.) For an accelerated observer, the vacuum is full of heat radiation. We will discuss this below. This fact has an interesting consequence for accelerated mirrors: a mirror in accelerated motion reflects the heat radiation it encounters. In short, *an accelerated mirror emits light*! Unfortunately, the intensity of this so-called *Unruh radiation* is so weak that it has not been measured directly, up to now. We will explore the issue in more detail below. (Can you explain why accelerated mirrors emit light, but not matter?)

Page 146
Challenge 75 s

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Photons hitting photons

Usually, light can cross light undisturbed: interference is the proof and the result of this basic property of light. But there is an exception. When virtual particles are taken into account, light beams can 'bang' onto each other – though only slightly. This result is in full contrast to classical electrodynamics.

Indeed, QED shows that the appearance of virtual electron-positron pairs allow photons to hit each other. And such pairs are found in any light beam. However, the cross-section for photons banging onto each other is small. In other words, the bang is extremely weak. When two light beams cross, most photons will pass undisturbed. The cross-section A is approximately

$$A \approx \frac{973}{10\,125\pi}\alpha^4\left(\frac{\hbar}{m_e c}\right)^2\left(\frac{\hbar\omega}{m_e c^2}\right)^6 \tag{21}$$

for the everyday case that the energy $\hbar\omega$ of the photon is much smaller than the rest energy $m_e c^2$ of the electron. This low-energy value is about 18 orders of magnitude smaller than what was measurable in 1999; the future will show whether the effect will ever be observable for visible light. However, for high energy photons these effects are observed daily in particle accelerators. In these settings one observes not only interaction through virtual electron–antielectron pairs, but also through virtual muon–antimuon pairs, virtual quark–antiquark pairs, and much more.

Everybody who consumes science fiction knows that matter and antimatter annihilate and transform into pure light. More precisely, a matter particle and an antimatter particle annihilate into two or more photons. Interestingly, quantum theory predicts that the opposite process is also possible: photons hitting photons can produce matter! In 1997, this prediction was also confirmed experimentally. Ref. 100

At the Stanford particle accelerator, photons from a high energy laser pulse were bounced off very fast electrons. In this way, the reflected photons acquired a large energy, when seen in the inertial frame of the experimenter. The green laser pulse, of 527 nm wavelength or 2.4 eV photon energy, had a peak power density of $10^{22}\,\mathrm{W/m^2}$, about the highest achievable so far. That is a photon density of $10^{34}\,/\mathrm{m^3}$ and an electric field of $10^{12}\,\mathrm{V/m}$, both of which were record values at the time. When this green laser pulse was reflected off a 46.6 GeV electron beam, the returning photons had an energy of 29.2 GeV and thus had become high-energy gamma rays. These gamma rays then collided with other, still incoming green photons and produced electron–positron pairs through the reaction Challenge 76 e

$$\gamma_{29.2\mathrm{GeV}} + n\,\gamma_{\mathrm{green}} \to \mathrm{e}^+ + \mathrm{e}^- \tag{22}$$

for which both final particles were detected by special apparatuses. The experiment thus showed that light can hit light in nature, and above all, that doing so can produce matter. This is the nearest we can get to the science fiction fantasy of light swords or of laser swords *banging* onto each other.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

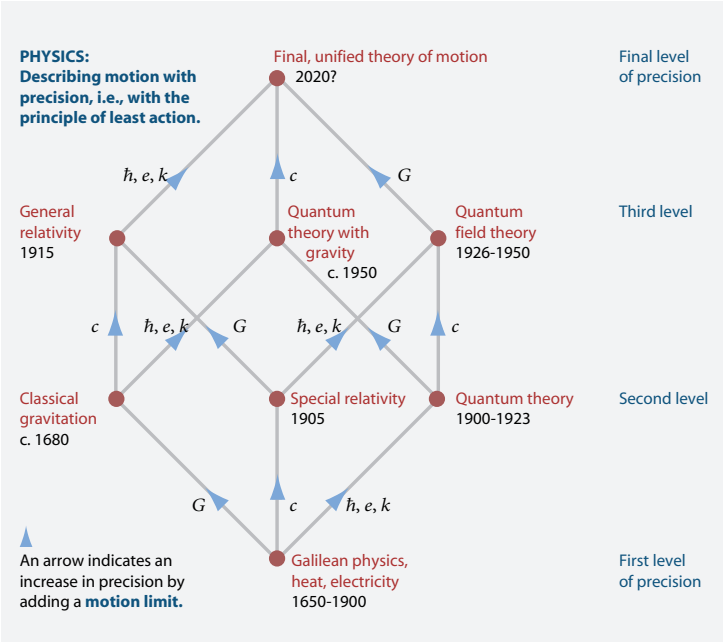


FIGURE 181 A simplified history of the description of motion in physics, by giving the limits to motion included in each description. The arrows show which constant of nature needs to be added and taken into account to reach the next level of precision. (The electric charge e is taken to represent all three discrete gauge charges.)

though only *in its domain*. And even though the limits of each domain are obvious, no differences between experiment and theory are known.

From the third level theories, the edges lead to the last missing corner: the (unified) theory of motion that takes into account *all limits* of nature. Only this theory is a complete and unified description of nature. Since we already know all limits to motion, in order to arrive at the last level, we do not need new experiments. We do not need new knowledge. We only have to advance, in the right direction, with careful thinking. And we can start from three different points. This is the topic of the last volume of our adventure.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 26 (Continued) *Everything* the standard model and general relativity *cannot* explain.

Observable	Property unexplained since the year 2000
$R \times S^3$	the observed topology of the universe
$G^{\mu\nu}$	the origin and nature of curvature, the metric and horizons
$\delta W = 0$	the origin of the least action principle in general relativity
$W = \int L_{GR} dt$	the origin of the Lagrangian of general relativity

The millennium list has several notable aspects. First of all, neither quantum mechanics nor general relativity explain any property unexplained in the other field. The two theories do not help each other; the unexplained parts of both fields simply add up. Secondly, both in quantum theory and in general relativity, motion still remains the change of position with time. In short, so far, we did not achieve our goal: we still do not understand motion! We are able to describe motion with full precision, but we still do not know what it is. Our basic questions remain: What are time and space? What is mass? What is charge and what are the other properties of objects? What are fields? Why are all the electrons the same?

Page 316

We also note that the millennium list of open questions, Table 26, contains extremely *different* concepts. This means that at this point of our walk there is *a lot* we do not understand. Finding the answers will require effort.

On the other hand, the millennium list of unexplained properties of nature is also *short*. The description of nature that our adventure has produced so far is concise and precise. No discrepancies from experiments are known. In other words, we have a good description of motion *in practice*. Going further is unnecessary if we only want to improve measurement precision. Simplifying the above list is mainly important from the *conceptual* point of view. For this reason, the study of physics at university often stops at this point. However, as the millennium list shows, even though we have *no* known discrepancies with experiments, we are *not* at the top of Motion Mountain.

The physics cube

Page 8

Another review of the progress and of the open issues of physics, already given in the introduction, is shown in Figure 181: the *physics cube*. From the lowest corner of the cube, representing Galilean physics and related topics from everyday life, three edges – labelled c, G and $\hbar$, e, k – lead to classical gravity, special relativity and quantum theory. Each constant implies a limit to motion; in the corresponding theory, this *one* limit is taken into account, thus improving the precision of the description. From these second level theories, similar edges lead upwards to general relativity, quantum field theory and quantum theory with gravity. Each of these third level theories takes into account *two* of the limits and thus improves precision even more.* The present volume completes the third level of precision. We stress that each theory in the second and third level is *exact*,

* Of course, Figure 181 gives a simplified view of the history of physics. A more precise diagram might use different arrows for $\hbar$ (with k) and e, making the figure a four-dimensional cube. However, not all of its corners would have dedicated theories (can you confirm this?). Also the weak and the strong coupling constants might have to be added. The diagram would be far less appealing. And most of all, the conclusions mentioned in the text would not change.

Challenge 178 e

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Is the vacuum a bath?

If the vacuum is a sea of virtual photons and particle–antiparticle pairs, vacuum could be suspected to act as a bath. In general, the answer is negative. Quantum field theory works because the vacuum is *not* a bath for single particles. However, there is always an exception. For dissipative systems made of many particles, such as electrical conductors,

Ref. 101

the vacuum *can* act as a viscous fluid. Irregularly shaped, neutral, but conducting bodies can emit photons when accelerated, thus damping such type of motion. This is due to the Fulling–Davies–Unruh effect, as described above. The damping depends on the shape and thus also on the direction of the body's motion.

Vol. I, page 389

In 1998, Gour and Sriramkumar even predicted that Brownian motion should also appear for an imperfect, i.e., partly absorbing *mirror* placed in vacuum. The fluctuations

Ref. 102

of the vacuum should produce a mean square displacement

$$\langle d^2 \rangle = \frac{\hbar}{m} t \tag{23}$$

that increases linearly with time; however, the extremely small displacement produced in this way is out of experimental reach so far. But the result is not a surprise. Are you

Challenge 77 ny

able to give another, less complicated explanation for it?

Renormalization – why is an electron so light?

In classical physics, the field energy of a point-like charged particle, and hence its mass,

Vol. III, page 239

was predicted to be infinite. QED effectively *smears out* the charge of the electron over its Compton wavelength; as a result, the field energy contributes only a small correction to its total mass. Can you confirm this?

Challenge 78 s

QED is a *perturbative* description. This means, that any predicted result R is found as a Taylor series of powers of a small parameter:

$$R = R_0 + R_1\alpha + R_2\alpha^2 + R_3\alpha^3 + R_4\alpha^4 + \dots \tag{24}$$

In QED, the small parameter is the fine structure constant $\alpha = 1/137.036(1)$. With the help of the perturbation series, the exact result R is approximated more and more precisely.

Now, in QED, many intermediate results in the perturbation expansion are divergent integrals, i.e., integrals with infinite value. The divergence is due to the assumption that infinitely small distances are possible in nature. The divergences thus are artefacts that can be eliminated; the elimination procedure is called renormalization.

Sometimes it is claimed that the infinities appearing in quantum electrodynamics in the intermediate steps of the calculation show that the theory is incomplete or wrong. However, this type of statement would imply that classical physics is also incomplete or wrong, on the ground that in the definition of the velocity v with space x and time t, namely

$$v = \frac{dx}{dt} = \lim_{\Delta t \to 0} \frac{\Delta x}{\Delta t} = \lim_{\Delta t \to 0} \Delta x \frac{1}{\Delta t} , \tag{25}$$

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

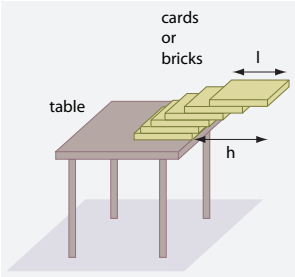


FIGURE 81 What is the maximum possible value of h/l?

one gets an infinity as intermediate step. Indeed, dt being vanishingly small, one could argue that one is dividing by zero. Both arguments show the difficulty to accept that the result of a limit process can be a finite quantity even if infinite quantities appear in the calculation. The parallel between electron mass and velocity is closer than it seems; both intermediate 'infinities' stem from the assumption that space-time is continuous, i.e., infinitely divisible. The infinities necessary in limit processes for the definition of differentiation, integration or for renormalization appear only when space-time is approximated, as physicists say, as a 'continuous' set, or as mathematicians say, as a 'complete' set.

On the other hand, the conviction that the appearance of an infinity might be a sign of incompleteness of a theory was an interesting development in physics. It shows how uncomfortable many physicists had become with the use of infinity in our description
Ref. 103 of nature. Notably, this was the case for Paul Dirac himself, who, after having laid in his youth the basis of quantum electrodynamics, has tried for the rest of his life to find a way, without success, to change the theory so that intermediate infinities are avoided.

Renormalization is a procedure that follows from the requirement that continuous space-time and gauge theories must work together. In particular, renormalization follows form the requirement that the particle concept is consistent, i.e., that perturbation expansions are possible. Intermediate infinities are not an issue. In a bizarre twist, a few decades after Dirac's death, his wish has been fulfilled after all, although in a different manner than he envisaged. The final part of this mountain ascent will show the way out
Vol. VI, page 36 of the issue.

Curiosities and fun challenges of quantum electrodynamics

Motion is an interesting topic, and when a curious person asks a question about it, most of the time quantum electrodynamics is needed for the answer. Together with gravity, quantum electrodynamics explains almost all of our everyday experience, including numerous surprises. Let us have a look at some of them.

* *

A famous riddle, illustrated in Figure 81, asks how far the last card (or the last brick) of a stack can hang over the edge of a table. Of course, only gravity, no glue nor any other

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 26 (Continued) *Everything* the standard model and general relativity *cannot* explain.

Observable	Property unexplained since the year 2000
α_s	the value of the strong coupling constant at one specific energy value
m_q	the values of the 6 quark masses
m_l	the values of 6 lepton masses
m_W	the value of the mass of the W vector boson
m_H	the value of the mass of the scalar Higgs boson
$\theta_{12}, \theta_{13}, \theta_{23}$	the value of the three quark mixing angles
δ	the value of the CP violating phase for quarks
$\theta^{\nu}_{12}, \theta^{\nu}_{13}, \theta^{\nu}_{23}$	the value of the three neutrino mixing angles
$\delta^{\nu}, \alpha_1, \alpha_2$	the value of the three CP violating phases for neutrinos
$3 \cdot 4$	the number of fermion generations and of particles in each generation
J, P, C, etc.	the origin of all quantum numbers of each fermion and each boson
Concepts unexplained by the standard model	
$c, \hbar, k$	the origin of the invariant Planck units of quantum field theory
3 + 1	the number of dimensions of physical space and time
SO(3,1)	the origin of Poincaré symmetry, i.e., of spin, position, energy, momentum
Ψ	the origin and nature of wave functions
$S(n)$	the origin of particle identity, i.e., of permutation symmetry
Gauge symmetry	the origin of the gauge groups, in particular:
U(1)	the origin of the electromagnetic gauge group, i.e., of the quantization of electric charge, of the vanishing of magnetic charge, and of minimal coupling
SU(2)	the origin of weak interaction gauge group, its breaking and P violation
SU(3)	the origin of strong interaction gauge group and its CP conservation
Renorm. group	the origin of renormalization properties
$\delta W = 0$	the origin of the least action principle in quantum theory
$W = \int L_{SM}\, dt$	the origin of the Lagrangian of the standard model of particle physics
Global quantities unexplained by general relativity and cosmology	
0	the observed flatness, i.e., vanishing curvature, of the universe
$1.2(1) \cdot 10^{26}$ m	the distance of the horizon, i.e., the 'size' of the universe (if it makes sense)
$\rho_{de} = \Lambda c^4/(8\pi G)$ $\approx 0.5\,\mathrm{nJ/m^3}$	the value and nature of the observed vacuum energy density, dark energy or cosmological constant
$(5 \pm 4) \cdot 10^{79}$	the number of baryons in the universe (if it makes sense), i.e., the average visible matter density in the universe
ρ_{dm}	the density and nature of dark matter
$f_0(1, ..., c.\ 10^{90})$	the initial conditions for $c.\ 10^{90}$ particle fields in the universe (if or as long as they make sense), including the homogeneity and isotropy of matter distribution, and the density fluctuations at the origin of galaxies
Concepts unexplained by general relativity and cosmology	
c, G	the origin of the invariant Planck units of general relativity

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 25 (Continued) Selected comparisons between classical physics, quantum theory and experiment.

Observable	Classical prediction	Prediction of quantum theory[a]	Measurement	Cost estimate[b]
Superconductivity (metal)	none	exists	exists	100 k€
Superconductivity (high T)	none	*none yet*	exists	100 k€

a. All these predictions are calculated from the fundamental quantities given in the millennium list.

b. Sometimes the cost for the calculation of the prediction is higher than that of the experimental observation. (Can you spot the examples?) The sum of the two is given.

Challenge 177 s

We notice that the values predicted by quantum theory do not differ from the measured ones. In contrast, classical physics does not allow us to calculate any of the observed values. This shows the progress that quantum physics has brought in the description of nature.

In short, in the microscopic domain quantum theory is in *perfect* correspondence with nature; despite prospects of fame and riches, despite the largest number of researchers ever, no contradiction with observation has been found yet. But despite this impressive agreement, there still are *unexplained* observations; they form the so-called *millennium list*.

What is unexplained by quantum theory and general relativity?

Vol. II, page 287

The material gathered in this quantum part of our mountain ascent, together with the earlier summary of general relativity, allows us to describe *all* observed phenomena connected to motion. For the first time, there are no known differences between theory and practice.

Despite the precision of the description of nature, some things are missing. Whenever we ask 'why?' about an observation and continue doing so after each answer, we arrive at one of the *unexplained* properties of nature listed in Table 26. The table lists all issues about fundamental motion that were unexplained in the year 2000, so that we can call it the *millennium list* of open problems.

TABLE 26 The millennium list: *everything* the standard model and general relativity *cannot* explain; thus, also the list of the *only* experimental data available to test the final, unified description of motion.

Observable	Property unexplained since the year 2000
Local quantities unexplained by the standard model: particle properties	
$\alpha = 1/137.036(1)$	the low energy value of the electromagnetic coupling or fine structure constant
α_w or θ_w	the low energy value of the weak coupling constant or the value of the weak mixing angle

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Challenge 79 s

means is allowed to keep the cards on the table. After you solved the riddle, can you give the solution in case that the quantum of action is taken into account?

* *

Ref. 104 Challenge 80 s Page 153

Quantum electrodynamics explains why there are only a *finite* number of different atom types. In fact, it takes only two lines to prove that pair production of electron–antielectron pairs make it impossible that a nucleus has more than about 137 protons. Can you show this? In short, the fine structure constant limits the number of chemical elements in nature. The effect at the basis of this limit, the polarization of the vacuum, also plays a role in much larger systems, such as charged black holes, as we will see shortly.

* *

Ref. 105

Stripping 91 of the 92 electrons off an uranium atom allows researchers to check with high precision whether the innermost electron still is described by QED. The electric field near the uranium nucleus, 1 EV/m, is the highest achievable in the laboratory; the field value is near the threshold for spontaneous pair production. The field is the highest constant field producible in the laboratory, and an ideal testing ground for precision QED experiments. The effect of virtual photons is to produce a Lamb shift; but even for these extremely high fields, the value matches the calculation.

* *

Challenge 81 ny

Is there a *critical magnetic field* in nature, like there is a critical electric field, limited by spontaneous pair production?

* *

Ref. 106 Page 342

Microscopic evolution can be pretty slow. Light, especially when emitted by single atoms, is always emitted by some metastable state. Usually, the decay times, being induced by the vacuum fluctuations, are much shorter than a microsecond. However, there are metastable atomic states with a lifetime of ten years: for example, an ytterbium ion in the $^2F_{7/2}$ state achieves this value, because the emission of light requires an octupole transition, in which the angular momentum changes by $3\hbar$; this is an extremely unlikely process.

In radioactive decay, the slowness record is held by ^{209}Bi, with over 10^{19} years of half-life.

* *

Challenge 82 s

Microscopic evolution can be pretty fast. Can you imagine how to deduce or to measure the speed of electrons inside atoms? And inside metals?

* *

Challenge 83 s Ref. 109

If an electrical wire is sufficiently narrow, its electrical conductance is quantized in steps of $2e^2/\hbar$. The wider the wire, the more such steps are added to its conductance. Can you explain the effect? By the way, quantized conductance has also been observed for light and for phonons.

* *

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

The Casimir effect, as well as other experiments, imply that there is a specific and *finite* energy density that can be ascribed to the vacuum. Does this mean that we can apply the Challenge 84 d Banach–Tarski effect to pieces of vacuum?

* *

Challenge 85 s Can you explain why mud is not clear?

* *

The instability of the vacuum also yields a (trivial) limit on the fine structure constant. The fine structure constant value of around 1/137.036 cannot be explained by quantum Ref. 201 electrodynamics. However, it can be deduced that it must be lower than 1 to lead to a consistent theory. Indeed, if its value were larger than 1, the vacuum would become unstable and would spontaneously generate electron-positron pairs.

* *

Challenge 86 s Can the universe ever have been smaller than its own Compton wavelength?

* *

In the past, the description of motion with formulae was taken rather seriously. Before computers appeared, only those examples of motion were studied that could be described with simple formulae. But this narrow-minded approach turns out to be too restrictive. Indeed, mathematicians showed that Galilean mechanics cannot solve the three-body problem, special relativity cannot solve the two-body problem, general relativity the one-body problem and quantum field theory the zero-body problem. It took some time to the community of physicists to appreciate that understanding motion does not depend on the description by formulae, but on the description by clear equations based on space and time.

* *

In fact, quantum electrodynamics, or QED, provides a vast number of curiosities and every year there is at least one interesting new discovery. We now conclude the theme with a more general approach.

How can one move on perfect ice? – The ultimate physics test

In our quest, we have encountered motion of many sorts. Therefore, the following test – not to be taken too seriously – is the ultimate physics test, allowing you to check your understanding and to compare it with that of others.

Imagine that you are on a perfectly frictionless surface and that you want to move to its border. How many methods can you find to achieve this? Any method, so tiny its effect may be, is allowed.

Classical physics provided quite a number of methods. We saw that for rotating ourselves, we just need to turn our arm above the head. For translation motion, throwing a shoe or inhaling vertically and exhaling horizontally are the simplest possibilities. Can Challenge 87 s you list at least six additional methods, maybe some making use of the location of the surface on Earth? What would you do in space?

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 25 (Continued) Selected comparisons between classical physics, quantum theory and experiment.

OBSERVABLE	CLASSICAL PREDICTION	PREDICTION OF QUANTUM THEORY[a]	MEASUREMENT	COST ESTIMATE[b]
Colours of objects				
Spectrum of hot objects	diverges	$\lambda_{max} = hc/(4.956\,kT)$	$(1 \pm 10^{-4})\ \Delta\lambda$	10 k€
Lamb shift	none	$\Delta\lambda = 1057.86(1)$ MHz	$(1 \pm 10^{-6})\,\Delta\lambda$	50 k€
Rydberg constant	none	$R_\infty = m_e c\alpha^2/2h$	$(1 \pm 10^{-9})\,R_\infty$	50 k€
Stefan–Boltzmann constant	none	$\sigma = \pi^2 k^4/60\hbar^3 c^2$	$(1 \pm 3 \cdot 10^{-8})\,\sigma$	20 k€
Wien's displacement constant	none	$b = \lambda_{max} T$	$(1 \pm 10^{-5})\,b$	20 k€
Refractive index of water	none	1.34	a few %	1 k€
Photon-photon scattering	0	from QED: finite	agrees	50 M€
Laser radiation exists	no	yes	agrees	10€
Particle and interaction properties				
Electron gyromagnetic ratio	1 or 2	2.002 319 304 3(1)	2.002 319 304 3737(82)	30 M€
Z boson mass	none	$m_Z^2 = m_W^2(1 + \sin\theta_W^2)$	$(1 \pm 10^{-3})\,m_Z$	100 M€
Proton mass	none	$(1 \pm 5\,\%)\,m_p$	m_p =1.67 yg	1 M€
Proton lifetime	≈ 1 µs	∞	$> 10^{35}$ a	100 M€
Chemical reaction rate	0	from QED	correct within errors	2 k€
Composite matter properties				
Atom lifetime	≈ 1 µs	∞	$> 10^{20}$ a	1 €
Molecular size	none	from QED	within 10^{-3}	20 k€
Von Klitzing constant	∞	$h/e^2 = \mu_0 c/2\alpha$	$(1 \pm 10^{-7})\,h/e^2$	1 M€
AC Josephson constant	0	$2e/h$	$(1 \pm 10^{-6})\,2e/h$	5 M€
Heat capacity of metals at 0 K	25 J/K	0	$< 10^{-3}$ J/K	10 k€
Heat capacity of diatomic gas at 0 K	25 J/K	0	$< 10^{-3}$ J/K	10 k€
Water density	none	1000.00 kg/m^3 at 4 °C	agrees	10 k€
Minimum electr. conductivity	0	$G = 2e^2/h$	$G(1 \pm 10^{-3})$	3 k€
Ferromagnetism	none	exists	exists	2 €
Superfluidity	none	exists	exists	200 k€
Bose–Einsein condensation	none	exists	exists	2 M€

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

110 elements, where a tree takes the material to make its wood and why we are able to move our right hand at our own will. Quantum theory explains the origin of material properties and the origin of the properties of life.

Quantum field theory describes all material properties, be they mechanical, optical, electric or magnetic. It describes all waves that occur in materials, such as sound and phonons, magnetic waves and magnons, light, plasmons, and all localized excitations. Quantum field theory also describes collective effects in matter, such as superconductivity, semiconductor effects and superfluidity. Finally, quantum field theory describes all interactions between matter and radiation, from colour to antimatter creation.

Quantum field theory also clarifies that the particle description of nature, including the conservation of particle number – defined as the difference between particles and antiparticles – follows from the possibility to describe interactions *perturbatively*. A perturbative description of nature is possible only at low energies. At extremely high energies, higher than those observed in experiments, the situation is expected to change and non-perturbative effects should come into play. These situations will be explored in the next volume.

Achievements in precision

Classical physics is unable to predict *any* property of matter. Quantum field theory predicts all properties of matter, and to the full number of digits – sometimes thirteen – that can be measured today. The precision is usually *not* limited by the inaccuracy of the theory, it is limited by the measurement accuracy. In other words, the agreement between quantum field theory and experiment is only limited by the amount of money one is willing to spend. Table 25 shows some predictions of classical physics and of quantum field theory. The predictions are deduced from the properties of nature collected in the millennium list, which is given in the next section.

TABLE 25 Selected comparisons between classical physics, quantum theory and experiment.

Observable	Classical prediction	Prediction of quantum theory[a]	Measurement	Cost estimate[b]
Simple motion of bodies				
Indeterminacy	0	$\Delta x \Delta p \geqslant \hbar/2$	$(1 \pm 10^{-2})\,\hbar/2$	10 k€
Matter wavelength	none	$\lambda p = 2\pi\hbar$	$(1 \pm 10^{-2})\,\hbar$	10 k€
Tunnelling rate in α decay	0	$1/\tau$ is finite	$(1 \pm 10^{-2})\,\tau$	5 k€
Compton wavelength	none	$\lambda_c = h/m_e c$	$(1 \pm 10^{-3})\,\lambda$	20 k€
Pair creation rate	0	σE	agrees	100 k€
Radiative decay time in hydrogen	none	$\tau \sim 1/n^3$	(1 ± 10^{-2})	5 k€
Smallest angular momentum	0	$\hbar/2$	$(1 \pm 10^{-6})\,\hbar/2$	10 k€
Casimir effect/pressure	0	$p = (\pi^2\hbar c)/(240 r^4)$	(1 ± 10^{-3})	30 k€

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Electrodynamics and thermodynamics taught us that in vacuum, heating one side of the body more than the other will work as motor; the imbalance of heat radiation will push you, albeit rather slowly. Are you able to find at least four other methods from these two domains? Challenge 88 s

General relativity showed that turning one arm will emit gravitational radiation unsymmetrically, leading to motion as well. Can you find at least two better methods? Challenge 89 s

Quantum theory offers a wealth of methods. Of course, quantum mechanics shows that we actually are always moving, since the indeterminacy relation makes rest an impossibility. However, the average motion can be zero even if the spread increases with time. Are you able to find at least four methods of moving on perfect ice due to quantum effects? Challenge 90 s

Materials science, geophysics, atmospheric physics and astrophysics also provide ways to move, such as cosmic rays or solar neutrinos. Can you find four additional methods? Challenge 91 s

Self-organization, chaos theory and biophysics also provide ways to move, when the inner workings of the human body are taken into account. Can you find at least two methods? Challenge 92 s

Assuming that you read already the section following the present one, on the effects of semiclassical *quantum gravity*, here is an additional puzzle: is it possible to move by accelerating a pocket mirror, using the emitted Unruh radiation? Can you find at least two other methods to move yourself using quantum gravity effects? Can you find one from string theory? Challenge 93 s

If you want points for the test, the marking is simple. For students, every working method gives one point. Eight points is ok, twelve points is good, sixteen points is very good, and twenty points or more is excellent. For graduated physicists, the point is given only when a back-of-the-envelope estimate for the ensuing momentum or acceleration is provided.

A summary of quantum electrodynamics

The shortest possible summary of quantum electrodynamics is the following:

▷ Everyday matter is made of charged elementary particles that interact through photon exchange in the way described by Figure 82.

No additional information is necessary. In a bit more detail, quantum electrodynamics starts with *elementary particles* – characterized by their mass, spin, charge, and parities – and with the *vacuum*, essentially a sea of virtual particle–antiparticle pairs. *Interactions* between charged particles are described as the exchange of virtual photons, and electromagnetic *decay* is described as the interaction with the virtual photons of the vacuum.

▷ The Feynman diagram of Figure 82 provides an *exact* description of *all* electromagnetic phenomena and processes.

No contradiction between observation and calculation are known. In particular, the Feynman diagram is equivalent to the QED Lagrangian of equation (18). Because QED is a perturbative theory, the Feynman diagram directly describes the first order effects; Page 126

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

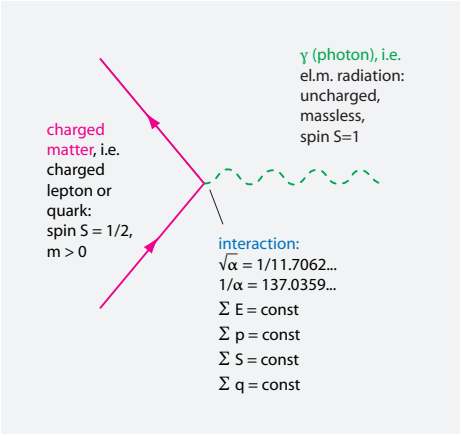


FIGURE 82 The basis of QED; more precisely, the fundamental diagram of QED as a perturbation theory in space-time.

its composite diagrams describe effects of higher order. QED is a perturbative theory.

QED describes all everyday properties of matter and radiation. It describes the *divisibility* down to the smallest constituents, the *isolability* from the environment and the *impenetrability* of matter. It also describes the *penetrability* of radiation. All these properties are due to electromagnetic interactions of constituents and follow from Figure 82. Matter is divisible because the interactions are of finite strength, matter is also divisible because the interactions are of finite range, and matter is impenetrable because interactions among the constituents increase in intensity when they approach each other, in particular because matter constituents are fermions. Radiation is divisible into photons, and is penetrable because photons are bosons and first order photon-photon interactions do not exist.

Both matter and radiation are made of *elementary* constituents. These elementary constituents, whether bosons or fermions, are indivisible, isolable, indistinguishable, and point-like.

It is necessary to use quantum electrodynamics in all those situations for which the characteristic dimensions d are of the order of the Compton wavelength

$$d \approx \lambda_C = \frac{h}{m\,c} \,. \tag{26}$$

In situations where the dimensions are of the order of the de Broglie wavelength, or equivalently, where the action is of the order of the Planck value, simple quantum mechanics is sufficient:

$$d \approx \lambda_{dB} = \frac{h}{m\,v} \,. \tag{27}$$

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

▷ Quantum *field* theory is the part of quantum physics that includes the description of *particle transformations*.

The possibility of particle transformations – including particle reactions, particle emission and particle absorption – results from the existence of a minimum action and of a maximum speed in nature. Emission of light, radioactivity, the burning of the Sun and the history of the composite matter we are made of are due to particle transformations.

Vol. IV, page 30

Due to the possibility of particle transformations, quantum field theory introduces a limit for the localization of particles. In fact, any object of mass m can be localized only within intervals of the Compton wavelength

$$\lambda_C = \frac{h}{mc} = \frac{2\pi\hbar}{mc} \,, \tag{132}$$

where c is the speed of light. At the latest at this distance we have to abandon the classical description and use quantum field theory. If we approach the Compton wavelength, particle transformations become so important that classical physics and even simple quantum theory are not sufficient.

Quantum electrodynamics is the quantum field description of electromagnetism. It includes and explains all particle transformations that involve photons. The Lagrangian of QED is determined by the electromagnetic gauge group U(1), the requirements of space-time (Poincaré) symmetry, permutation symmetry and renormalizability. The latter requirement follows from the continuity of space-time. Through the effects of virtual particles, QED describes electromagnetic decay, lamps, lasers, pair creation, Unruh radiation for accelerating observers, vacuum energy and the Casimir effect, i.e., the attraction of neutral conducting bodies. Particle transformations due to quantum electrodynamics also introduce corrections to classical electrodynamics; among others, particle transformations produce small departures from the superposition principle for electromagnetic fields, including the possibility of photon-photon scattering.

The theory of *weak nuclear interaction* describes parity violation, quark mixings, neutrino mixings, massive vector bosons and the Higgs field for the breaking of the weak SU(2) gauge symmetry. The weak interaction explains a large part of radioactivity, including the heat production inside the Earth, and describes processes that make the Sun shine.

Quantum chromodynamics, the field theory of the strong nuclear interaction, describes all particle transformations that involve gluons. At fundamental scales, the strong interaction is mediated by eight elementary gluons. At larger, femtometre scales, the strong interaction effectively acts through the exchange of spin 0 pions, is strongly attractive, and leads to the formation of atomic nuclei. The strong interaction determines nuclear fusion and fission. Quantum chromodynamics, or QCD, explains the masses of mesons and baryons through their description as bound quark states.

Page 200

By including particle transformations, quantum field theory provides a common basis of concepts and descriptions to materials science, nuclear physics, chemistry, biology, medicine and to most of astronomy. For example, the same concepts allow us to answer questions such as why water is liquid at room temperature, why copper is red, why the rainbow is coloured, why the Sun and the stars continue to shine, why there are about

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Page 261

▷ An *elementary quantum particle* or *elementary quanton* is a countable entity, smaller than its own Compton wavelength, described by energy–momentum, mass, spin, C, P and T parity, electric charge, colour, weak isospin, isospin, strangeness, charm, topness, beauty, lepton number and baryon number.

All moving entities are made of elementary quantum particles. To see how deep this result is, you can apply it to all those moving entities for which it is usually forgotten, such as ghosts, spirits, angels, nymphs, daemons, devils, gods, goddesses and souls. You can check yourself what happens when their particle nature is taken into account.

Challenge 176 e

Quantum particles are never at rest, cannot be localized, move probabilistically, behave as particles or as waves, interfere, can be polarized, can tunnel, are indistinguishable, have antiparticles, interact locally, define length and time scales and they limit measurement precision.

Quantum particles come in two types:

▷ Matter is composed of *fermions:* quarks and leptons. There are 6 quarks that make up nuclei, and 6 leptons – 3 charged leptons, including the electron, and 3 uncharged neutrinos. Elementary fermions have spin 1/2 and obey the Pauli exclusion principle.
▷ Radiation is due to the three gauge interactions and is composed of *bosons*: photons, the weak vector bosons and the 8 gluons. These elementary bosons all have spin 1.

In our adventure, we wanted to know what matter and interactions are. Now we know: they are due to elementary quantum particles. The exploration of motion inside matter, including particle reactions and virtual particle exchange, showed us that matter is made of a *finite number* of elementary quantum particles. Experiments show:

▷ In flat space, elementary particles interact in one of three ways: there is the *electromagnetic interaction*, the *strong nuclear interaction* and the *weak nuclear interaction*.
▷ The three interactions are *exchanges of virtual bosons*.
▷ The three interactions are described by the gauge symmetries U(1), SU(3) and a broken, i.e., approximate SU(2) symmetry.

The three gauge symmetries fix the Lagrangian of every physical system in flat spacetime. The most simple description of the Lagrangians is with the help of Feynman diagrams and the gauge groups.

▷ In all interactions, energy, momentum, angular momentum, electric charge, colour charge, CPT parity, lepton number and baryon number are conserved.

The list of conserved quantities implies:

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

For even larger dimensions, classical physics will do.

Together with gravity, quantum electrodynamics explains almost all observations of motion on Earth; QED unifies the description of matter and electromagnetic radiation in daily life. All everyday objects and all images are described, including their properties, their shape, their transformations and their other changes. This includes self-organization and chemical or biological processes. In other words, QED gives us full grasp of the effects and the variety of motion due to electromagnetism.

Open questions in QED

Even though QED describes motion due to electromagnetism without any discrepancy from experiment, that does not mean that we understand every detail of every example of such motion. For example, nobody has described the motion of an animal with QED yet.* In fact, there is beautiful and fascinating research going on in many branches of electromagnetism.

Ref. 111

Atmospheric physics still provides many puzzles and regularly delivers new, previously unknown phenomena. For example, the detailed mechanisms at the origin of aurorae are still controversial; and the recent unexplained discoveries of discharges *above*

Ref. 112

clouds should not make one forget that even the precise mechanism of charge separation *inside* clouds, which leads to lightning, is not completely clarified. In fact, all examples of electrification, such as the charging of amber through rubbing, the experiment which gave electricity its name, are still poorly understood.

Materials science in all its breadth, including the study of solids, fluids, and plasmas, as well as biology and medicine, still provides many topics of research. In particular, the twenty-first century will undoubtedly be the century of the life sciences.

The study of the interaction of atoms with intense light is an example of present research in atomic physics. Strong lasers can strip atoms of many of their electrons; for such phenomena, there are not yet precise descriptions, since they do not comply to the weak field approximations usually assumed in physical experiments. In strong fields, new

Ref. 113

effects take place, such as the so-called Coulomb explosion.

But also the skies have their mysteries. In the topic of cosmic rays, it is still not clear

Ref. 114

how rays with energies of 10^{22} eV are produced outside the galaxy. Researchers are intensely trying to locate the electromagnetic fields necessary for their acceleration and to understand their origin and mechanisms.

In the theory of quantum electrodynamics, discoveries are expected by all those who

Ref. 115

study it in sufficient detail. For example, Dirk Kreimer has discovered that higher order interaction diagrams built using the fundamental diagram of Figure 82 contain relations to the theory of knots. This research topic will provide even more interesting results in the near future. Relations to knot theory appear because QED is a *perturbative* description, with the vast richness of its non-perturbative effects still hidden. Studies of QED at high energies, where perturbation is *not* a good approximation and where particle numbers are not conserved, promise a wealth of new insights.

* On the other hand, outside QED, there is beautiful work going on how humans move their limbs; it seems that any general human movement is constructed in the brain by combining a small set of fundamental

Ref. 110

movements.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



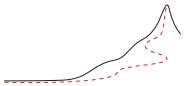
FIGURE 83 The rainbow can only be explained fully if the fine structure constant α can be calculated (© ed g2s, Christophe Afonso).

If we want to be very strict, we need to add that we do *not* fully understand any colour, because we still do not know the origin of the fine structure constant. In particular, the fine structure constant determines the refractive index of water, and thus the formation of a rainbow, as pictured in Figure 83.

Ref. 116

Many other open issues of more practical nature have not been mentioned. Indeed, by far the largest numbers of physicists get paid for some form of applied QED. In our

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



CHAPTER 12

QUANTUM PHYSICS IN A NUTSHELL – AGAIN

Compared to classical physics, quantum theory is definitely more complex. The basic idea however, is simple: in nature there is a smallest change, or a smallest action, with the value $\hbar = 1.1 \cdot 10^{-34}$ Js. The smallest action value leads to all the strange observations made in the microscopic domain, such as wave behaviour of matter, indeterminacy relations, decoherence, randomness in measurements, indistinguishability, quantization of angular momentum, tunnelling, pair creation, decay, particle reactions and virtual particle exchange.

QUANTUM FIELD THEORY IN A FEW SENTENCES

> Deorum offensae diis curae.
> Voltaire, *Traité sur la tolérance.*

All of quantum theory can be resumed in a few sentences.

▷ In nature, actions smaller than $\hbar = 1.1 \cdot 10^{-34}$ Js are not observed.

The existence of a smallest action in nature directly leads to the main lesson we learned about motion in the quantum part of our adventure:

▷ If something moves, it is made of quantons, or quantum particles.

▷ There are *elementary* quantum particles.

These statements apply to everything, thus to all objects and to all images, i.e., to matter and to radiation. Moving stuff is made of *quantons*. Stones, water waves, light, sound waves, earthquakes, tooth paste and everything else we can interact with is made of moving quantum particles. Experiments show:

▷ All intrinsic object properties observed in nature – such as electric charge, weak charge, colour charge, spin, parity, lepton number, etc., with the only exception of mass – appear as *integer* numbers of a smallest unit; in composed systems they either add or multiply.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

change, explored eversion, studied vortices, fluids, polymers, knots and their rearrangement, and explored the motion of dislocations in solids. We found that shape change is described by gauge theory, eversion is described by space-duality, vortices follow the Schrödinger equation, fluids and polymers resemble general relativity and black holes, knot shapes are hard to calculate and dislocations behave relativistically.

The motion of wobbly objects is a neglected topic in textbooks on motion. Research is progressing at full speed; it is expected that many beautiful analogies with traditional physics will be discovered in the near future. For example, in this chapter we have not explored any possible analogy for the motion of light. Similarly, including quantum theory into the description of wobbly bodies' motion remains a fascinating issue for anybody aiming to publish in a new field.

Challenge 175 r

In summary, we found that wobbly entities can reproduce most fields of modern physics. Are there wobbly entities that reproduce *all* of modern physics? We will explore the question in the last volume.



Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

adventure however, our quest is the description of the *fundamentals* of motion. And so far, we have not achieved it. In particular, we still need to understand motion in the realm of atomic nuclei and the effect of the quantum of action in the domain of gravitation. We start with the latter topic.



Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Chapter 4

QUANTUM MECHANICS WITH GRAVITATION – FIRST STEPS

Gravitation is a weak effect. Indeed, every seaman knows that storms, not gravity, cause the worst accidents. Despite its weakness, the inclusion of gravity into quantum theory raises a number of issues. We must solve them all in order to complete our mountain ascent.

Gravity acts on quantum systems: in the chapter on general relativity we already mentioned that light frequency changes with height. Thus gravity has a simple and measurable effect on photons. But gravity also acts on all other quantum systems, such as atoms and neutrons, as we will see. And the quantum of action plays an important role in the behaviour of black holes. We explore these topics now.

Falling atoms

In 2004 it finally became possible to repeat Galileo's leaning tower experiment with single atoms instead of steel balls. This is not an easy experiment because even the smallest effects disturb the motion. The result is as expected: single atoms do fall like stones. In particular, atoms of different mass fall with the same acceleration, within the experimental precision of one part in 6 million.

Ref. 117

The experiment was difficult to perform, but the result is not surprising, because all falling everyday objects are made of atoms. Indeed, Galileo himself had predicted that atoms fall like stones, because parts of a body have to fall with the same acceleration as the complete body. But what is the precise effect of gravity on wave functions? This question is best explored with the help of neutrons.

Vol. I, page 202

Playing table tennis with neutrons

The gravitational potential also has directly measurable effects on quantum particles. Classically, a table tennis ball follows a parabolic path when bouncing over a table tennis table, as long as friction can be neglected. The general layout of the experiment is shown in Figure 84. How does a quantum particle behave in the same setting?

In the gravitational field, a bouncing quantum particle is still described by a wave function. In contrast to the classical case however, the possible energy values of a falling quantum particle are discrete. Indeed, the quantization of the action implies that for a

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 180 A flying snake, *Chrysopelea paradisii*, performing the feat that gave it its name (QuickTime film © Jake Socha).

* *

A striking example of how wobbly entities can behave is given in Figure 180. There is indeed a family of snakes that like to jump off a tree and sail through the air to a neighbouring tree. Both the jump and the sailing technique have been studied in recent years. The website www.flyingsnake.org by Jake Socha provides additional films. His fascinating publications tell more about these intriguing reptiles.

Ref. 267

* *

When a plane moves at supersonic speed through humid air, sometimes a conical cloud forms and moves with the plane. How does this cloud differ from the ones studied above?

Vol. I, page 325

Challenge 173 e

* *

One of the toughest challenges about clouds: is it possible to make rain on demand? So far, there are almost no positive results. Inventing a method, possibly based on hygroscopic salt injection or with the help of lasers, will be a great help to mankind.

Challenge 174 ny

* *

Do knots have a relation to elementary particles? The question is about 150 years old. It was first investigated by William Thomson-Kelvin and Peter Tait in the late nineteenth century. So far, no proof of a relation has been found. Knots might be of importance at Planck scales, the smallest dimensions possible in nature. We will explore how knots and the structure of elementary particles might be related in the last volume of this adventure.

Summary on wobbly objects

We can sum up the possible motions of extended systems in a few key themes. In earlier chapters we studied waves, solitons and interpenetration. These observations are described by wave equations. In this chapter we explored the way to move through shape

Vol. I, page 315

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

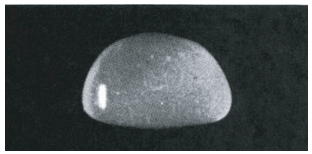


FIGURE 178 A large raindrop falling downwards.



FIGURE 179 Is this possible?

lear interactions, and to define more elaborate knot invariants, a discovery that brought him the Fields medal.

* *

If we move along a knot and count the crossings where we stay above and subtract the number of crossings where we pass below, we get a number called the *writhe* of the knot. It is not an invariant, but usually a tool in building them. Indeed, the writhe is not necessarily invariant under one of the three Reidemeister moves. Can you see which one, using Figure 172? However, the writhe is invariant under flypes.

Challenge 167 e

* *

Modern knot research is still a topic with many open questions. A recent discovery is the *quasi-quantization of three-dimensional writhe* in tight knots. Many discoveries are still expected in the domain of geometric knot theory.

Ref. 265

* *

There are two ways to tie your shoes. Can you find them?

Challenge 168 e

* *

What is the shape of raindrops? Try to picture it. However, use your reason, not your prejudice! By the way, it turns out that there is a maximum size for raindrops, with a value of about 4 mm. The shape of such a large raindrop is shown in Figure 178. Can you imagine where the limit comes from?

Challenge 169 s

Ref. 266

For comparison, the drops in clouds, fog or mist are in the range of 1 to 100 µm, with a peak at 10 to 15 µm. In situations where all droplets are of similar size and where light is scattered only once by the droplets, one can observe coronae, glories or fogbows.

Vol. III, page 163

Vol. III, page 130

* *

What is the entity shown in Figure 179 – a knot, a braid or a link?

Challenge 170 s

* *

Can you find a way to classify tie knots?

Challenge 171 d

* *

Are you able to find a way to classify the way shoe laces can be threaded?

Challenge 172 s

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

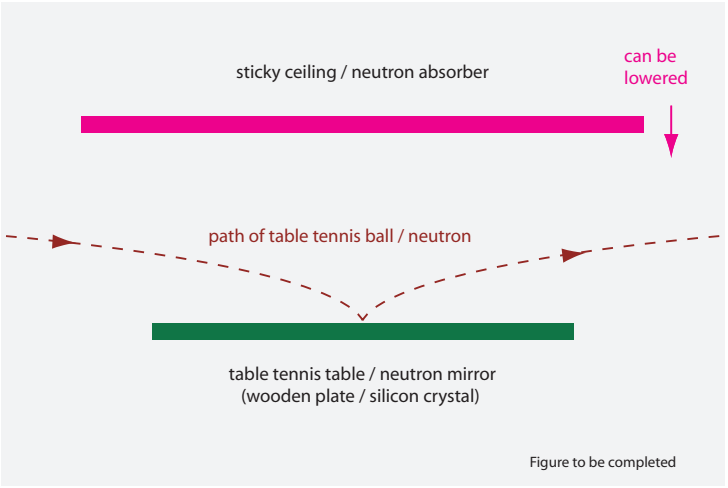


FIGURE 84 Table tennis and neutrons.

bounce of energy E_n and duration t_n,

Challenge 94 e

$$n\hbar \sim E_n t_n \sim \frac{E_n^{3/2}}{gm^{1/2}} \,. \tag{28}$$

In other words, only discrete bounce heights, distinguished by the number n, are possible in the quantum case. The discreteness leads to an expected probability density that changes with height in discrete steps, as shown in Figure 84.

The best way to realize the experiment with quantum particles is to produce an intense beam of neutral particles, because neutral particles are not affected by the stray electromagnetic fields that are present in every laboratory. Neutrons are ideal, as they are produced in large quantities by nuclear reactors. The experiment was first performed in 2002, by Hartmut Abele and his group, after years of preparations. Using several clever tricks, they managed to slow down neutrons from a nuclear reactor to the incredibly small value of 8 m/s, comparable to the speed of a table tennis ball. (The equivalent temperature of these ultracold neutrons is 1 mK, or 100 neV.) They then directed the neutrons onto a neutron mirror made of polished glass – the analogue of the table tennis table – and observed the neutrons bouncing back up. To detect the bouncing, they lowered an absorber – the equivalent of a sticky ceiling – towards the table tennis table, i.e., towards the neutron mirror, and measured how many neutrons still reached the other end of the table. (Both the absorber and the mirror were about 20 cm in length.)

Ref. 118

Why did the experiment take so many years of work? The lowest energy levels for neutrons due to gravity are $2.3 \cdot 10^{-31}$ J, or 1.4 peV, followed by 2.5 peV,3.3 peV, 4.1 peV,

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

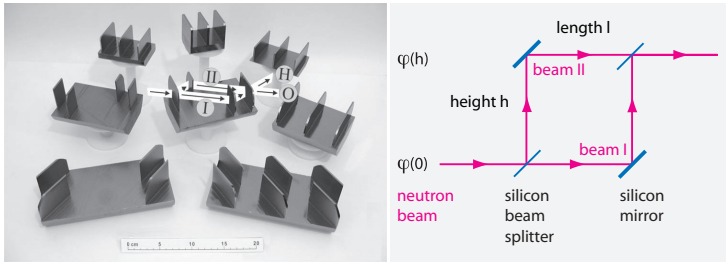


FIGURE 85 The weakness of gravitation. A neutron interferometer made of a silicon single crystal (with the two neutron beams I and II) can be used to detect the effects of gravitation on the phase of wave functions (photo © Helmut Rauch and Erwin Seidl).

and so forth. To get an impression of the smallness of these values, we can compare it to the value of $2.2 \cdot 10^{-18}$ J or 13.6 eV for the lowest state in the hydrogen atom. Despite these small energy values, the team managed to measure the first few discrete energy levels. The results confirmed the prediction of the Schrödinger equation, with the gravitational potential included, to the achievable measurement precision.

In short, gravity influences wave functions. In particular, gravity changes the phase of wave functions, and does so as expected.

The gravitational phase of wave functions

Not only does gravity change the shape of wave functions; it also changes their *phase*. Can you imagine why? (Challenge 95 s) The prediction was first confirmed in 1975, using a device invented by Helmut Rauch and his team. (Ref. 119) Rauch had developed neutron interferometers based on single silicon crystals, shown in Figure 85, in which a neutron beam – again from a nuclear reactor – is split into two beams and the two beams are then recombined and brought to interference.

By rotating the interferometer mainly around the horizontal axis, Samuel Werner and his group let the two neutron beams interfere after having climbed a small height h at two different locations. (Ref. 120) The experiment is shown schematically on the right of Figure 85. The neutron beam is split; the two beams are deflected upwards, one directly, one a few centimetres further on, and then recombined.

For such a experiment in gravity, quantum theory predicts a phase difference $\Delta\varphi$ between the two beams given by (Challenge 96 ny)

$$\Delta\varphi = \frac{mghl}{\hbar v} \,, \tag{29}$$

where l is the horizontal distance between the two climbs and v and m are the speed and mass of the neutrons. All experiments – together with several others of similar simple elegance – have confirmed the prediction by quantum theory within experimental errors.

In the 1990s, similar experiments have even been performed with complete atoms. (Ref. 121)

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

an example. The hagfish uses this motion to cover its body with a slime that prevents predators from grabbing it; it also uses this motion to escape the grip of predators, to get rid of the slime after the danger is over, and to push against a prey it is biting in order to extract a piece of meat. All studied knot fish form only left handed trefoil knots, by the way; this is another example of chirality in nature.

* *

Proteins, the molecules that make up many cell structures, are chains of aminoacids. (Ref. 261) It seems that very few proteins are knotted, and that most of these form trefoil knots. However, a figure-eight knotted protein has been discovered in 2000 by William Taylor.

* *

One of the most incredible discoveries of recent years is related to knots in DNA molecules. The *DNA molecules* inside cell nuclei can be hundreds of millions of base pairs long; they regularly need to be packed and unpacked. When this is done, often the same happens as when a long piece of rope or a long cable is taken out of a closet.

It is well known that you can roll up a rope and put it into a closet in such a way that it looks orderly stored, but when it is pulled out at one end, a large number of knots is suddenly found. (Ref. 263) In 2007, this effects was finally explored in detail. Strings of a few metres in length were put into square boxes and shaken, in order to speed up the effect. The result, shown partly in Figure 177, was astonishing: almost every imaginable knot – up to a certain complexity that depends on the length and flexibility of the string – was formed in this way.

To make a long story short, the tangling also happens to nature when it unpacks DNA in cell nuclei. Life requires that DNA molecules move inside the cell nucleus without hindrance. So what does nature do? Nature takes a simpler approach: when there are unwanted crossings, it cuts the DNA, moves it over and puts the ends together again. In cell nuclei, there are special enzymes, the so-called topoisomerases, which perform this process. The details of this fascinating process are still object of modern research.

* *

The great mathematician Carl-Friedrich Gauß – often written as 'Gauss' in English – was the first person to ask what happens when an electrical current I flows along a wire A that is *linked* with a wire B. (Ref. 264) He discovered a beautiful result by calculating the effect of the magnetic field of one wire onto the other:

$$\frac{1}{4\pi I}\int_A \mathrm{d}\boldsymbol{x}_A \cdot \boldsymbol{B}_B = \frac{1}{4\pi}\int_A \mathrm{d}\boldsymbol{x}_A \cdot \int_B \mathrm{d}\boldsymbol{x}_B \times \frac{(\boldsymbol{x}_A - \boldsymbol{x}_B)}{|\boldsymbol{x}_A - \boldsymbol{x}_B|^3} = n \,, \tag{131}$$

where the integrals are performed along the wires. Gauss found that the number n does not depend on the precise shape of the wires, but only on the way they are linked. Deforming the wires does not change the resulting number n. Mathematicians call such a number a *topological invariant*. In short, Gauss discovered a physical method to calculate a mathematical invariant for links; the research race to do the same for other invariants, and in particular for knots and braids, is still going on today.

In the 1980s, Edward Witten was able to generalize this approach to include the nuc-

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

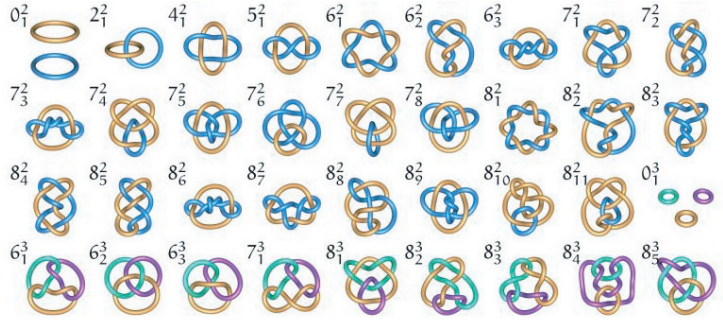


FIGURE 175 The diagrams for the simplest links with two and three components (© Robert Scharein).



FIGURE 176 A hagfish tied into a knot (© Christine Ortlepp).

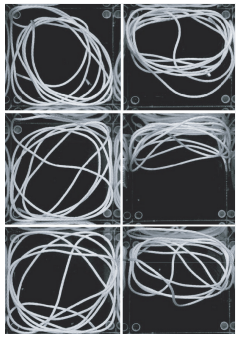


FIGURE 177 How apparent order for long rope coils (left) changes over time when shaking the container (right) (© 2007 PNAS).

The physics of human swimming is fascinating. To learn the details on how to move in order to swim as rapidly as possible, explore the wonderful website coachsci.sdsu.edu/swim by Brent Rushall. He tells how to move the arms, the trunk and the legs and he shows how champions perform these movements. Rushall also tells about the bizarre theories that are aired in the field of swimming, such as the mistaken idea that lift plays a role in human swimming.

* *

Ref. 262 A famous type of eel, the *knot fish Myxine glutinosa*, also called hagfish or slime eel, is able to make a knot in his body and move this knot from head to tail. Figure 176 shows

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

These atom interferometers are so sensitive that local gravity g can be measured with a precision of more than eight significant digits.

In short, neutrons, atoms and photons show no surprises in gravitational fields. Gravity can be included into all quantum systems of everyday life. By including gravity in the potential, the Schrödinger and Dirac equations can thus be used, for example, to describe the growth and the processes inside trees. Trees can mostly be described with quantum electrodynamics in weak gravity.

The gravitational Bohr atom

Challenge 97 ny Can gravity lead to *bound* quantum systems? A short calculation shows that an electron circling a proton due to gravity alone, without electrostatic attraction, would do so at a gravitational Bohr radius of

$$r_{\text{gr.B.}} = \frac{\hbar^2}{G m_e^2 m_p} = 1.1 \cdot 10^{29}\,\text{m} \tag{30}$$

which is about a thousand times the distance to the cosmic horizon. A gravitational Bohr atom would be larger than the universe. This enormous size is the reason that in a normal hydrogen atom there is not a *single way* to measure gravitational effects between its components. (Are you able to confirm this?) Challenge 98 e

But why is gravity so weak? Or equivalently, why are the universe and normal atoms so much smaller than a gravitational Bohr atom? At the present point of our quest these questions cannot be answered. Worse, the weakness of gravity even means that with high probability, future experiments will provide little additional data helping to decide among competing answers. The only help is careful thought.

We might conclude from all this that gravity does not require a quantum description. Indeed, we stumbled onto quantum effects because classical electrodynamics implies, in stark contrast with reality, that atoms decay in about 0.1 ns. Classically, an orbiting electron would emit radiation until it falls into the nucleus. Quantum theory is thus necessary to explain the existence of matter.

Challenge 99 ny When the same stability calculation is performed for the emission of gravitational radiation by orbiting electrons, one finds a decay time of around 10^{37} s. (True?) This extremely large value, trillions of times longer than the age of the universe, is a result of the low emission of gravitational radiation by rotating masses. Therefore, the existence of normal atoms does not require a quantum theory of gravity.

Vol. II, page 178

Curiosities about quantum theory and gravity

Due to the influence of gravity on phases of wave functions, some people who do not believe in bath induced decoherence have even studied the influence of gravity on the decoherence process of usual quantum systems in flat space-time. Predictably, the calculated results do not reproduce experiments. Ref. 145

* *

Despite its weakness, gravitation provides many puzzles. Most famous are a number of

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

curious coincidences that can be found when quantum mechanics and gravitation are combined. They are usually called 'large number hypotheses' because they usually involve large dimensionless numbers. A pretty, but less well known version connects the Ref. 146 Planck length, the cosmic horizon R_0, and the number of baryons N_b:

$$(N_b)^3 \approx \left(\frac{R_0}{l_{Pl}}\right)^4 = \left(\frac{t_0}{t_{Pl}}\right)^4 \approx 10^{244} \tag{31}$$

in which $N_b = 10^{81}$ and $t_0 = 1.2 \cdot 10^{10}$ a were used. There is no known reason why the number of baryons and the horizon size R_0 should be related in this way. This coincidence is equivalent to the one originally stated by Dirac,* namely

$$m_p^3 \approx \frac{\hbar^2}{Gct_0} \,. \tag{33}$$

where m_p is the proton mass. This approximate equality seems to suggest that certain microscopic properties, namely the mass of the proton, is connected to some general properties of the universe as a whole. This has lead to numerous speculations, especially since the time dependence of the two sides differs. Some people even speculate whether relations (31) or (33) express some long-sought relation between local and global topo- Ref. 148 logical properties of nature. Up to this day, the only correct statement seems to be that they are *coincidences* connected to the time at which we happen to live, and that they should not be taken too seriously.

* *

Photons not travelling parallel to each other attract each other through gravitation and thus deflect each other. Could two such photons form a bound state, a sort of atom of light, in which they would circle each other, provided there were enough empty space Challenge 100 s for this to happen?

In summary, quantum gravity is unnecessary in every single domain of everyday life. However, we will see now that quantum gravity is necessary in domains which are more remote, but also more fascinating.

Ref. 147 * The equivalence can be deduced using $Gn_b m_p = 1/t_0^2$, which, as Weinberg explains, is required by several Vol. VI, page 103 cosmological models. Indeed, this can be rewritten simply as

$$m_0^2/R_0^2 \approx m_{Pl}^2/R_{Pl}^2 = c^4/G^2 \,. \tag{32}$$

Together with the definition of the baryon density $n_b = N_b/R_0^3$ one gets Dirac's large number hypothesis, substituting protons for pions. Note that the Planck time and length are defined as $\sqrt{\hbar G/c^5}$ and $\sqrt{\hbar G/c^3}$, and are the natural units of length and time. We will study them in detail in the last part of the mountain ascent.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

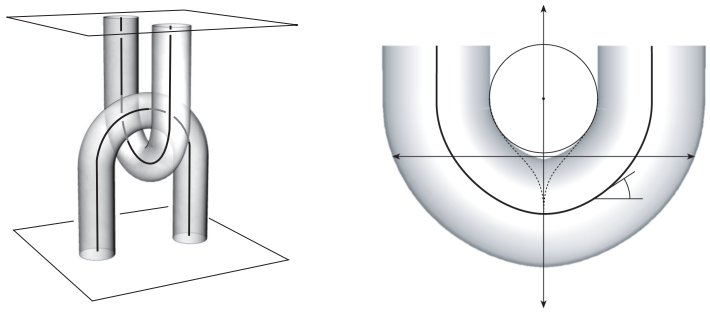


FIGURE 174 The ropelength problem for the simple clasp, and the candidate configuration that probably minimizes ropelength, leaving a gap between the two ropes (© Jason Cantarella).

the tightening process, see the animations on the website www.jasoncantarella.com/movs. But what is the formula giving the ropelength values? Nobody knows, because the precise shape of the trefoil knot – or of any other knot – is unknown. Lou Kauffman has a simple comment for the situation: 'It is a scandal of mathematics!'

— Mathematicians also study more general structures than knots. *Links* are the generalization of knots to several closed strands. *Braids* and *long links* are the generalization of links to *open* strands. Now comes the next surprise, illustrated in Figure 174. Even for two ropes that form a simple *clasp*, i.e., two linked letters 'U', the ropelength Ref. 260 problem is unsolved – and there is not even a knot involved! In fact, in 2004, Jason Cantarella and his colleagues have presented a candidate for the shape that minimizes ropelength. Astonishingly, the candidate configuration leaves a small gap between the two ropes, as shown in Figure 174.

In short, the shape of knots is a research topic that has barely taken off. Therefore we have to leave these questions for a future occasion.

Curiosities and fun challenges on knots and wobbly entities

Challenge 166 r Knots appear rarely in nature. For example, tree branches or roots do not seem to grow many knots during the lifetime of a plant. How do plants avoid this? In other words, why are there no knotted bananas or knotted flower stems in nature?

Recent research has also explored how octopusses avoid knots in their arms. It was found that the arms secrete a chemical substance that prevents arms or parts of the arms from sticking together.

* *

Not only knot, also links can be classified. The simplest links, i.e., the links for which the simplest configuration has the smallest number of crossings, are shown in Figure 175.

* *

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

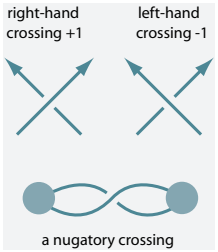


FIGURE 171 Crossing types in knots.

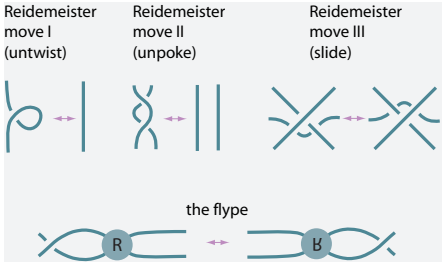


FIGURE 172 The Reidemeister moves and the flype.



FIGURE 173 A tight open overhand knot and a tight open figure-eight knot (© Piotr Pieranski)

there is no surface *embedded* in four dimensions which has as $t = 0$ slice a knot, and as $t = 1$ slice the circle. Such a surface embedding needs at least five dimensions.

In higher dimensions, knots are thus possible *only* if n-spheres are tied instead of circles; for example, as just said, 2-spheres can be tied into knots in 4 dimensions, 3-spheres in 5 dimensions and so forth.

The hardest open problems that you can tell your grandmother

Even though mathematicians have achieved good progress in the classification of knots, surprisingly, they know next to nothing about the *shapes* of knots. Here are a few problems that are still open today:

Challenge 165 r

— This is the simplest unsolved knot problem: Imagine an ideally wobbly rope, that is, a rope that has the same radius everywhere, but whose curvature can be changed as one prefers. Tie a trefoil knot into the rope. By how much do the ends of the rope get nearer? In 2006, there are only numerical estimates for the answer: about 10.1 radiuses. There is no formula yielding the number 10.1. Alternatively, solve the following problem: what is the rope length of a closed trefoil knot? Also in this case, only numerical values are known – about 16.33 radiuses – but no exact formula. The same is valid for any other knot, of course.

Ref. 259

— For mathematical knots, i.e., *closed* knots, the problem is equally unsolved. For example: the ropelength of the tight trefoil knot is known to be around 16.33 diameters, and that of the figure-eight knot about 21.04 diameters. For beautiful visualizations of

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

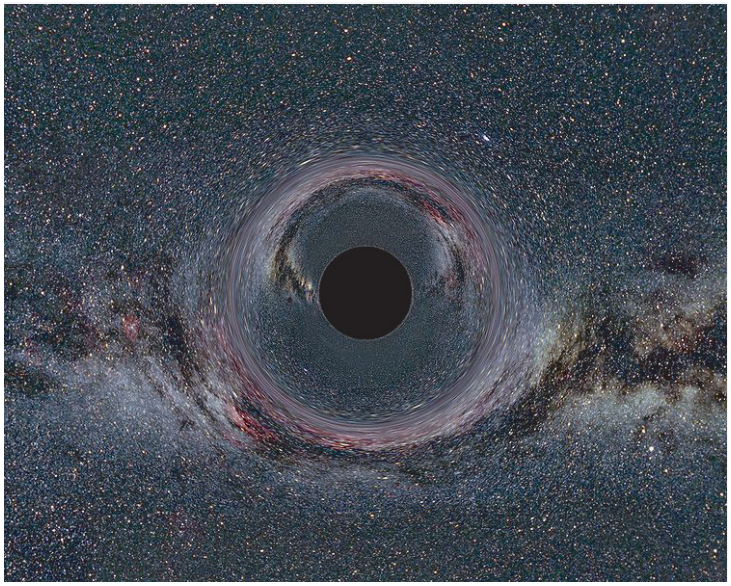


FIGURE 86 A simplified simulated image – not a photograph – of how a black hole of ten solar masses, with Schwarzschild radius of 30 km, seen from a constant distance of 600 km, will distort an image of the Milky Way in the background (image © Ute Kraus at www.tempolimit-lichtgeschwindigkeit.de).

Gravitation and limits to disorder

> Die Energie der Welt ist constant.
> Die Entropie der Welt strebt einem Maximum zu.*
> Rudolph Clausius

Vol. I, page 256

We have already encountered the famous statement by Clausius, the father of the term 'entropy'. We have also found that the Boltzmann constant k is the smallest entropy value found in nature.

What is the influence of gravitation on entropy, and on thermodynamics in general? For a long time, nobody was interested in this question. In parallel, for many decades nobody asked whether there also exists a theoretical *maximum* for entropy. The situations changed dramatically in 1973, when Jacob Bekenstein discovered that the two issues are related.

Ref. 122

Bekenstein was investigating the consequences gravity has for quantum physics. He

* 'The energy of the universe is constant. Its entropy tends towards a maximum.'

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

found that the entropy S of an object of energy E and size L is bound by

$$S \leqslant EL\frac{k\pi}{\hbar c} \tag{34}$$

for all physical systems, where k is the Boltzmann constant. In particular, he deduced that (nonrotating) *black holes* saturate the bound. We recall that black holes are the densest systems for a given mass. They occur when matter collapses completely. Figure 86 shows an artist's impression.

Vol. II, page 262

Challenge 101 s

Bekenstein found that black holes have an entropy given by

$$S = A\,\frac{kc^3}{4G\hbar} = M^2\,\frac{4\pi kG}{\hbar c} \tag{35}$$

where A is now the area of the *horizon* of the black hole. It is given by $A = 4\pi R^2 = 4\pi(2GM/c^2)^2$. In particular, the result implies that every black hole has an entropy. Black holes are thus disordered systems described by thermodynamics. In fact, *black holes are the most disordered systems known*.*

Challenge 102 s

As an interesting note, the maximum entropy also implies an upper memory limit for memory chips. Can you find out how?

Ref. 124

Challenge 103 s

Black hole entropy is somewhat mysterious. What are the different microstates leading to this macroscopic entropy? It took many years to convince physicists that the microstates are due to the various possible states of the black hole horizon itself, and that they are somehow due to the diffeomorphism invariance at this boundary. As Gerard 't Hooft explains, the entropy expression implies that the number of degrees of freedom of a black hole is about (but not exactly) one per Planck area of the horizon.

If black holes have entropy, they must have a temperature. What does this temperature mean? In fact, nobody believed this conclusion until two unrelated developments confirmed it within a short time.

Measuring acceleration with a thermometer: Fulling–Davies–Unruh radiation

Ref. 125

Independently, Stephen Fulling in 1973, Paul Davies in 1975 and William Unruh in 1976 made the same theoretical discovery while studying quantum theory: if an inertial observer observes that he is surrounded by vacuum, a second observer *accelerated* with respect to the first does not: he observes black body radiation. The appearance of radiation for an accelerated observer in vacuum is called the *Fulling–Davies–Unruh effect*. All

* The precise discussion that black holes are the most disordered systems in nature is quite subtle. The issue is summarized by Bousso. Bousso claims that the area appearing in the maximum entropy formula cannot be taken naively as the area at a given time, and gives four arguments why this should be not allowed. However, all four arguments are wrong in some way, in particular because they assume that lengths smaller than the Planck length or larger than the universe's size can be measured. Ironically, he brushes aside some of the arguments himself later in the paper, and then deduces an improved formula, which is exactly the same as the one he criticizes first, just with a different interpretation of the area A. Later in his career, Bousso revised his conclusions; he now supports the maximum entropy bound. In short, the expression of black hole entropy is indeed the maximum entropy for a physical system with surface A.

Ref. 123

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Ref. 256

In 1949, Schubert proved that every knot can be decomposed in a unique way as sum of prime knots. Knots thus behave similarly to integers.

If prime knots are ordered by their crossing numbers, as shown in Figure 170, the trivial knot (0_1) is followed by the trefoil knot (3_1) and by the figure-eight knot (4_1). The figure only shows *prime knots*, i.e., knots that cannot be decomposed into two knots that are connected by two parallel strands. In addition, the figure only shows one of the often possible two mirror versions.

Ref. 256

Together with the search for invariants, the tabulation of knots – a result of their classification – is a modern mathematical sport. Flat knot diagrams are usually ordered by the minimal number of crossings as done in Figure 170. There is 1 knot with zero, 1 with three and 1 with four crossings (not counting mirror knots); there are 2 knots with five and 3 with six crossings, 7 knots with seven, 21 knots with eight, 41 with nine, 165 with ten, 552 with eleven, 2176 with twelve, 9988 with thirteen, 46 972 with fourteen, 253 293 with fifteen and 1 388 705 knots with sixteen crossings.

The mirror image of a knot usually, but not always, is different from the original. If you want a challenge, try to show that the trefoil knot, the knot with three crossings, is different from its mirror image. The first mathematical proof was by Max Dehn in 1914.

Ref. 257

Antiknots do not exist. An *antiknot* would be a knot on a rope that cancels out the corresponding knot when the two are made to meet along the rope. It is easy to prove that this is impossible. We take an infinite sequence of knots and antiknots on a string, $K - K + K - K + K - K$.... On the one hand, we could make them disappear in this way $K-K+K-K+K-K... = (K-K)+(K-K)+(K-K)... = 0$. On the other hand, we could do the same thing using $K-K+K-K+K-K... = K(-K+K)+(-K+K)+(-K+K)... = K$. The only knot K with an antiknot is thus the unknot $K = 0$.*

How do we describe such a knot through the telephone? Mathematicians have spent a lot of time to figure out smart ways to achieve it. The obvious way is to flatten the knot onto a plane and to list the position and the type (below or above) of the crossings. (See Figure 171.) But what is the *simplest* way to describe knots by the telephone? The task is not completely finished, but the end is in sight. Mathematicians do not talk about 'telephone messages', they talk about *knot invariants*, i.e., about quantities that do not depend on the precise shape of the knot. At present, the best description of knots use polynomial invariants. Most of them are based on a discovery by Vaughan Jones in 1984. However, though the Jones polynomial allows us to uniquely describe most simple knots, it fails to do so for more complex ones. But the Jones polynomial finally allowed mathematicians to prove that a diagram which is alternating and eliminates nugatory crossings (i.e., if it is 'reduced') is indeed one which has minimal number of crossings. The polynomial also allows showing that any two reduced alternating diagrams are related by a sequence of flypes.

In short, the simplest way to describe a knot through the telephone is to give its Kauffman polynomial, together with a few other polynomials.

Since knots are stable in time, a knotted line in three dimensions is equivalent to a knotted surface in space-time. When thinking in higher dimensions, we need to be careful. Every knot (or knotted line) can be untied in four or more dimensions. However,

* This proof does *not* work when performed with numbers; we would be able to deduce $1 = 0$ by setting K=1. Why is this proof valid with knots but not with numbers?

Challenge 164 s

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

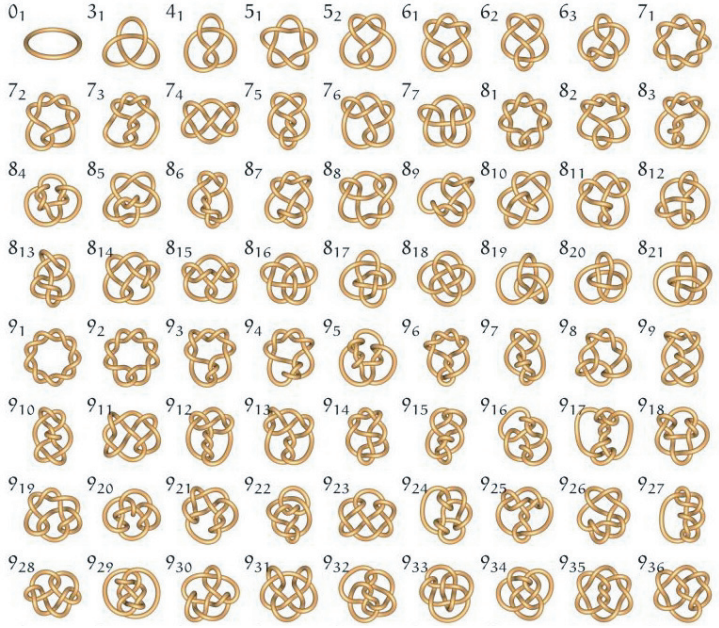


FIGURE 170 The knot diagrams for the simplest prime knots (© Robert Scharein).

It is sure, however, that polymers are often knotted and linked.

Knots and links

> "Don't touch this, or I shall tie your fingers into knots!"
>
> (Nasty, but surprisingly efficient child education technique.)

Knots and their generalization are central to the study of wobbly object motion. A *(mathematical) knot* is a closed piece of rubber string, i.e., a string whose ends have been glued together, which cannot be deformed into a circle or a simple loop. The simple loop is also called the *trivial knot*.

Knots are of importance in the context of this chapter as they visualize the limitations of the motion of wobbly entities. In addition, we will discover other reasons to study knots later on. In this section, we just have a bit of fun.* Ref. 255

* Beautiful illustrations and detailed information about knots can be found on the Knot Atlas website at katlas.math.toronto.edu and at the KnotPlot website at www.knotplot.com.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

these results about black holes were waiting to be discovered since the 1930s; incredibly, nobody had thought about them for the subsequent 40 years.

The radiation has a spectrum corresponding to the temperature

$$T = \frac{\hbar}{2\pi kc}\, a\,, \tag{36}$$

where a is the magnitude of the acceleration. The result means that there is no vacuum on Earth, because any observer on its surface can maintain that he is accelerated with $9.8\,\mathrm{m/s^2}$, thus leading to $T = 40\,\mathrm{zK}$! We can thus measure gravity, at least in principle, using a thermometer. However, even for the largest practical accelerations the temperature values are so small that it is questionable whether the effect will ever be confirmed experimentally in this precise way. But if it will, it will be a beautiful experimental result. Ref. 126

When this effect was predicted, people explored all possible aspects of the argument. For example, also an observer in rotational motion detects radiation following expression (36). But that was not all. It was found that the simple acceleration of a *mirror* leads to radiation *emission*! Mirrors are thus harder to accelerate than other bodies of the same mass.

When the acceleration is high enough, also *matter* particles can be emitted and detected. If a particle counter is accelerated sufficiently strongly across the vacuum, it will start counting particles! We see that the difference between vacuum and matter becomes fuzzy at large accelerations. This result will play an important role in the search for unification, as we will discover later on. Vol. VI, page 64

Surprisingly, at the end of the twentieth century it became clear that the Fulling–Davies–Unruh effect possibly had already been observed *before* it was predicted! The Fulling–Davies–Unruh effect turned out be related to a well-established observation: the so-called *Sokolov–Ternov effect*. Ref. 127 In 1963, the Russian physicist Igor Ternov, together with Arsenji Sokolov, had used the Dirac equation to predict that electrons in circular accelerators and in storage rings that circulate at high energy would automatically polarize. The prediction was first confirmed by experiments at the Russian Budker Institute of Nuclear Physics in 1971, and then confirmed by experiments in Orsay, in Stanford and in Hamburg. Nowadays, the effect is used routinely in many accelerator experiments. In the 1980s, Bell and Leinaas realized that the Sokolov–Ternov effect is the *same* effect as the Fulling–Davies–Unruh effect, but seen from a different reference frame! Ref. 127 The equivalence is somewhat surprising. In charges moving in a storage ring, the emitted radiation is not thermal, so that the analogy is not obvious or simple. But the effect that polarizes the beam – namely the difference in photon emission for spins that are parallel and antiparallel to the magnetic field – is the same as the Fulling–Davies–Unruh effect. We thus have another case of a theoretical discovery that was made much later than necessary. In 2006 however, this equivalence was put into question again. Ref. 127 The issue is not closed.

Black holes aren't black

In 1973 and 1974, Jacob Bekenstein, and independently, Stephen Hawking, famous for the intensity with which he fights a disease which forces him into the wheelchair, surprised the world of general relativity with a fundamental theoretical discovery. They found that

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

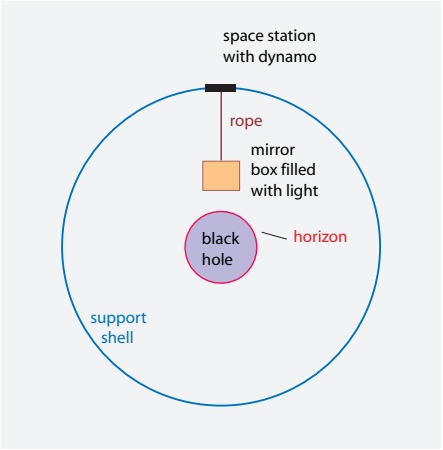


FIGURE 87 A thought experiment allowing you to deduce the existence of black hole radiation.

if a virtual particle–antiparticle pair appeared in the vacuum near the horizon, there is a finite chance that one particle escapes as a real particle, while the virtual antiparticle is captured by the black hole. The virtual antiparticle is thus of negative energy, and reduces the mass of the black hole. The mechanism applies both to fermions and bosons. From far away this effect looks like the emission of a particle. A detailed investigation showed that the effect is most pronounced for photon emission. In short, Bekenstein and Hawking showed that *black holes radiate as black bodies*.

Black hole radiation confirms both the result on black hole entropy by Bekenstein and the effect for observers accelerated in vacuum found by Fulling, Davies and Unruh. When all this became clear, a beautiful thought experiment was published by William Unruh and Robert Wald, showing that the whole result could have been deduced already 50 years earlier! Ref. 128

Shameful as this delay of the discovery is for the community of theoretical physicists, the story itself remains beautiful. It starts in the early 1970s, when Robert Geroch studied the issue shown in Figure 87. Imagine a mirror box full of heat radiation, thus full of light. The mass of the box is assumed to be negligible, such as a box made of thin aluminium paper. We lower the box, with all its contained radiation, from a space station towards a black hole. On the space station, lowering the weight of the heat radiation allows generating energy. Obviously, when the box reaches the black hole horizon, the heat radiation is red-shifted to infinite wavelength. At that point, the full amount of energy originally contained in the heat radiation has been provided to the space station. We can now do the following: we can open the box on the horizon, let drop out whatever is still inside, and wind the empty and massless box back up again. As a result, we have completely converted heat radiation into mechanical energy. Nothing else has changed: the black hole has the same mass as beforehand.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

ence can be calculated. Let us explore an example.

If L is the contour length of a free, ideal, unbranched polymer molecule, the *average* end-to-end distance R is proportional to the square root of the length L:

$$R = \sqrt{Ll} \sim \sqrt{L} \quad \text{or} \quad R \sim \sqrt{N} \tag{127}$$

where N is the number of monomers and l is an effective monomer length describing the scale at which the polymer molecule is effectively stiff. R is usually much smaller than L; this means that free, ideal polymer molecules are usually in a *coiled* state.

Obviously, the end-to-end distance R varies from molecule to molecule, and follows a Gaussian distribution for the probability P of a end-to-end distance R:

$$P(R) \sim \mathrm{e}^{\frac{-3R^2}{2Nl^2}} . \tag{128}$$

The average end-to-end distance mentioned above is the root-mean-square of this distribution. Non-ideal polymers are polymers which have, like non-ideal gases, interactions with neighbouring molecules or with solvents. In practice, polymers follow the ideal behaviour quite rarely: polymers are ideal only in certain solvents and in melts.

If a polymer is *stretched*, the molecules must rearrange. This changes their entropy and produces an elastic force f that tries to inhibit the stretching. For an ideal polymer, the force is not due to molecular interactions, but is entropic in nature. Therefore the force can be deduced from the *free energy*

$$F \sim -T \ln P(R) \tag{129}$$

of the polymer: the force is then simply given as $f = \partial F(R)/\partial R$. For an ideal polymer, using its probability distribution, the force turns out to be proportional to the stretched length. Thus the spring constant k can be introduced, given by Challenge 163 e

$$k = \frac{f}{R} = \frac{3T}{Ll} . \tag{130}$$

We thus deduced a material property, the spring constant k, from the simple idea that polymers are made of long, flexible molecules. The proportionality to temperature T is a result of the entropic nature of the force; the dependence on L shows that longer molecules are more easy to stretch. For a real, non-ideal polymer, the calculation is more complex, but the procedure is the same. Indeed, this is the mechanism at the basis of the elasticity of rubber.

Using the free energy of polymer conformations, we can calculate the material properties of macromolecules in many other situations, such as their reaction to compression, their volume change in the melt, their interactions in solutions, the effect of branched molecules, etc. This is a vast field of knowledge on its own, which we do not pursue here. Modern research topics include the study of knotted polymers and the study of polymer mixtures. Extensive computer calculations and experiments are regularly compared.

Do polymers have some relation to the structure of physical space? The issue is open.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

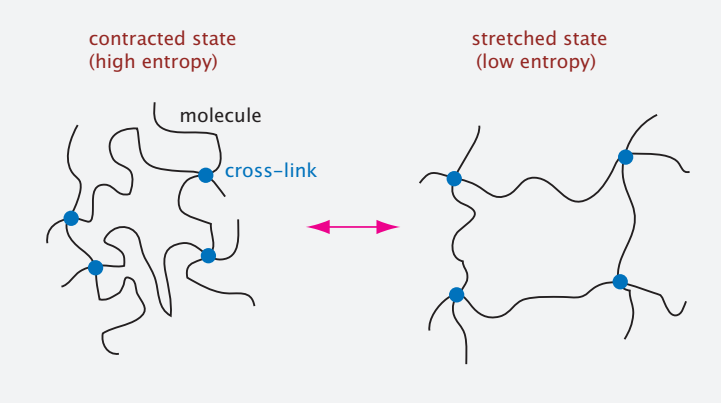


FIGURE 169 An illustration of the relation between polymer configurations and elasticity. The molecules in the stretched situation have fewer possible shape configurations and thus lower entropy; therefore, the material tends back to the contracted situation.

speed of sound is the limit speed for dislocations in the same way that the speed of light is the limit speed for objects.

Does this mean that elementary particles are dislocations of space or even of space-time, maybe even dislocation rings? The speculation is appealing, even though it supposes that space-time is a solid crystal, and thus contradicts the model of space or space-time as a fluid. Worse, we will soon encounter other reasons to reject modelling space-time as a lattice; maybe you can find a few arguments already by yourself. Still, expressions (125) and (126) for dislocations continue to fascinate.

Vol. VI, page 75
Challenge 162 s

At this point, we are confused. Space-time seems to be solid and liquid at the same time. Despite this contrast, the discussion somehow gives the impression that there is something waiting to be discovered. But what? We will find out in the last part of our adventure.

Polymers

Ref. 254 The study of polymers is both economically important and theoretically fascinating. Polymers are materials built of long and flexible macromolecules that are sequences of many ('poly' in Greek) similar monomers. These macromolecules are thus wobbly entities.

Polymers form *solids*, like rubber or plexiglas, *melts*, like those used to cure teeth, and many kinds of *solutions*, like glues, paints, eggs, or people. Polymer gases are of lesser importance.

All the material properties of polymers, such as their elasticity, their viscosity, their electric conductivity or their unsharp melting point, depend on the number of monomers and the topology of their constituent molecules. In many cases, this depend-

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

But the lack of change contradicts the second principle of thermodynamics! Geroch concluded that something must be wrong. We must have forgotten an effect which makes this process impossible.

In the 1980s, William Unruh and Robert Wald showed that black hole radiation is precisely the forgotten effect that puts everything right. Because of black hole radiation, the box feels buoyancy, so that it cannot be lowered down to the horizon completely. The box floats somewhat above the horizon, so that the heat radiation inside the box has not yet *zero* energy when it falls out of the opened box. As a result, the black hole does increase in mass and thus in entropy when the box is opened. In summary, when the empty box is pulled up again, the final situation is thus the following: only part of the energy of the heat radiation has been converted into mechanical energy, part of the energy went into the increase of mass and thus of entropy of the black hole. The second principle of thermodynamics is saved.

Well, the second principle of thermodynamics is only saved if the heat radiation has precisely the right energy density at the horizon and above. Let us have a look. The centre of the box can only be lowered up to a hovering distance d above the horizon. At the horizon, the acceleration due to gravity is $g_{\text{surf}} = c^4/4GM$. The energy E gained by lowering the box is

$$E = c^2 m - m g_{\text{surf}} \frac{d}{2} = c^2 m \left(1 - \frac{dc^2}{8GM}\right) . \tag{37}$$

The efficiency of the process is $\eta = E/c^2 m$. To be consistent with the second principle of thermodynamics, this efficiency must obey

$$\eta = \frac{E}{c^2 m} = 1 - \frac{T_{\text{BH}}}{T} , \tag{38}$$

where T is the temperature of the radiation inside the box. We thus find a black hole temperature T_{BH} that is determined by the hovering distance d. The hovering distance is roughly given by the size of the box. The box size in turn must be at least the wavelength of the thermal radiation; in first approximation, Wien's relation gives $d \approx \hbar c/kT$. A precise calculation introduces a factor π, giving the result

$$T_{\text{BH}} = \frac{\hbar c^3}{8\pi k G M} = \frac{\hbar c}{4\pi k} \frac{1}{R} = \frac{\hbar}{2\pi k c} g_{\text{surf}} \quad \text{with} \quad g_{\text{surf}} = \frac{c^4}{4GM} , \tag{39}$$

where R and M are the radius and the mass of the black hole. The quantity T_{BH} is either called the *black-hole temperature* or the *Bekenstein–Hawking temperature*. As an example, a black hole with the mass of the Sun would have the rather small temperature of 62 nK, whereas a smaller black hole with the mass of a mountain, say 10^{12} kg, would have a temperature of 123 GK. That would make quite a good oven. All known black hole candidates have masses in the range from a few to a few million solar masses. The radiation is thus extremely weak – much too weak to be detectable.

Challenge 104 ny
Ref. 129 The reason for the weakness of black hole radiation is that the emitted wavelength is of the order of the black hole radius, as you might want to check. The radiation emitted by black holes is often also called *Bekenstein–Hawking radiation*.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 10 The principles of thermodynamics and those of horizon mechanics.

PRINCIPLE	THERMODYNAMICS	HORIZONS
Zeroth principle	the temperature T is the same across a body at equilibrium	the surface gravity a is the same across the horizon
First principle	energy is conserved: $\mathrm{d}E = T\mathrm{d}S - p\mathrm{d}V + \mu\mathrm{d}N$	energy is conserved: $\mathrm{d}(c^2m) = \frac{ac^2}{8\pi G}\mathrm{d}A + \Omega\mathrm{d}J + \Phi\mathrm{d}q$
Second principle	entropy never decreases: $\mathrm{d}S \geqslant 0$	surface area never decreases: $\mathrm{d}A \geqslant 0$ (except for black hole radiation)
Third principle	$T = 0$ cannot be achieved	$a = 0$ cannot be achieved

All thermodynamic principles are valid for black holes, of course. A summary of the meaning of each thermodynamic principle in the case of black holes is given in Table 10.

Challenge 105 ny

Black hole radiation is thus so weak that we must speak of an academic effect! It leads to a luminosity that increases with decreasing mass or size as

$$L \sim \frac{1}{M^2} \sim \frac{1}{R^2} \quad \text{or} \quad L = nA\sigma T^4 = \frac{n}{15 \cdot 2^{11}\pi}\frac{c^6\hbar}{G^2M^2} \tag{40}$$

Vol. III, page 235

where σ is the Stefan–Boltzmann or *black body radiation constant*, n is the number of particle degrees of freedom that can be radiated; as long as only photons are radiated –

Ref. 130

the only case of practical importance – we have $n = 2$.

Black holes thus shine, and the more the smaller they are. For example, a solar-mass black holes emits less than 0.1 xW. This is a genuine *quantum* effect, since classically, black holes, as the name says, cannot emit any light at all. Even though the effect is academically weak, it will be of importance later on. In actual systems, many other effects around black holes increase the luminosity far above the Bekenstein–Hawking value; indeed, black holes are usually brighter than normal stars, due to the radiation emitted by the matter falling into them. But that is another story. Here we are treating isolated black holes, surrounded only by pure vacuum.

THE LIFETIME OF BLACK HOLES

Challenge 106 ny

Due to the emitted radiation, black holes gradually lose mass. Therefore their theoretical lifetime is *finite*. A calculation shows that the lifetime is given by

$$t = M^3 \frac{20\,480\,\pi G^2}{\hbar c^4} \approx M^3\ 3.4 \cdot 10^{-16}\,\mathrm{s/kg^3} \tag{41}$$

as function of their initial mass M. For example, a black hole with mass of 1 g would have a lifetime of $3.4 \cdot 10^{-25}$ s, whereas a black hole of the mass of the Sun, $2.0 \cdot 10^{30}$ kg, would have a lifetime of about 10^{68} years. Again, these numbers are purely academic.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

continuing fascination. This argument is connected to a famous property of the motion of dislocations.

Dislocations are one-dimensional construction faults in crystals, as shown in Figure 168. A general dislocation is a mixture of the two pure dislocation types: *edge dislocations* and *screw dislocations*. Both are shown in Figure 168.

Challenge 161 e

If one explores how the atoms involved in dislocations can rearrange themselves, one finds that edge dislocations can only move perpendicularly to the added plane. In contrast, screw dislocations can move in all directions.* An important case of general, mixed dislocations, i.e., of mixtures of edge and screw dislocations, are closed *dislocation rings*. On such a dislocation ring, the degree of mixture changes continuously from place to place.

Any dislocation is described by its *strength* and by its effective *size*; they are shown, respectively, in red and blue in Figure 168. The *strength* of a dislocation is measured by the so-called *Burgers vector*; it measures the misfits of the crystal around the dislocation. More precisely, the Burgers vector specifies by how much a section of perfect crystal needs to be displaced, after it has been cut open, to produce the dislocation. Obviously, the strength of a dislocation is quantized in multiples of a minimal Burgers vector. In fact, dislocations with large Burgers vectors can be seen as composed of dislocations of minimal Burgers vector, so that one usually studies only the latter.

The size or *width* of a dislocation is measured by an *effective width* w. Also the width is a multiple of the lattice vector. The width measures the size of the deformed region of the crystal around the dislocation. Obviously, the size of the dislocation depends on the elastic properties of the crystal, can take continuous values and is direction-dependent. The width is thus related to the energy content of a dislocation.

A general dislocation can move, though only in directions which are both perpendicular to its own orientation and to its Burgers vector. Screw dislocations are simpler: they can move in any direction. Now, the motion of screw dislocations has a peculiar property. We call c the speed of sound in a pure (say, cubic) crystal. As Frenkel and Kontorowa

Ref. 253

found in 1938, when a screw dislocation moves with velocity v, its width w changes as

$$w = \frac{w_0}{\sqrt{1 - v^2/c^2}}\,. \tag{125}$$

In addition, the energy of the moving dislocation obeys

$$E = \frac{E_0}{\sqrt{1 - v^2/c^2}}\,. \tag{126}$$

A screw dislocation thus cannot move faster than the speed of sound c in a crystal and its width shows a speed-dependent contraction. (Edge dislocations have similar, but more complex behaviour.) The motion of screw dislocations in solids is thus described by the same effects and formulae that describe the motion of bodies in special relativity; the

* See the uet.edu.pk/dmems/edge_dislocation.htm, uet.edu.pk/dmems/screw_dislocation.htm and uet.edu.pk/dmems/mixed_dislocation.htm web pages to watch a moving dislocation.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

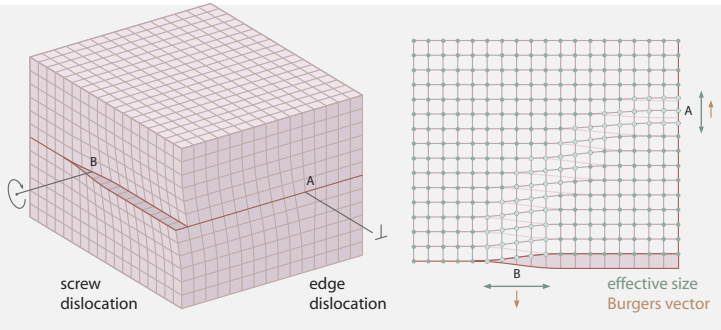


FIGURE 168 The two pure dislocation types, edge and screw dislocations, seen from the outside of a cubic crystal (left) and the mixed dislocation – a quarter of a dislocation loop – joining them in a horizontal section of the same crystal (right) (© Ulrich Kolberg).

Fluid space-time

General relativity shows that space can move and oscillate: space is a wobbly entity. Is space more similar to clouds, to fluids, or to solids?

An intriguing approach to space-time as a fluid was published in 1995 by Ted Jacobson. He explored what happens if space-time, instead of assumed to be continuous, is assumed to be the statistical average of numerous components moving in a disordered fashion.

Ref. 252

The standard description of general relativity describes space-time as an entity similar to a flexible mattress. Jacobson studied what happens if the mattress is assumed to be made of a fluid. A fluid is a collection of (undefined) components moving randomly and described by a temperature varying from place to place.

Vol. II, page 144

Jacobson started from the Fulling–Davies–Unruh effect and assumed that the local fluid temperature is given by a multiple of the local gravitational acceleration. He also used the proportionality – correct on horizons – between area and entropy. Since the energy flowing through a horizon can be called heat, one can thus translate the expression $\delta Q = T\delta S$ into the expression $\delta E = a\delta A(c^2/4G)$, which describes the behaviour of space-time at horizons. As we have seen, this expression is fully equivalent to general relativity.

Page 129

Vol. VI, page 32

In other words, imagining space-time as a fluid is a powerful analogy that allows deducing general relativity. Does this mean that space-time actually *is* similar to a fluid? So far, the analogy is not sufficient to answer the question and we have to wait for the last part of our adventure to settle it. In fact, just to confuse us a bit more, there is an old argument for the opposite statement.

Dislocations and solid space-time

General relativity tells us that space behaves like a deformable mattress; space thus behaves like a solid. There is a second argument that underlines this point and that exerts a

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

The important point is that *black holes evaporate*. However, this extremely slow process for usual black holes determines their lifetime only if no other, faster process comes into play. We will present a few such processes shortly. Bekenstein–Hawking radiation is the weakest of all known effects. It is not masked by stronger effects only if the black hole is non-rotating, electrically neutral and with no matter falling into it from the surroundings.

So far, none of these quantum gravity effects has been confirmed experimentally, as the values are much too small to be detected. However, the deduction of a Hawking temperature has been beautifully confirmed by a theoretical discovery of William Unruh, who found that there are configurations of fluids in which sound waves cannot escape, so-called '*silent holes*'. Consequently, these silent holes radiate sound waves with a temperature satisfying the same formula as real black holes. A second type of analogue system, namely *optical black holes*, are also being investigated.

Ref. 131

Ref. 132

Black holes are all over the place

Around the year 2000, astronomers amassed a large body of evidence that showed something surprising: there seems to be a *supermassive* black hole at the centre of almost all galaxies. The most famous of all is of course the black hole at the centre of our own galaxy. Also quasars, active galactic nuclei and gamma-ray bursters seem to be due to supermassive black holes at the centre of galaxies. The masses of these black holes are typically higher than a million solar masses.

Astronomers also think that many other, smaller astrophysical objects contain black holes: ultraluminous X-ray sources and x-ray binary stars are candidates for black holes of *intermediate* mass.

Finally, one candidate explanation for dark matter on the outskirts of galaxies is a hypothetical cloud of *small* black holes.

In short, black holes seem to be quite common across the universe. Whenever astronomers observe a new class of objects, two questions arise directly: how do the objects form? And how do they disappear? We have seen that quantum mechanics puts an upper limit to the life time of a black hole. The upper limit is academic, but that is not important. The main point is that it exists. Indeed, astronomers think that most black holes disappear in other ways, and much before the Bekenstein–Hawking limit, for example through mergers. All this is still a topic of research. The detectors of gravitational waves might clarify these processes in the future.

Vol. II, page 173

How are black holes born? It turns out that the birth of black holes can actually be observed.

Fascinating gamma-ray bursts

Nuclear explosions produce flashes of γ rays, or gamma rays. In the 1960s, several countries thought that detecting γ ray flashes, or better, their absence, using satellites, would be the best way to ensure that nobody was detonating nuclear bombs above ground. But when the military sent satellites into the sky to check for such flashes, they discovered something surprising. They observed about two γ flashes *every* day. For fear of being laughed at, the military kept this result secret for many years.

It took the military six years to understand what an astronomer could have told

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

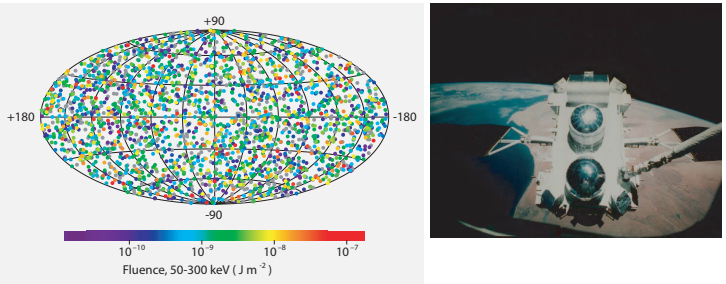


FIGURE 88 The location and energy of the 2704 γ ray bursts observed in the sky between 1991 and 2000 by the BATSE experiment on board of the Compton Gamma Ray Observatory, a large satellite deployed by the space shuttle after over 20 years of planning and construction. The Milky Way is located around the horizontal line running from +180 to −180 (NASA).

them in five minutes: the flashes, today called *gamma-ray bursts*, were coming from outer space. Finally, the results were published; this is probably the only discovery about nature that was made by the military. Another satellite, this time built by scientists, the Compton Gamma Ray Observatory, confirmed that the bursts were *extragalactic* in origin, as proven by the map of Figure 88.

Ref. 134

Measurements of gamma-ray bursts are done by satellites because most gamma rays do not penetrate the atmosphere. In 1996, the Italian-Dutch BeppoSAX satellite started mapping and measuring gamma-ray bursts systematically. It discovered that they were followed by an *afterglow* in the X-ray domain, lasting many hours, sometimes even days. In 1997, afterglow was discovered also in the optical domain. The satellite also allowed researchers to find the corresponding X-ray, optical and radio sources for each burst. These measurements in turn allowed determining the distance of the burst sources; redshifts between 0.0085 and 4.5 were measured. In 1999 it finally became possible to detect the *optical* bursts corresponding to gamma-ray bursts.*

Ref. 135

All this data together showed that gamma-ray bursts have durations between milliseconds and about an hour. Gamma-ray bursts seem to fall into (at least) two classes: the *short bursts*, usually below 3 s in duration and emitted from closer sources, and the *long bursts*, emitted from distant galaxies, typically with a duration of 30 s and more, and with a softer energy spectrum. The long bursts produce luminosities estimated to be up to 10^{45} W. This is about one hundredth of the brightness all stars of the whole visible universe taken together! Put differently, it is the same amount of energy that is released when converting several solar masses into radiation within a few seconds.

Ref. 137

Challenge 107 s

In fact, the measured luminosity of long bursts is near the theoretical maximum luminosity a body can have. This limit is given by

Vol. II, page 108

$$L < L_{\text{Pl}} = \frac{c^5}{4G} = 0.9 \cdot 10^{52}\,\text{W}\,, \tag{42}$$

* For more detail about this fascinating topic, see the www.aip.de/~jcg/grb.html website by Jochen Greiner.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Schrödinger's equation is linear in Φ. Therefore the fundamental solution is

$$\Phi(x, y, z, t) = a\, e^{i(\tau x - \omega t)} \quad \text{with} \quad \omega = \eta\tau^2 \quad \text{and} \quad \kappa = a\tau^2\,. \tag{120}$$

The amplitude a and the wavelength or pitch $b = 1/\tau$ can be freely chosen, as long as the approximation of small deviation is fulfilled; this condition translates as $a \ll b$.* In the present interpretation, the fundamental solution corresponds to a vortex line that is deformed into a *helix*, as shown in Figure 167. The angular speed ω is the rotation speed around the axis of the helix.

Challenge 158 ny

A helix moves along the axis with a speed given by

$$v_{\text{helix along axis}} = 2\eta\tau\,. \tag{121}$$

In other words, for extended entities following evolution equation (115), rotation and translation are coupled.** The momentum p can be defined using $\partial\Phi/\partial x$, leading to

$$p = \tau = \frac{1}{b}\,. \tag{122}$$

Momentum is thus inversely proportional to the helix wavelength or pitch, as expected. The energy E is defined using $\partial\Phi/\partial t$, leading to

$$E = \eta\tau^2 = \frac{\eta}{b^2}\,. \tag{123}$$

Energy and momentum are connected by

$$E = \frac{p^2}{2\mu} \quad \text{where} \quad \mu = \frac{1}{2\eta}\,. \tag{124}$$

In other words, a vortex with a coefficient η – describing the coupling between environment and vortex – is thus described by a number μ that behaves like an effective mass. We can also define the (real) quantity $|\Phi| = a$; it describes the *amplitude* of the deformation.

Page 295

In the Schrödinger equation (119), the second derivative implies that the deformation 'wave packet' has tendency to spread out over space. Can you confirm that the wavelength–frequency relation for a vortex wave group leads to something like the indeterminacy relation (however, without a $\hbar$ appearing explicitly)?

Challenge 160 ny

In summary, the complex amplitude Φ for a linear vortex in a rotating liquid behaves like the one-dimensional wave function of a non-relativistic free particle. In addition, we found a suggestion for the reason that complex numbers appear in the Schrödinger equation of quantum theory: they could be due to the intrinsic rotation of an underlying substrate. Is this suggestion correct? We will find out in the last part of our adventure.

Vol. VI, page 172

* The curvature is given by $\kappa = a/b^2$, the torsion by $\tau = 1/b$. Instead of $a \ll b$ one can thus also write $\kappa \ll \tau$.

Challenge 159 ny

** A wave packet moves along the axis with a speed given by $v_{\text{packet}} = 2\eta\tau_0$, where τ_0 is the torsion of the helix of central wavelength.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

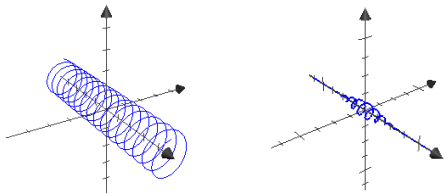


FIGURE 167 Motion of a vortex: the fundamental helical solution and a moving helical 'wave packet'.

the x-axis, we can write

$$\boldsymbol{r} = (x, y(x,t), z(x,t)) \,. \tag{116}$$

Slight deformations imply $\partial s \approx \partial x$ and therefore

$$\begin{aligned} \boldsymbol{e} &= (1, \frac{\partial y}{\partial x}, \frac{\partial z}{\partial x}) \approx (1,0,0) \,, \\ \kappa \boldsymbol{n} &\approx (0, \frac{\partial^2 y}{\partial x^2}, \frac{\partial^2 z}{\partial x^2}) \text{ , and} \\ \boldsymbol{v} &= (0, \frac{\partial y}{\partial t}, \frac{\partial z}{\partial t}) \,. \end{aligned} \tag{117}$$

We can thus rewrite the evolution equation (115) as

$$(0, \frac{\partial y}{\partial t}, \frac{\partial z}{\partial t}) = \eta\, (0, -\frac{\partial^2 z}{\partial x^2}, \frac{\partial^2 y}{\partial x^2}) \,. \tag{118}$$

This equation is well known; if we drop the first coordinate and introduce complex numbers by setting $\Phi = y + iz$, we can rewrite it as

$$\frac{\partial \Phi}{\partial t} = i\eta \frac{\partial^2 \Phi}{\partial x^2} \,. \tag{119}$$

Ref. 251 This is the one-dimensional Schrödinger equation for the evolution of a free wave function! The complex function Φ specifies the transverse deformation of the vortex. In other words, we can say that the Schrödinger equation in one dimension describes the evolution of the deformation for an almost linear vortex in a rotating liquid. We note that there is no constant $\hbar$ in the equation, as we are exploring a *classical* system.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Challenge 108 e as you might want to check yourself. In short, the sources of gamma ray bursts are the biggest bombs found in the universe. The are explosions of almost unimaginable proportions. Recent research seems to suggest that long gamma-ray bursts are not isotropic, but that they are *beamed*, so that the huge luminosity values just mentioned might need to be divided by a factor of 1000.

Ref. 135 However, the mechanism that leads to the emission of gamma rays is still unclear. It is often speculated that short bursts are due to merging neutron stars, whereas long bursts are emitted when a black hole is formed in a supernova or hypernova explosion. In this case, long gamma-ray bursts would be 'primal screams' of black holes *in formation*. However, a competing explanation states that long gamma-ray bursts are due to the *death* of black holes.

Ref. 133 Indeed, already 1975, a powerful radiation emission mechanism was predicted for dying *charged* black holes by Damour and Ruffini. Charged black holes have a much shorter lifetime than neutral black holes, because during their formation a second process takes place. In a region surrounding them, the electric field is larger than the so-called vacuum polarization value, so that large numbers of electron-positron pairs are produced, which then almost all annihilate. This process effectively reduces the charge of the black hole to a value for which the field is below critical everywhere, while emitting large amounts of high energy light. It turns out that the mass is reduced by up to 30 % in a time of the order of seconds. That is quite shorter than the 10^{68} years predicted by Bekenstein–Hawking radiation! This process thus produces an extremely intense gamma-ray burst.

Ruffini took up his 1975 model again in 1997 and with his collaborators showed that the gamma-ray bursts generated by the annihilation of electron-positrons pairs created by vacuum polarization, in the region they called the *dyadosphere*, have a luminosity and a duration exactly as measured, if a black hole of about a few up to 30 solar masses is assumed. Charged black holes therefore reduce their charge and mass through the vacuum polarization and electron positron pair creation process. (The process reduces the mass because it is one of the few processes which is *reversible*; in contrast, most other attempts to reduce charge on a black hole, e.g. by throwing in a particle with the opposite charge, increase the mass of the black hole and are thus irreversible.) The left over remnant then can lose energy in various ways and also turns out to be responsible for the afterglow discovered by the BeppoSAX satellite. Among others, Ruffini's team speculates that the remnants are the sources for the high energy cosmic rays, whose origin had not been Ref. 136 localized so far. All these exciting studies are still ongoing.

Understanding long gamma-ray bursts is one of the most fascinating open questions in astrophysics. The relation to black holes is generally accepted. But many processes leading to emission of radiation from black holes are possible. Examples are matter falling into the black hole and heating up, or matter being ejected from rotating black holes Vol. II, page 271 through the Penrose process, or charged particles falling into a black hole. These mechanisms are known; they are at the origin of *quasars*, the extremely bright quasi-stellar sources found all over the sky. They are assumed to be black holes surrounded by matter, in the development stage following gamma-ray bursters. But even the details of what happens in quasars, the enormous voltages (up to 10^{20} V) and magnetic fields generated, as well as their effects on the surrounding matter are still object of intense research in astrophysics.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Material properties of black holes

Once the concept of entropy of a black hole was established, people started to think about black holes like about any other material object. For example, black holes have a matter density, which can be defined by relating their mass to a fictitious volume defined by $4\pi R^3/3$, where R is their radius. This density is then given by

$$\rho = \frac{1}{M^2}\,\frac{3c^6}{32\pi G^3} \tag{43}$$

and can be quite low for large black holes. For the largest black holes known, with 1000 million solar masses or more, the density is of the order of the density of air. Nevertheless, even in this case, the density is the highest possible in nature for that mass.

Challenge 109 e

By the way, the gravitational acceleration at the horizon is still appreciable, as it is given by

$$g_{\text{surf}} = \frac{1}{M}\,\frac{c^4}{4G} = \frac{c^2}{2R} \tag{44}$$

which is still $15\,\text{km/s}^2$ for an air density black hole.

Challenge 110 e

Obviously, the black hole temperature is related to the entropy S by its usual definition

$$\frac{1}{T} = \left.\frac{\partial S}{\partial E}\right|_{\rho} = \left.\frac{\partial S}{\partial (c^2 M)}\right|_{\rho} \tag{45}$$

All other thermal properties can be deduced by the standard relations from thermostatics.

In particular, black holes are the systems in nature with the largest possible entropy. Can you confirm this statement?

Challenge 111 e

It also turns out that black holes have a *negative* heat capacity: when heat is added, they cool down. In other words, black holes cannot achieve equilibrium with a bath. This is not a real surprise, since *any* gravitationally bound material system has negative specific heat. Indeed, it takes only a bit of thinking to see that any gas or matter system collapsing under gravity follows $dE/dR > 0$ and $dS/dR > 0$. That means that while collapsing, the energy and the entropy of the system shrink. (Can you find out where they go?) Since temperature is defined as $1/T = dS/dE$, temperature is always positive; from the temperature increase $dT/dR < 0$ during collapse one deduces that the specific heat dE/dT is negative.

Challenge 112 ny

Challenge 113 s

Ref. 138

Black holes, like any object, oscillate when slightly perturbed. These vibrations have also been studied; their frequency is proportional to the mass of the black hole.

Ref. 139

Nonrotating black holes have no magnetic field, as was established already in the 1960s by Russian physicists. On the other hand, black holes have something akin to a finite electrical conductivity and a finite viscosity. Some of these properties can be understood if the horizon is described as a membrane, even though this model is not always applicable. In any case, we can study and describe isolated macroscopic black holes like any other macroscopic material body. The topic is not closed.

Ref. 130

Ref. 140

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

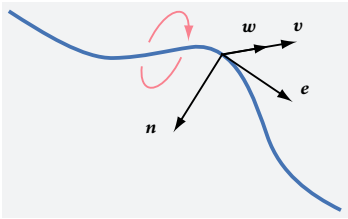


FIGURE 166 The mutually perpendicular tangent $\boldsymbol{e}$, normal $\boldsymbol{n}$, torsion $\boldsymbol{w}$ and velocity $\boldsymbol{v}$ of a vortex in a rotating fluid.

deformable, and it is observed to wriggle around. Larger vortices appear as tornadoes on Earth and on other planets, as *waterspouts*, and at the ends of wings or propellers of all kinds. Smaller, quantized vortices appear in superfluids. An example is shown in Figure 165; also the spectacular fire whirls and fire tornados observed every now and then are vortices.

Page 105

Vortices, also called *vortex tubes* or *vortex filaments*, are thus wobbly entities. Now, a beautiful result from the 1960s states that a vortex filament in a rotating liquid is described by the one-dimensional Schrödinger equation. Let us see how this is possible.

Ref. 250

Any deformable linear vortex, as illustrated in Figure 166, is described by a continuous set of position vectors $\boldsymbol{r}(t, s)$ that depend on time t and on a single parameter s. The parameter s specifies the relative position along the vortex. At each point on the vortex, there is a unit tangent vector $\boldsymbol{e}(t, s)$, a unit normal curvature vector $\boldsymbol{n}(t, s)$ and a unit torsion vector $\boldsymbol{w}(t, s)$. The three vectors, shown in Figure 166, are defined as usual as

$$\begin{aligned} \boldsymbol{e} &= \frac{\partial \boldsymbol{r}}{\partial s}\,, \\ \kappa \boldsymbol{n} &= \frac{\partial \boldsymbol{e}}{\partial s}\,, \\ \tau \boldsymbol{w} &= -\frac{\partial (\boldsymbol{e} \times \boldsymbol{n})}{\partial s}\,, \end{aligned} \tag{114}$$

where κ specifies the value of the curvature and τ specifies the value of the torsion. In general, both numbers depend on time and on the position along the line.

In the simplest possible case the rotating environment induces a local velocity $\boldsymbol{v}$ for the vortex that is proportional to the curvature κ, perpendicular to the tangent vector $\boldsymbol{e}$ and perpendicular to the normal curvature vector $\boldsymbol{n}$:

$$\boldsymbol{v} = \eta \kappa (\boldsymbol{e} \times \boldsymbol{n})\,, \tag{115}$$

Ref. 250

where η is the so-called *coefficient of local self-induction* that describes the coupling between the liquid and the vortex motion. This is the evolution equation of the vortex.

We now assume that the vortex is deformed only *slightly* from the straight configuration. Technically, we are thus in the *linear* regime. For such a linear vortex, directed along

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 165 A vortex in nature: a waterspout (© Zé Nogueira).

Challenge 157 s into a thinner and thinner structure?

Two rain clouds can merge. So can two atomic electron clouds. So can galaxies. But only atomic clouds are able to *cross* each other. We remember that a normal atom can be Vol. IV, page 185 inside a Rydberg atom and leave it again without change. In contrast, rain clouds, stars, galaxies or other macroscopic clouds cannot cross each other. When their paths cross, they can only merge or be ripped into pieces. Due to this lack of crossing ability, only microscopic clouds can be counted. In the macroscopic cases, there is no real way to define a 'single' cloud in an accurate way. If we aim for full precision, we are unable to claim that there is more than one rain cloud, as there is no clear-cut boundary between them. Electronic clouds are different. True, in a piece of solid matter we can argue that there is only a single electronic cloud throughout the object; however, when the object is divided, the cloud is divided in a way that makes the original atomic clouds reappear. We thus can speak of 'single' electronic clouds.

If one wants to be strict, galaxies, stars and rain clouds can be seen as made of localized particles. Their cloudiness is only apparent. Could the same be true for electron clouds? And what about space itself? Let us explore some aspects of these questions.

Vortices and the Schrödinger equation

Fluid dynamics is a topic with many interesting aspects. Take the *vortex* that can be observed in any deep, emptying bath tub: it is an extended, one-dimensional 'object', it is

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

How do black holes evaporate?

When a nonrotating and uncharged black hole loses mass by radiating Hawking radiation, eventually its mass reaches values approaching the Planck mass, namely a few micrograms. Expression (41) for the lifetime, applied to a black hole of Planck mass, yields a value of over sixty thousand Planck times. A surprising large value. What happens in those last instants of evaporation?

A black hole approaching the Planck mass at some time will get smaller than its own Compton wavelength; that means that it behaves like an elementary particle, and in particular, that quantum effects have to be taken into account. It is still unknown how these final evaporation steps take place, whether the mass continues to diminish smoothly or in steps (e.g. with mass values decreasing as $\sqrt{n}$ when n approaches zero), how its internal structure changes, whether a stationary black hole starts to rotate (as the author predicts), or how the emitted radiation deviates from black body radiation. There is still enough to study. However, one important issue *has* been settled.

The information paradox of black holes

When the thermal radiation of black holes was discovered, one question was hotly debated for many years. The matter forming a black hole can contain lots of information; e.g., we can imagine the black hole being formed by a large number of books collapsing onto each other. On the other hand, a black hole radiates thermally until it evaporates. Since thermal radiation carries no information, it seems that information somehow disappears, or equivalently, that entropy increases.

An incredible number of papers have been written about this problem, some even claiming that this example shows that physics as we know it is incorrect and needs to be changed. As usual, to settle the issue, we need to look at it with precision, laying all prejudice aside. Three intermediate questions can help us finding the answer.

— What happens when a book is thrown into the Sun? When and how is the information radiated away?
— How precise is the sentence that black hole radiate *thermal* radiation? Could there be a slight deviation?
— Could the deviation be measured? In what way would black holes radiate information?

Challenge 114 e You might want to make up your own mind before reading on.

Let us walk through a short summary. When a book or any other highly complex – or low entropy – object is thrown into the Sun, the information contained is radiated away. The information is contained in some slight deviations from black hole radiation, namely in slight correlations between the emitted radiation emitted over the burning time of the Sun. A short calculation, comparing the entropy of a room temperature book and the information contained in it, shows that these effects are extremely small and difficult to measure.

Ref. 141 A clear exposition of the topic was given by Don Page. He calculated what information would be measured in the radiation if the system of black hole and radiation *together* would be in a *pure* state, i.e., a state containing specific information. The result is simple. Even if a system is large – consisting of many degrees of freedom – and in pure state, any smaller *sub*system nevertheless looks almost perfectly thermal. More specifically, if

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

a total system has a Hilbert space dimension $N = nm$, where n and $m \leqslant n$ are the dimensions of two subsystems, and if the total system is in a pure state, the subsystem m would have an entropy S_m given by

Challenge 115 ny

$$S_m = \frac{1-m}{2n} + \sum_{k=n+1}^{mn} \frac{1}{k} \tag{46}$$

which is approximately given by

$$S_m = \ln m - \frac{m}{2n} \quad \text{for} \quad m \gg 1 \,. \tag{47}$$

To discuss the result, let us think of n and m as counting degrees of freedom, instead of Hilbert space dimensions. The first term in equation (47) is the usual entropy of a mixed state. The second term is a small deviation and describes the amount of specific information contained in the original pure state; inserting numbers, one finds that it is extremely small compared to the first. In other words, the subsystem m is almost indistinguishable from a mixed state; it looks like a thermal system even though it is not.

A calculation shows that the second, small term on the right of equation (47) is indeed sufficient to radiate away, during the lifetime of the black hole, any information contained in it. Page then goes on to show that the second term is so small that not only it is lost in measurements; it is also lost in the usual, perturbative calculations for physical systems.

The question whether any radiated information could be measured can now be answered directly. As Don Page showed, even measuring half of the system only gives about one half of a bit of the radiated information. It is thus necessary to measure almost the *complete* radiation to obtain a sizeable chunk of the radiated information. In other words, it is extremely hard to determine the information contained in black hole radiation.

Ref. 142

In summary, at any given instant, the amount of information radiated by a black hole is negligible when compared with the total black hole radiation; it is practically impossible to obtain valuable information through measurements or even through calculations that use usual approximations.

More paradoxes

A black hole is a macroscopic object, similar to a star. Like all objects, it can interact with its environment. It has the special property to swallow everything that falls into them. This immediately leads us to ask if we can use this property to cheat around the usual everyday 'laws' of nature. Some attempts have been studied in the section on general relativity and above; here we explore a few additional ones.

Vol. II, page 275

* *

Apart from the questions of entropy, we can look for methods to cheat around conservation of energy, angular momentum, or charge. But every thought experiment comes to the same conclusions. No cheats are possible. Every reasoning confirms that the maximum number of degrees of freedom in a region is proportional to the surface area of

Challenge 116 ny

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Several computer videos of sphere eversions are now available.* The most famous ones are *Outside in*, which shows an eversion due to William P. Thurston, and *The Optiverse*, which shows the most efficient method known so far, discovered by a team led by John Sullivan and shown in Figure 164.

Ref. 249

Why is sphere eversion of interest to physicists? If elementary particles were extended and at the same time were of spherical shape, eversion might be a particle symmetry. To see why, we summarize the effects of eversion on the whole surrounding space, not only on the sphere itself. The final effect of eversion is the transformation

$$(x, y, z) \to \frac{(x, y, -z)\, R^2}{r^2} \tag{113}$$

where R is the radius of the sphere and r is the length of the coordinate vector (x, y, z), thus $r = \sqrt{x^2 + y^2 + z^2}$. Due to the minus sign in the z-coordinate, eversion differs from inversion, but not by too much. As we will find out in the last part of our adventure, a transformation similar to eversion, space-time duality, is a fundamental symmetry of nature.

Vol. VI, page 112

Clouds

Clouds are another important class of wobbly objects. The lack of a definite boundary makes them even more fascinating than amoebas, bacteria or falling cats. We can observe the varieties of clouds from any aeroplane.

Vol. III, page 214

The common cumulus or cumulonimbus in the sky, like all the other meteorological clouds, are vapour and water droplet clouds. Galaxies are clouds of stars. Stars are clouds of plasma. The atmosphere is a gas cloud. Atoms are clouds of electrons. Nuclei are clouds of protons and neutrons, which in turn are clouds of quarks. Comparing different cloud types is illuminating and fun.

Clouds of all types can be described by a shape and a size, even though in theory they have no bound. An *effective* shape and size can be defined by that region in which the cloud density is only, say, 1 % of the maximum density; slightly different procedures can also be used. All clouds are described by *probability densities* of the components making up the cloud. All clouds show *conservation* of the number of their constituents.

Vol. I, page 256

Whenever we see a cloud, we can ask why it does not collapse. Every cloud is an aggregate; all aggregates are kept from collapse in only *three* ways: through rotation, through pressure, or through the Pauli principle, i.e., the quantum of action. For example, galaxies are kept from collapsing by rotation. Most stars, the atmosphere and rain clouds are kept from collapsing by gas pressure. Neutron stars, the Earth, atomic nuclei, protons or the electron clouds of atoms are kept apart by the quantum of action.

A rain cloud is a method to keep several thousand tons of water suspended in the air. Can you explain what keeps it afloat, and what else keeps it from continuously diffusing

* Summaries of the videos can be seen at the website www.geom.umn.edu/docs/outreach/oi, which also has a good pedagogical introduction. Another simple eversion and explanation is given by Erik de Neve on his website www.usefuldreams.org/sphereev.htm. It is even possible to run the eversion film software at home; see the website www.cslub.uwaterloo.ca/~mjmcguff/eversion. Figure 164 is from the website new.math.uiuc.edu/optiverse.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

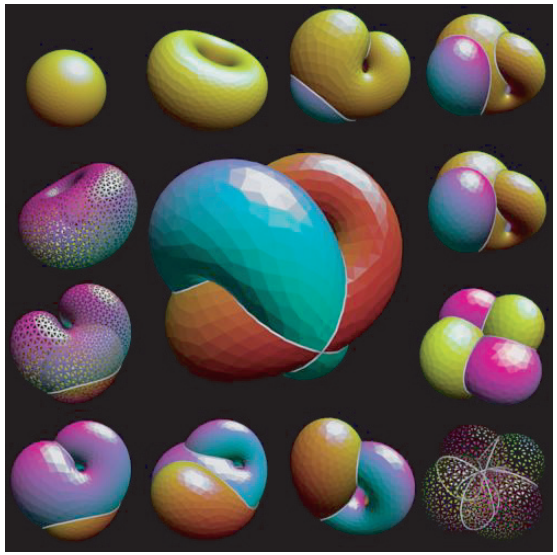


FIGURE 164 A way to turn a sphere inside out, with intermediate steps ordered clockwise (© John Sullivan).

Turning a sphere inside out

> A text should be like a lady's dress; long enough to cover the subject, yet short enough to keep it interesting.
>
> Anonymous

Exploring the theme of motion of wobbly entities, a famous example cannot be avoided. Ref. 246 In 1957, the mathematician Stephen Smale proved that a sphere can be turned inside out. The discovery brought him the Fields medal in 1966, the highest prize for discoveries in mathematics. Mathematicians call his discovery the *eversion* of the sphere.

To understand the result, we need to describe more clearly the rules of mathematical eversion. First of all, it is assumed that the sphere is made of a thin membrane which has the ability to stretch and bend without limits. Secondly, the membrane is assumed to be able to *intersect* itself. Of course, such a ghostly material does not exist in everyday life; but in mathematics, it can be imagined. A third rule requires that the membrane must be deformed in such a way that the membrane is not punctured, ripped nor creased; in short, everything must happen *smoothly* (or differentiably, as mathematicians like to say).

Even though Smale proved that eversion is possible, the first way to actually perform Ref. 247, Ref. 248 it was discovered by the blind topologist Bernard Morin in 1961, based on ideas of Arnold Shapiro. After him, several additional methods have been discovered.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

the region, and *not* to its volume. This intriguing result will keep us busy for quite some time.

* *

A black hole transforms matter into antimatter with a certain efficiency. Indeed, a black hole formed by collapsing matter also radiates antimatter. Thus one might look for de- Challenge 117 ny partures from particle number conservation. Are you able to find an example?

* *

Black holes deflect light. Is the effect polarization dependent? Gravity itself makes no difference of polarization; however, if virtual particle effects of QED are included, the Ref. 143 story might change. First calculations seem to show that such an effect exists, so that gravitation might produce rainbows. Stay tuned.

* *

If lightweight boxes made of mirrors can float in radiation, one might deduce a strange consequence: such a box could self-accelerate in free space. In a sense, an accelerated box could float on the Fulling–Davies–Unruh radiation it creates by its own acceleration. Are you able to show the that this situation is impossible because of a small but significant Challenge 118 ny difference between gravity and acceleration, namely the absence of tidal effects? (Other reasons, such as the lack of perfect mirrors, also make the effect impossible.)

* *

In 2003, Michael Kuchiev has made the spectacular prediction that matter and radiation with a wavelength *larger* than the diameter of a black hole is partly reflected when it hits Ref. 144 a black hole. The longer the wavelength, the more efficient the reflection would be. For stellar or even larger black holes, he predicts that only photons or gravitons are reflected. Black holes would thus not be complete trash cans. Is the effect real? The discussion is still ongoing.

Quantum mechanics of gravitation

Let us take a conceptual step at this stage. So far, we looked at quantum theory *with* gravitation; now we have a glimpse at quantum theory *of* gravitation.

If we bring to our mind the similarity between the electromagnetic field and the gravitational 'field,' our next step should be to find the quantum description of the gravitational field. However, despite attempts by many brilliant minds for almost a century, this search was not successful. Indeed, modern searches take another direction, as will be explained in the last part of our adventure. But let us see what was achieved and why the results are not sufficient.

Do gravitons exist?

Quantum theory says that everything that moves is made of particles. What kind of particles are gravitational waves made of? If the gravitational field is to be treated quantum mechanically like the electromagnetic field, its waves should be quantized. Most properties of these quanta of gravitation can be derived in a straightforward way.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

The $1/r^2$ dependence of universal gravity, like that of electricity, implies that the quanta of the gravitational field have *vanishing* mass and move at light speed. The independence of gravity from electromagnetic effects implies a *vanishing* electric charge.

We observe that gravity is always attractive and never repulsive. This means that the field quanta have *integer* and *even* spin. Vanishing spin is ruled out, since it implies no coupling to energy. To comply with the property that 'all energy has gravity', spin $S = 2$ is needed. In fact, it can be shown that *only* the exchange of a massless spin 2 particle leads, in the classical limit, to general relativity.

Ref. 149

The coupling strength of gravity, corresponding to the fine structure constant of electromagnetism, is given either by

$$\alpha_{G1} = \frac{G}{\hbar c} = 2.2 \cdot 10^{-15}\,\mathrm{kg}^{-2} \quad \text{or by} \quad \alpha_{G2} = \frac{Gmm}{\hbar c} = \left(\frac{m}{m_{Pl}}\right)^2 = \left(\frac{E}{E_{Pl}}\right)^2 . \tag{48}$$

However, the first expression is not a pure number; the second expression is, but depends on the mass we insert. These difficulties reflect the fact that gravity is not properly speaking an interaction, as became clear in the section on general relativity. It is often argued that m should be taken as the value corresponding to the energy of the system in question. For everyday life, typical energies are 1 eV, leading to a value $\alpha_{G2} \approx 1/10^{56}$. Gravity is indeed weak compared to electromagnetism, for which $\alpha_{em} = 1/137.036$.

If all this is correct, *virtual* field quanta would also have to exist, to explain static gravitational fields. However, up to this day, the so-called *graviton* has not yet been detected, and there is in fact little hope that it ever will. On the experimental side, nobody knows yet how to build a graviton detector. Just try! On the theoretical side, the problems with the coupling constant probably make it impossible to construct a *renormalizable* theory of gravity; the lack of renormalization means the impossibility to define a perturbation expansion, and thus to define particles, including the graviton. It might thus be that relations such as $E = \hbar\omega$ or $p = \hbar/2\pi\lambda$ are not applicable to gravitational waves. In short, it may be that the particle concept has to be changed before applying quantum theory to gravity. The issue is still open at this point.

Challenge 119 s

Space-time foam

The indeterminacy relation for momentum and position also applies to the gravitational field. As a result, it leads to an expression for the indeterminacy of the metric tensor g in a region of size l, which is given by

$$\Delta g \approx 2\frac{{l_{Pl}}^2}{l^2} , \tag{49}$$

where $l_{Pl} = \sqrt{\hbar G/c^3}$ is the Planck length. Can you deduce the result? Quantum theory thus shows that like the momentum or the position of a particle, also the metric tensor g is a *fuzzy* observable.

Challenge 120 ny

But that is not all. Quantum theory is based on the principle that actions below $\hbar$ cannot be observed. This implies that the observable values for the metric g in a region

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

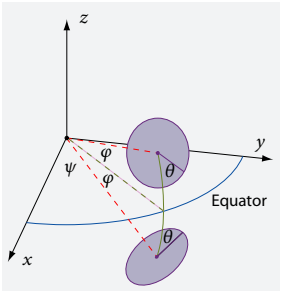


FIGURE 163 Swimming on a curved surface using two discs.

Swimming in curved space

In flat space it is not possible to produce translation through shape change. Only orientation changes are possible. Surprisingly, if space is *curved*, motion does become possible. A simple example was published in 2003 by Jack Wisdom. He found that cyclic changes in the shape of a body can lead to net translation, a rotation of the body, or both.

Ref. 245

Indeed, we know from Galilean physics that on a frictionless surface we cannot move, but that we can change orientation. This is true only for a flat surface. On a curved surface, we can use the ability to turn and translate it into motion.

Take two massive discs that lie on the surface of a frictionless, spherical planet, as shown in Figure 163. Consider the following four steps: 1. the disc separation φ is increased by the angle $\Delta\varphi$, 2. the discs are rotated oppositely about their centres by the angle $\Delta\theta$, 3. their separation is decreased by $-\Delta\varphi$, and 4. they are rotated back by $-\Delta\theta$. Due to the conservation of angular momentum, the two-disc system changes its longitude $\Delta\psi$ as

Challenge 156 ny

$$\Delta\psi = \frac{1}{2}\gamma^2\Delta\theta\Delta\varphi , \tag{112}$$

where γ is the angular radius of the discs. This cycle can be repeated over and over. The cycle allows a body, located on the surface of the Earth, to swim along the surface. Unfortunately, for a body of size of one metre, the motion for each swimming cycle is only around 10^{-27} m.

Wisdom showed that the same procedure also works in curved space, thus in the presence of gravitation. The mechanism thus allows a falling body to swim away from the path of free fall. Unfortunately, the achievable distances for everyday objects are negligibly small. Nevertheless, the effect exists.

In other words, there is a way to swim through curved space that looks similar to swimming at low Reynolds numbers, where swimming results of simple shape change. Does this tell us something about fundamental descriptions of motion? The last part of our ascent will tell.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 24 The correspondence between shape change and gauge theory.

CONCEPT	SHAPE CHANGE	GAUGE THEORY
System	deformable body	matter–field combination
Gauge freedom	freedom of description of body orientation and position	freedom to define vector potential
Gauge-dependent quantity	shape's angular orientation and position	vector potential, phase
	orientation and position change along an open path	vector potential and phase change along open path
Gauge transformation	changes angular orientation and position	changes vector potential
Gauge-independent quantities	orientation and position after full stroke	phase difference on closed path, integral of vector potential along a closed path
	deformations	field strengths
Gauge group	e.g. possible rotations SO(3) or motions E(3)	U(1), SU(2), SU(3)

of the speed of the stroke. The same experience can be made when rotating oneself on an office chair by rotating the arm above the head: the chair rotation angle after arm turn is independent of the arm speed. Stroke motion leads to a puzzle: what is the largest angle that a cat can turn in one stroke?

Challenge 155 d

Rotation in strokes has a number of important implications. First of all, the number of strokes is a quantity that all observers agree upon: it is observer-invariant. Secondly, the orientation change after a *complete* stroke is also observer-invariant. Thirdly, the orientation change for *incomplete* strokes is observer-dependent: it depends on the way that orientation is defined. For example, if orientation is defined by the direction of the body diagonal through the black mass (see Figure 162), it changes in a certain way during a stroke. If the orientation is defined by the direction of the fixed bar attached to the black mass, it changes in a different way during a stroke. Only when a full stroke is completed do the two values coincide. Mathematicians say that the choice of the definition and thus the value of the orientation is *gauge-dependent*, but that the value of the orientation change at a full stroke is *gauge-invariant*.

In summary, the square cat shows three interesting points. First, already rather simple deformable bodies can change their orientation in space. Secondly, the orientation of a deformable body can only change if the deformations it can perform are *non-commuting*. Thirdly, such deformable bodies are described by *gauge theories*: certain aspects of the bodies are gauge-invariant, others are gauge-dependent. This summary leads to a question: Can we use these ideas to increase our understanding of the gauge theories of the electromagnetic, weak and strong interaction? Shapere and Wilczek say no. We will explore this issue in the next volume. In fact, shape change bears even more surprises.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

of size L are bound by

$$g \geqslant \frac{2\hbar G}{c^3}\frac{1}{L^2} \,. \tag{50}$$

Can you confirm this? The result has far-reaching consequences. A minimum value for the metric depending inversely on the region size implies that it is impossible to say what happens to the shape of space-time at extremely small dimensions. In other words, at extremely high energies, the concept of space-time itself becomes fuzzy. John Wheeler introduced the term *space-time foam* to describe this situation. The term makes clear that space-time is not continuous nor a manifold in those domains. But this was the basis on which we built our description of nature so far! We are forced to deduce that our description of nature is built on sand. This issue will be essential in the last volume of our mountain ascent.

Vol. VI, page 58

DECOHERENCE OF SPACE-TIME

General relativity taught us that the gravitational field and space-time are the same. If the gravitational field evolves like a quantum system, we may ask why no superpositions of different macroscopic space-times are observed.

Ref. 150

The discussion is simplified for the simplest case of all, namely the superposition, in a vacuum region of size l, of a homogeneous gravitational field with value g and one with value g'. As in the case of a superposition of macroscopic distinct wave functions, such a superposition *decays*. In particular, it decays when particles cross the volume. A short calculation yields a decay time given by

Vol. IV, page 147

Challenge 121 ny

$$t_{\mathrm{d}} = \left(\frac{2kT}{\pi m}\right)^{3/2} \frac{nl^4}{(g-g')^2} \,, \tag{51}$$

where n is the particle number density, kT their kinetic energy and m their mass. Inserting typical numbers, we find that the variations in gravitational field strength are *extremely* small. In fact, the numbers are so small that we can deduce that the gravitational field is the *first* variable which behaves classically in the history of the universe. Quantum gravity effects for space-time will thus be extremely hard to detect.

Challenge 122 e

In short, matter not only tells space-time how to curve, it also tells it to behave with class.

QUANTUM THEORY AS THE ENEMY OF SCIENCE FICTION

How does quantum theory change our ideas of space-time? The end of the twentieth century has brought several unexpected but strong results in semiclassical quantum gravity.

Ref. 151

In 1995 Ford and Roman found that *worm holes*, which are imaginable in general relativity, cannot exist if quantum effects are taken into account. They showed that macroscopic worm holes require unrealistically large negative energies. (For microscopic worm holes the issue is still unclear.)

Ref. 152

In 1996 Kay, Radzikowski and Wald showed that *closed time-like curves* do not exist in semiclassical quantum gravity; there are thus no time machines in nature.

Ref. 153

In 1997 Pfenning and Ford showed that *warp drive* situations, which are also imagin-

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

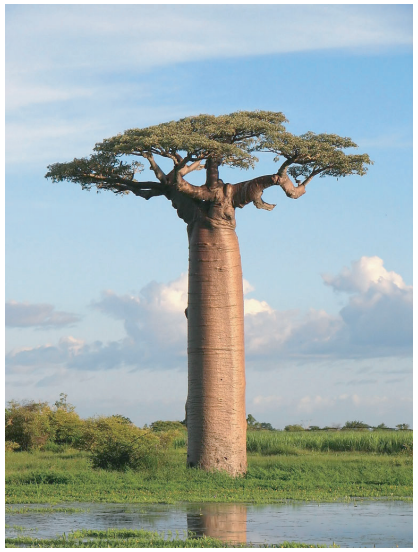


FIGURE 89 Every tree, such as this beautiful Madagascar baobab (*Adansonia grandidieri*), shows that nature, in contrast to physicists, is able to combine quantum theory and gravity (© Bernard Gagnon).

able in general relativity, cannot exist if quantum effects are taken into account. Such situations require unrealistically large negative energies.

In short, the inclusion of quantum effects destroys all those fantasies which were started by general relativity.

No vacuum means no particles

Vol. IV, page 114

Gravity has an important consequence for quantum theory. To count and define particles, quantum theory needs a defined vacuum state. However, the vacuum state cannot be defined when the curvature radius of space-time, instead of being larger than the Compton wavelength, becomes comparable to it. In such highly curved space-times, particles cannot be defined. The reason is the impossibility to distinguish the environment from the particle in these situations: in the presence of strong curvatures, the vacuum is full of spontaneously generated matter, as black holes show. Now we just saw that at small dimensions, space-time fluctuates wildly; in other words, space-time is highly curved at small dimensions or high energies. In other words, strictly speaking particles cannot be defined; the particle concept is only a low energy approximation! We will explore this strange conclusion in more detail in the final part of our mountain ascent.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

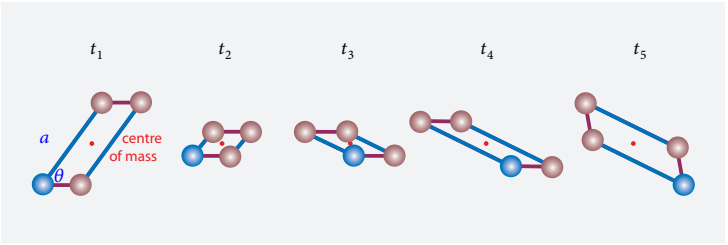


FIGURE 162 The square cat: in free space, or also on perfect ice, a deformable body in the shape of a parallelogram made of four masses and rods that is able to change the body angle θ and two rod lengths a is able to rotate itself around the centre of mass without outside help. One mass and the length-changing rods are coloured to illustrate the motion.

Vol. I, page 120

centuries, as shown in the old photograph given in Figure 160. In fact, cats confirm in three dimensions what we already knew for two dimensions:

▷ A deformable body can change its own orientation in space *without* outside help.

This is in strong contrast to translation, for which outside help is always needed. Archimedes famously said: Give me a place to stand, and I'll move the Earth. But to *rotate* the Earth, a place to stand is *not* needed!

Not only cats, also humans can perform the feat: simply observe the second, lateral rotation of the diver in Figure 161. Cosmonauts in space stations and passengers of parabolic 'zero-gravity' flights regularly do the same, as do many artificial satellites sent into space.

Ref. 243

In the 1980s, the work by Berry, Wilczek, Zee and ShapereBerry, MichaelWilczek, FrankZee, AnthonyShapere, Alfred showed that all motion due to shape change is described by a gauge theory. The equivalence between the two situations is detailed in Table 24.

Ref. 244

A simple and beautiful example for these ideas has been given by Putterman and Raz and is illustrated in Figure 162. Imagine four spheres on perfect ice, all of the same mass and size, connected by four rods forming a parallelogram. Now imagine that this parallelogram, using some built-in motors, can change length along one side, called a, and that it can also change the angle θ between the sides. Putterman and Raz call this the *square cat*. The figure shows that the square cat can change its own orientation on the ice while, obviously, keeping its centre of mass at rest. The figure also shows that the change of orientation only works because the two motions that the cat can perform, the stretching and the angle change, do *not* commute. The order in which these deformations occur is essential for achieving the desired rotation.

The rotation of the square cat occurs in *strokes*; large rotations are achieved by repeating strokes, similar to the situation of swimmers. If the square cat would be swimming in a liquid, the cat could thus rotate itself – though it could not advance.

When the cat rotates itself, each stroke results in a rotation angle that is independent

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

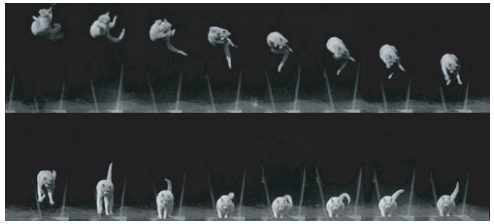


FIGURE 160 Cats can turn themselves, even with *no* initial angular momentum (photographs by Etienne-Jules Marey, 1894).

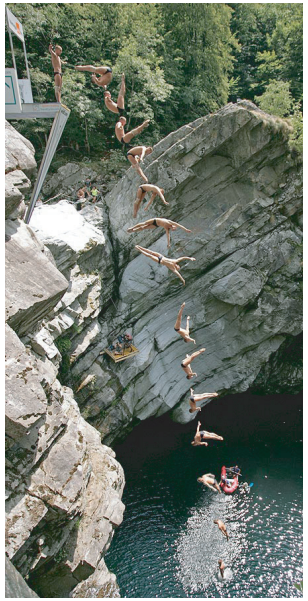


FIGURE 161 Humans can turn themselves in mid air like cats: see the second, lateral rotation of Artem Silchenko, at the 2006 cliff diving world championship (© World High Diving Federation).

air, about the achievable and achieved efficiency, and much more.

It is not a surprise that organized shape change can lead to *translational motion*. Amoebas, earthworms, caterpillars, snakes, and even human themselves move though shape change.

But shape change can also lead to a *rotation* of a body. In this case, the ideas are not restricted to microscopic systems, but apply at all scales. In particular, the theory of shape change is useful in explaining how falling cats manage to fall always on their feet. Cats are not born with this ability; they have to learn it. But the feat has fascinated people for

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Summary on quantum theory and gravity

Every tree tells us: everyday, *weak* gravitational fields can be included in quantum theory. *Weak* gravitational fields have measurable and predictable effects on wave functions: quantum particles fall and their phases change in gravitational fields. Conversely, the inclusion of quantum effects into general relativity leads to space-time foam, space-time superpositions and gravitons. The inclusion of quantum effects into gravity prevents the existence of wormholes, time-like curves and negative energy regions.

The inclusion of *strong* gravitational fields into quantum theory works for practical situations but leads to problems with the particle concept. Conversely, the inclusion of quantum effects into situations with high space-time curvature leads to problems with the concept of space-time.

In summary, the combination of quantum theory and gravitation leads to problems with both the particle concept and the space-time concept. The combination of quantum theory and general relativity puts into question the foundations of the description of nature that we used so far. As shown in Figure 89, nature is smarter than we are.

In fact, up to now we hid a simple fact: conceptually, quantum theory and general relativity *contradict* each other. This contradiction was one of the reasons that we stepped back to special relativity before we started exploring quantum theory. By stepping back we avoided many problems, because quantum theory does not contradict *special* relativity, but only *general* relativity. The issues are dramatic, changing everything from the basis of classical physics to the results of quantum theory. There will be surprising consequences for the nature of space-time, for the nature of particles, and for motion itself. Before we study these issues, however, we complete the theme of the present, quantum part of the mountain ascent, namely exploring motion inside matter, and in particular the motion of and in nuclei.

Vol. VI, page 17



Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Chapter 5

THE STRUCTURE OF THE NUCLEUS – THE DENSEST CLOUDS

Nuclear physics was born in 1896 in France, but is now a small activity. ot many open issues are left. But in its golden past, researchers produced ew ways for medical doctors to dramatically improve the healing rate of pa-
Ref. 154 tients. Researchers also discovered why stars shine, how powerful bombs work, and how cosmic evolution produced the atoms we are made of. We will explore these topics now. A fascinating spin-off of nuclear physics, high energy particle physics, will keep us busy later on.

> Nuclear physics is just low-density astrophysics.
> Anonymous

A physical wonder – magnetic resonance imaging

Arguably, the most spectacular tool that physical research produced in the twentieth century was *magnetic resonance imaging*, or MRI for short. This imaging technique allows one to image the interior of human bodies with a high resolution and with no damage or danger to the patient, in strong contrast to X-ray imaging. The technique is based on moving atomic nuclei. Though the machines are still expensive – costing up to several million euro – there is hope that they will become cheaper in the future. Such an MRI machine, shown in Figure 90, consists essentially of a large magnetic coil, a radio transmitter and a computer. Some results of putting part of a person into the coil are shown in Figure 91. The images allow detecting problems in bones, in the spine, in the beating heart and in general tissue. Many people owe their life and health to these machines; in many cases the machines allow making precise diagnoses and thus choosing the appropriate treatment for patients.

In MRI machines, a radio transmitter emits radio waves that are absorbed because hydrogen nuclei – protons – are small spinning magnets. The magnets can be parallel or antiparallel to the magnetic field produced by the coil. The transition energy E is absorbed from a radio wave whose frequency ω is tuned to the magnetic field B. The energy absorbed by a single hydrogen nucleus is given by

$$E = \hbar\omega = \hbar\gamma B \tag{52}$$

The material constant $\gamma/2\pi$ has a value of 42.6 MHz/T for hydrogen nuclei; it results from the non-vanishing spin of the proton. The absorption of the radio wave is a pure quantum effect, as shown by the appearance of the quantum of action $\hbar$. Using some cleverly ap-

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

flagellum is turned by a sophisticated rotation motor built into the cell, which the cell can control both in rotation direction and in angular velocity. For Coli bacteria, the
Ref. 240 range is between 0 and about 300 Hz.

A turning flagellum does not propel a bacterium like a propeller; as mentioned, the velocities involved are much too small, the Reynolds number being only about 10^{-4}. At these dimensions and velocities, the effect is better described by a corkscrew turning in honey or in cork: a turning corkscrew produces a motion against the material around it, in the direction of the corkscrew axis. The flagellum moves the bacterium in the same way that a corkscrew moves the turning hand with respect to the cork.

4. One group of bacteria, the spirochaetes, move as a whole like a cork-screw through water. An example is *Rhodospirillum rubrum*, whose motion can be followed in the video on www.microbiologybytes.com/video/motility.com. These bacteria have an internal motor round an axial filament, that changes the cell shape in a non-symmetrical fashion and yield cork-screw motion. A different bacterium is
Ref. 241 *Spiroplasma*, a helical bacterium – but not a spirochaete – that changes the cell shape, again in a non-symmetrical fashion, by propagating kink pairs along its body surface. Various other microorganisms move by changing their body shape.

To test your intuition, you may try the following puzzle: is microscopic swimming pos-
Challenge 154 s sible in two spatial dimensions? In four?

By the way, still smaller bacteria do not swim at all. Indeed, each bacterium faces a minimum swimming speed requirement: it must outpace diffusion in the liquid it lives
Ref. 242 in. Slow swimming capability makes no sense; numerous microorganisms therefore do not manage or do not swim at all. Some microorganisms are specialized to move along liquid–air interfaces. In fact, there are many types of interfacial swimming, including macroscopic types, but we do not cover them here. Other microorganisms attach themselves to solid bodies they find in the liquid. Some of them are able to *move* along these solids. The amoeba is an example for a microorganism moving in this way. Also the smallest active motion mechanisms known, namely the motion of molecules in muscles and
Page 21 in cell membranes, work this way.

Let us summarize these observations. All known active motion, or self-propulsion, (in flat space) takes place in fluids – be it air or liquids. All active motion requires shape change. Macroscopic swimming works by accelerating the fluid in the direction opposite to the direction of motion. Microscopic swimming works through smart shape change that makes the swimmer advance through the fluid. In order that shape change leads to motion, the environment, e.g. the fluid, must itself consist of moving components always pushing onto the swimming entity. The motion of the swimming entity can then be deduced from the particular shape change it performs. The mathematics of swimming through shape change is fascinating; it deserves to be explored.

Rotation, falling cats and the theory of shape change

At small dimensions, flying and swimming takes place through shape change. In the last decades, the description of shape change has changed from a fashionable piece of research to a topic whose results are both appealing and useful. There are many studies, both experimental and theoretical, about the exact way small systems move in water and

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

that no microscopic system can swim if it uses movable parts with only *one* degree of freedom. Thus it is impossible to move, at cell dimensions, using the method that the scallop uses on centimetre scale.

In order to swim, microorganisms thus need to use a more evolved, *two-dimensional motion* of their shape. Indeed, biologists found that all microorganisms use one of the following four swimming styles:

1. Microorganisms of compact shape of diameter between 20 µm and about 20 mm, use *cilia*. Cilia are hundreds of little hairs on the surface of the organism. Some organisms have cilia across their full surface, other only on part of it. These organisms move the cilia in waves wandering around their surface, and these surface waves make the body advance through the fluid. All children watch with wonder *Paramecium*, the unicellular animal they find under the microscope when they explore the water in which some grass has been left for a few hours. *Paramecium*, which is between 100 µm and 300 µm in size, as well as many plankton species* use cilia for its motion. The cilia and their motion are clearly visible in the microscope. A similar swimming method is even used by some large animals; you might have seen similar waves on the borders of certain ink fish; even the motion of the manta (partially) belongs into this class. Ref. 235 Ciliate motion is an efficient way to change the shape of a body making use of two dimensions and thus avoiding the scallop theorem.
2. Sperm and eukaryote microorganisms whose sizes are in the range between 1 µm and 50 µm swim using an (eukaryote) flagellum.** Flagella, Latin for 'small whips', work like flexible oars. Even though their motion sometimes appears to be just an oscillation, flagella get a kick only during one half of their motion, e.g. at every swing to the left. Flagella are indeed used by the cells like miniature oars. Some cells even twist their flagellum in a similar way that people rotate an arm. Some microorganisms, such as *Chlamydomonas*, even have two flagella which move in the same way Ref. 237 as people move their legs when they perform the breast stroke. Most cells can also change the sense in which the flagellum is kicked, thus allowing them to move either Ref. 238 forward or backward. Through their twisted oar motion, bacterial flagella avoid retracing the same path when going back and forward. As a result, the bacteria avoid the scallop theorem and manage to swim despite their small dimensions. The flexible oar motion they use is an example of a non-adiabatic mechanism; an important fraction of the energy is dissipated.
3. The smallest swimming organisms, bacteria with sizes between 0.2 µm and 5 µm, Ref. 239 swim using *bacterial* flagella. These flagella, also called prokaryote flagella, are different from the ones just mentioned. Bacterial flagella move like turning corkscrews. They are used by the famous *Escherichia coli* bacterium and by all bacteria of the genus *Salmonella*. This type of motion is one of the prominent exceptions to the non-existence of wheels in nature; we mentioned it in the beginning of our walk. Vol. I, page 89 Corkscrew motion is an example of an adiabatic mechanism.

A Coli bacterium typically has a handful of flagella, each about 30 nm thick and of corkscrew shape, with up to six turns; the turns have a 'wavelength' of 2.3 µm. Each

* See the www.liv.ac.uk/ciliate website for an overview.

Ref. 236 ** The largest sperm, of 6 cm length, are produced by the 1.5 mm sized *Drosophila bifurca* fly, a relative of the famous *Drosophila melanogaster*.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 90 A commercial MRI machine (© Royal Philips Electronics).

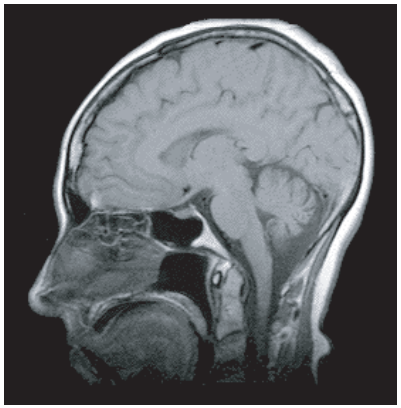




FIGURE 91 Sagittal images of the head and the spine (used with permission from Joseph P. Hornak, *The Basics of MRI*, www.cis.rit.edu/htbooks/mri, Copyright 2003).

plied magnetic fields, typically with a strength between 0.3 and 7 T for commercial and up to 21 T for experimental machines, the absorption for each volume element can be measured separately. Interestingly, the precise absorption *level* depends on the chemical compound the nucleus is built into. Thus the absorption value will depend on the chemical substance. When the intensity of the absorption is plotted as grey scale, an image is formed that retraces the different chemical compositions. Figure 91 shows two examples. Using additional tricks, modern machines can picture blood flow in the heart or air flow

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

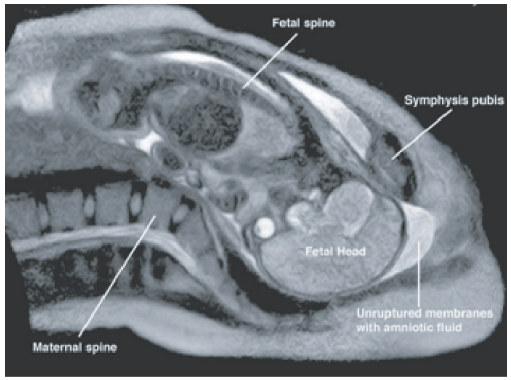


FIGURE 92 An image of the first magnetic resonance video of a human birth (© C. Bamberg).

Ref. 155 in lungs; they now routinely make films of the heart beat. Other techniques show how the location of sugar metabolism in the brain depends on what you are thinking about.*

Magnetic resonance imaging can even image the great wonders of nature. The first Ref. 156 video of a human birth, taken in 2010 and published in 2012, is shown in Figure 92. MRI Ref. 157 scans are loud, but otherwise harmless for unborn children. The first scan of a married couple making love has been taken by Willibrord Weijmar Schultz and his group in 1999. It is shown on page 399.

Every magnetic resonance image thus proves that

▷ Many – but not all – atoms have nuclei that spin.

Like any other object, nuclei have size, shape, colour, composition and interactions. Let us explore them.

The size of nuclei and the discovery of radioactivity

The magnetic resonance signal shows that hydrogen nuclei spin with high speed. Thus they must be small. Indeed, the g-factor of protons, defined using the magnetic moment μ, their mass m and charge e, is found to be

$$g = \mu 4 \frac{m}{e\hbar} \approx 5.6 \,. \tag{53}$$

Vol. IV, page 106 This is a small value. Using the expression that relates the g-factor and the radius of a composite object, we deduce that the radius of the proton is about 0.9 fm; this value

* The website www.cis.rit.edu/htbooks/mri by Joseph P. Hornak gives an excellent introduction to magnetic resonance imaging, both in English and Russian, including the physical basis, the working of the machines, and numerous beautiful pictures. The method of studying nuclei by putting them at the same time into magnetic and radio fields is also called *nuclear magnetic resonance*.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 159 A swimming scallop (here from the genus *Chlamys*) (© Dave Colwell).

use other effects. In fact, their only possibility is to change their body shape in controlled ways. Seen from far away, the swimming of microorganisms thus resembles the motion of particles through vacuum: like microorganisms, also particles have nothing to throw behind* them.

A good way to distinguish macroscopic from microscopic swimming is provided by scallops. *Scallops* are molluscs up to a few cm in size; an example is shown in Figure 159. Scallops have a double shell connected by a hinge that they can open and close. If they close it *rapidly*, water is expelled and the mollusc is accelerated; the scallop then can glide for a while through the water. Then the scallop opens the shell again, this time *slowly*, and repeats the feat. When swimming, the larger scallops look like clockwork false teeth. Scallops thus use a macroscopic swimming process.

If we reduce the size of the scallop by a thousand times to the size of a single cell we get a simple result: such a tiny scallop *cannot* swim. The lack of scalability of swimming methods is due to the changing ratio between inertial and dissipative effects at different Vol. I, page 427 scales. This ratio is measured by the *Reynolds number Re*. For the scallop the Reynolds number, is defined as $Re = vL/\eta$, where v is the relative speed between swimmer and water, L the length of the swimmer and η is the *kinematic viscosity* of the water, around $1\,\mathrm{mm}^2/\mathrm{s}$.

For the scallop, the Reynolds number is about 100, which shows that when it swims, inertial effects are much more important than dissipative, viscous effects. For a bacterium the Reynolds number is much smaller than 1, so that inertial effects effectively play no role. There is no way to accelerate water *away* from a bacterial-sized scallop, and thus no way to glide. Bacteria *cannot* swim like scallops or people do; bacteria cannot throw water behind them. And this is not the only problem microorganism face when they want to swim.

A well-known mathematical theorem states that no cell-sized being can move if the shape change is the same in the two halves of the motion, i.e., when opening and closing Ref. 233 are just the inverse of each other. Such a shape change would simply make it move back and forward. Another mathematical theorem, the so-called *scallop theorem*, that states

* There is an exception: gliding bacteria move by secreting slime, even though it is still not fully clear why this leads to motion.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

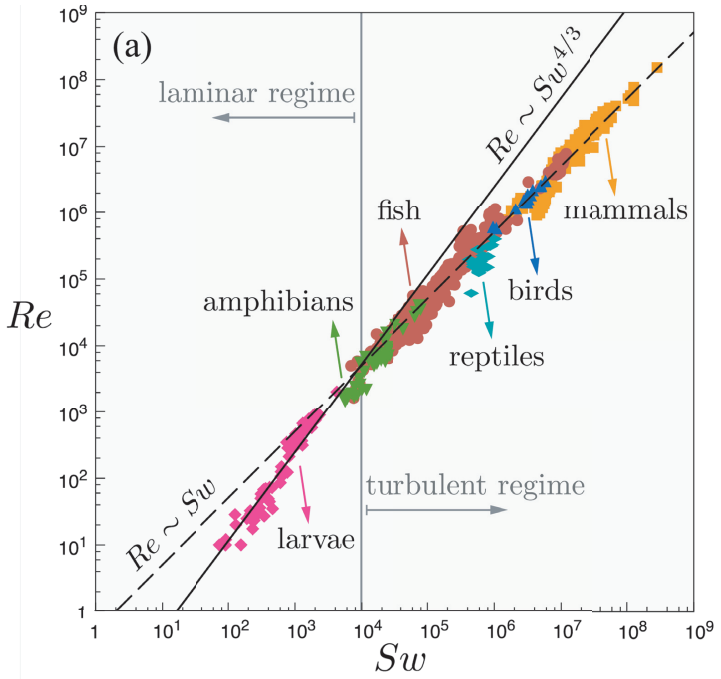


FIGURE 158 Undulatory swimming follows simple scaling rules for organisms that range from a few mm to 30 m in length. The Reynolds number *Re* describes the ratio between inertial effects (the water thrown behind) and the dissipative effects (the friction of the water). The swimming number *Sw* describes the body kinematics. (© L. Mahadevan/Macmillan from) Ref. 232

bulent swimming, the swimming speed v almost exclusively depends on the amplitude and frequency of the undulatory motion; for smaller organisms that swim in the laminar regime, the swimming speed also depends on the length of the organism. Challenge 153 e

In short, fish, dolphins, submarines and people swim in the same way that fireworks or rockets fly: by throwing matter behind them, through lift. Lift-based propulsion is the main type of macroscopic swimming. Do all organisms swim in this way? No. Several organisms swim by expelling water jets, for example cephalopods such as squids. And above all, *small* organisms advancing through the molecules of a liquid use a completely different, *microscopic* way of swimming. Ref. 234

Small organisms such as bacteria do *not* have the capacity to propel or accelerate water against their surroundings. Indeed, the water remains attached around a microorganism without ever moving away from it. Physically speaking, in these cases of swimming the kinetic energy of the water is negligible. In order to swim, unicellular beings thus need to

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 93 Henri Becquerel (1852–1908)



FIGURE 94 Marie Curie (1867–1934)

is confirmed by many experiments and other measurement methods. Protons are thus about 30 000 times smaller than hydrogen atoms, whose radius is about 30 pm. The proton is the smallest of all nuclei; the largest known nuclei have radii about 7 times as large.

The small size of nuclei is no news. It is known since the beginning of the twentieth century. The story starts on the first of March in 1896, when Henri Becquerel* discovered a puzzling phenomenon: minerals of uranium potassium sulphate blacken photographic plates. Becquerel had heard that the material is strongly fluorescent; he conjectured that fluorescence might have some connection to the X-rays discovered by Conrad Röntgen the year before. His conjecture was wrong; nevertheless it led him to an important new discovery. Investigating the reason for the effect of uranium on photographic plates, Becquerel found that these minerals emit an undiscovered type of radiation, different from anything known at that time; in addition, the radiation is emitted by any substance containing uranium. In 1898, Gustave Bémont named the property of these minerals *radioactivity*.

Radioactive rays are also emitted from many elements other than uranium. This radiation can be 'seen': it can be detected by the tiny flashes of light that appear when the rays hit a scintillation screen. The light flashes are tiny even at a distance of several metres from the source; thus the rays must be emitted from point-like sources. In short, radio-

* Henri Becquerel (b. 1852 Paris, d. 1908 Le Croisic), important physicist; his primary research topic was the study of radioactivity. He was the thesis adviser of Marie Curie, the wife of Pierre Curie, and was central to bringing her to fame. The SI unit for radioactivity is named after Becquerel. For his discovery of radioactivity he received the 1903 Nobel Prize in Physics; he shared it with the Curies.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 11 The main types of radioactivity and rays emitted by matter.

TYPE	PARTICLE	EXAMPLE	RANGE	DANGER	SHIELD	USE
α rays 3 to 10 MeV	helium nuclei	^{235}U, ^{238}U, ^{238}Pu, ^{238}Pu, ^{241}Am	a few cm in air	when eaten, inhaled, touched	any material, e.g. paper	thickness measurement
β rays 0 to 5 MeV	electrons and	^{14}C, ^{40}K, ^{3}H, ^{101}Tc	< 1 mm in metal	serious	metals	cancer treatment
	antineutrinos		light years	none	none	research
β^+ rays	positrons and	^{40}K, ^{11}C, ^{11}C, ^{13}N, ^{15}O	less than β	medium	any material	tomography
	neutrinos		light years	none	none	research
γ rays	high energy photons	^{110}Ag	several m in air	high	thick lead	preservation of herbs, disinfection
n reactions *c.* 1 MeV	neutrons	^{252}Cf, Po-Li (α,n), ^{38}Cl-Be (γ,n)	many m in air	high	0.3 m of paraffin	nuclear power, quantum gravity experiments
n emission typ. 40 MeV	neutrons	^{9}He, ^{24}N, ^{254}Cf	many m in air	high	0.3 m of paraffin	research experiments
p emission typ. 20 MeV	protons	^{5}Be, ^{161}Re	like α rays	small	solids	
spontaneous fission typ. 100 MeV	nuclei	^{232}Cm, ^{263}Rf	like α rays	small	solids	detection of new elements

activity has to be emitted from single atoms. Thus radioactivity confirmed unambiguously that atoms do exist. In fact, radioactivity even allows *counting* atoms: in a diluted radioactive substance, the flashes can be counted, either with the help of a photographic film or with a photon counting system.

Vol. IV, page 42

The intensity of radioactivity cannot be influenced by magnetic or electric fields; and it does not depend on temperature or light irradiation. In short, radioactivity does not depend on electromagnetism and is not related to it. Also the high energy of the emitted radiation cannot be explained by electromagnetic effects. Radioactivity must thus be due to another, new type of force. In fact, it took 30 years and a dozen of Nobel Prizes to fully understand the details. It turns out that several types of radioactivity exist; the types of emitted radiation behave differently when they fly through a magnetic field or when they encounter matter. The types of radiation are listed in Table 11. In the meantime, all

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

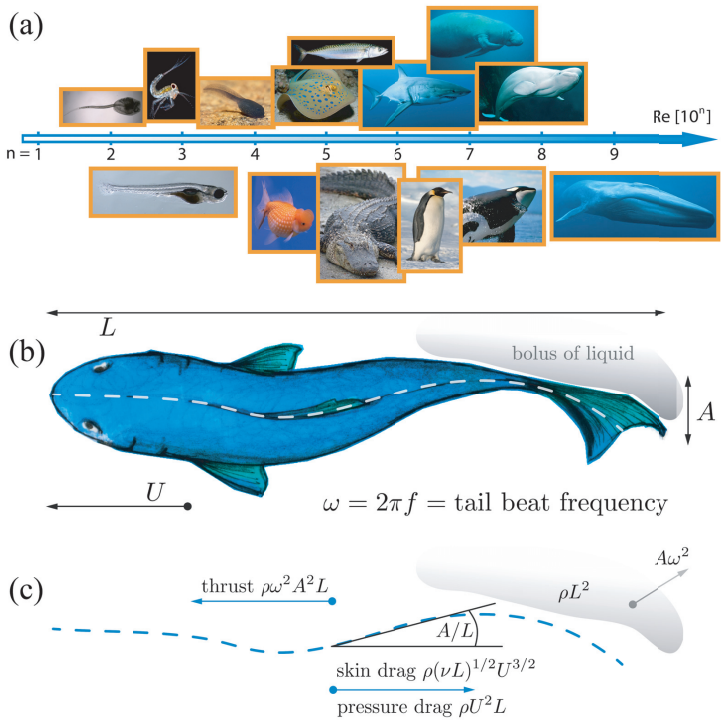


FIGURE 157 A selection of animals using undulatory swimming and the main variables that describe it. (© L. Mahadevan/Macmillan from)

Ref. 232

vation they then move forward.*

Most fish and aquatic mammals swim by bending their bodies and alternating between two extreme deformations. An overview of animals that use this type of swimming – experts call it *undulatory gait* – is given in Figure 157. For all such swimming, the Reynolds number obeys $\mathrm{Re} = vL/\nu >> 1$; here v is the swimming speed, L the body length and ν the kinematic viscocity. The wide range of Reynolds number values observed for swimming living beings is shown in the graph. The swimming motion is best described by the so-called swimming number $\mathrm{Sw} = \omega AL/\nu$, where ω and A are the circular beat frequency and amplitude. The next graph, Figure 158, shows that for tur-

Ref. 232

Vol. I, page 89

* Fish could use propellers, as the arguments against wheels we collected at the beginning of our walk do not apply for swimming. But propellers with blood supply would be a weak point in the construction, and thus make fish vulnerable. Therefore, nature has not developed fish with propellers.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 156 The wings of a few types of insects smaller than 1 mm (thrips, *Encarsia*, *Anagrus*, *Dicomorpha*) (HortNET).

4. The fourth type of wings is found at the smallest possible dimensions, for insects smaller than one millimetre; their wings are not membranes at all, but are optimized for viscous air flow. Typical are the cases of thrips and of parasitic wasps, which can be as small as 0.3 mm. All these small insects have wings which consist of a central *stalk* surrounded by hair. In fact, Figure 156 shows that some species of thrips have wings which look like miniature toilet brushes.
5. At even smaller dimensions, corresponding to Reynolds number below 10, nature does not use wings any more, though it still makes use of air transport. In principle, at the smallest Reynolds numbers gravity plays no role any more, and the process of flying merges with that of swimming. However, air currents are too strong compared with the speeds that such a tiny system could realize. No active navigation is then possible any more. At these small dimensions, which are important for the transport through air of spores and pollen, nature uses the air currents for passive transport, making use of special, but fixed shapes.

We summarize: active flying is only possible through shape change. Only two types of shape changes are possible for active flying: that of wings and that of propellers (including turbines). Engineers are studying with intensity how these shape changes have to take place in order to make flying most effective. Interestingly, a similar challenge is posed by swimming.

Ref. 230
Ref. 231

Swimming

Swimming is a fascinating phenomenon. The Greeks argued that the ability of fish to swim is a proof that water is made of atoms. If atoms would not exist, a fish could not advance through it. Indeed, swimming is an activity that shows that matter cannot be continuous. Studying swimming can thus be quite enlightening. But how exactly do fish swim?

Whenever dolphins, jellyfish, submarines or humans *swim*, they take water with their fins, body, propellers, hands or feet and push it backwards. Due to momentum conser-

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

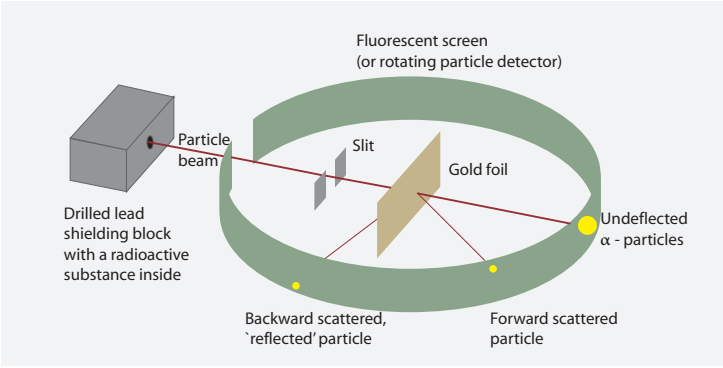


FIGURE 95 The schematics of the Rutherford–Geiger scattering experiment. The gold foil is about a square centimetre in size.

these rays have been studied in great detail, with the aim to understand the nature of the emitted entity and its interaction with matter.

In 1909, radioactivity inspired the 37 year old physicist Ernest Rutherford,* who had won the Nobel Prize just the year before, to another of his smart experiments. He asked his collaborator Hans Geiger to take an emitter of α radiation – a type of radioactivity which Rutherford had identified and named 10 years earlier – and to point the radiation at a thin metal foil. The quest was to find out where the α rays would end up. The experiment is shown in Figure 95. The research group followed the path of the particles by using scintillation screens; later on they used an invention by Charles Wilson: the cloud chamber. A *cloud chamber*, like its successor, the bubble chamber, produces white traces along the path of charged particles; the mechanism is the same as the one than leads to the white lines in the sky when an aeroplane flies by. Both cloud chambers and bubble chambers thus allow *seeing* radioactivity, as shown in the examples of Figure 96.

The radiation detectors around the thin gold foil give a consistent, but strange result: most α particles pass through the foil undisturbed, whereas a few are scattered and a few are reflected. In addition, those few which are reflected are not reflected by the surface, but in the inside of the foil. (Can you imagine how to show this?) Rutherford and Geiger deduced from their scattering experiment that first of all, the atoms in the metal foil are mainly transparent. Only transparency of atoms explains why most α particles pass the

Challenge 123 s

* Ernest Rutherford (b. 1871 Brightwater, d. 1937 Cambridge), important physicist. He emigrated to Britain and became professor at the University of Manchester. He coined the terms α particle, β particle, proton and neutron. A gifted experimentalist, he discovered that radioactivity transmutes the elements, explained the nature of α rays, discovered the nucleus, measured its size and performed the first nuclear reactions. Ironically, in 1908 he received the Nobel Prize in Chemistry, much to the amusement of himself and of the world-wide physics community; this was necessary as it was impossible to give enough physics prizes to the numerous discoverers of the time. He founded a successful research school of nuclear physics and many famous physicists spent some time at his institute. Ever an experimentalist, Rutherford deeply disliked quantum theory, even though it was and is the only possible explanation for his discoveries.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

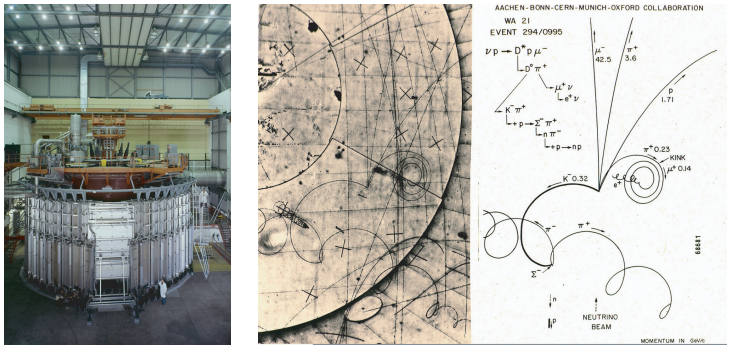


FIGURE 96 The 'Big European Bubble Chamber' – the biggest bubble chamber ever built – and an example of tracks of relativistic particles it produced, with the momentum values deduced from the photograph (© CERN).

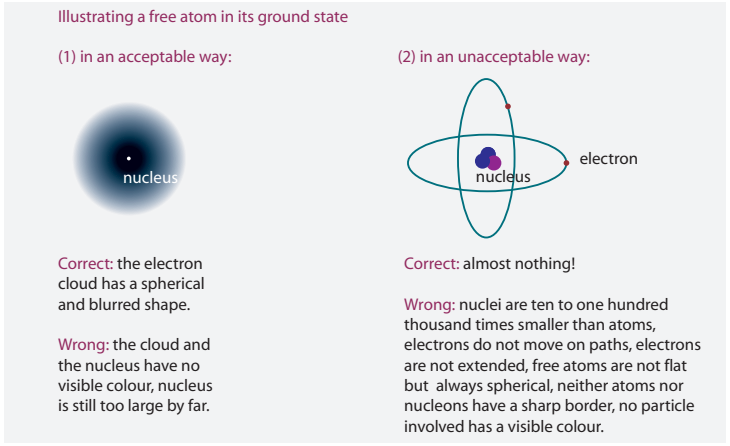


FIGURE 97 A reasonably realistic (left) and a misleading illustration of an atom (right) as is regularly found in school books. *Atoms in the ground state are spherical electron clouds with a tiny nucleus, itself a cloud, at its centre.* Interacting atoms, chemically bound atoms and some, but not all excited atoms have electron clouds of different shapes.

foil without disturbance, even though it was over 2000 atoms thick. But some particles were scattered by large angles or even reflected. Rutherford showed that the reflections must be due to a single scattering point. By counting the particles that were reflected (about 1 in 20000 for his 0.4 µm gold foil), Rutherford was also able to deduce the *size*

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 155 Examples of the three larger wing types in nature, all optimized for rapid flows: turkey vulture (*Cathartes aura*), ruby-throated hummingbird (*Archilochus colubris*) and a dragonfly (© S.L. Brown, Pennsylvania Game Commission/Joe Kosack and nobodythere).

know, pheasants make a loud 'clap' when they take off. The clap is due to the low pressure region thus created.

Both wing use and wing construction depend on size. In fact, there are four types of wings in nature.

1. First of all, all large flying objects, such aeroplanes and large birds, fly using *fixed* wings, except during take-off and landing. This wing type is shown on the left-hand side of Figure 155.
2. Second, common size birds use *flapping* wings. (Hummingbirds can have over 50 wing beats per second.) These first two types of wings have a thickness of about 10 to 15 % of the wing depth. This wing type is shown in the centre of Figure 155.
3. At smaller dimensions, a third wing type appears, the *membrane wing*. It is found in dragonflies and most everyday insects. At these scales, at Reynolds numbers of around 1000 and below, thin *membrane* wings are the most efficient. The *Reynolds number* measures the ratio between inertial and viscous effects in a fluid. It is defined as

$$\mathrm{Re} = \frac{lv\rho}{\eta} \tag{111}$$

where l is a typical length of the system, v the speed, ρ the density and η the dynamic *viscosity* of the fluid.* A Reynolds number much larger than one is typical for rapid air flow and fast moving water. In fact, the value of the Reynolds number distinguishes a 'rapid' or 'turbulent' flow on the one hand, and a 'slow', 'laminar' or 'viscous' flow on the other. An example of membrane wing is shown on the right-hand side of Figure 155. All the first three wing types are designed for *turbulent* flows.

Challenge 152 ny

* The viscosity is the resistance to flow a fluid poses. It is defined by the force F necessary to move a layer of surface A with respect to a second, parallel one at distance d; in short, the (coefficient of) *dynamic viscosity* is defined as $\eta = dF/Av$. The unit is 1 kg/s m or 1 Pa s or 1 N s/m^2, once also called 10 P or 10 poise. In other words, given a horizontal tube, the viscosity determines how strong the pump needs to be to pump the fluid through the tube at a given speed. The viscosity of air 20°C is 1.8×10^{-5} kg/s m or 18 µPa s and increases with temperature. In contrast, the viscosity of liquids decreases with temperature. (Why?) The viscosity of water at 0°C is 1.8 mPa s, at 20°C it is 1.0 mPa s (or 1 cP), and at 40°C is 0.66 mPa s. Hydrogen has a viscosity smaller than 10 µPa s, whereas honey has 25 Pa s and pitch 30 MPa s.

Physicists also use a quantity ν called the *kinematic viscosity*. It is defined with the help of the mass density of the fluid as $\nu = \eta/\rho$ and is measured in m^2/s, once called 10^4 stokes. The kinematic viscosity of water at 20°C is 1 mm^2/s (or 1 cSt). One of the smallest values is that of acetone, with 0.3 mm^2/s; a larger one is glycerine, with 2000 mm^2/s. Gases range between 3 mm^2/s and 100 mm^2/s.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

density of air is only a quarter of that on the ground, thus only 0.31 kg/m^3. We deduce (correctly) that a Boeing 747 has a mass of about 300 ton. For bumblebees with a speed of 3 m/s and a wing surface of 1 cm^2, we get a lifted mass of about 35 mg, far less than the weight of the bee, namely about 1 g. The mismatch is even larger for fruit flies. In other words, an insect cannot fly if it keeps its wings *fixed*. It could not fly with fixed wings even if it had tiny propellers attached to them!

Challenge 150 e

Due to the limitations of fixed wings at small dimensions, insects and small birds must *move* their wings, in contrast to aeroplanes. They must do so not only to take off or to gain height, but also to simply remain airborne in horizontal flight. In contrast, aeroplanes generate enough lift with *fixed* wings. Indeed, if you look at flying animals, such as the ones shown in Figure 155, you note that the larger they are, the less they need to move their wings (at cruising speed).

Can you deduce from equation (110) that birds or insects can fly but people cannot? Conversely, the formula also (partly) explains why human-powered aeroplanes must be so large.*

Challenge 151 s

But *how* do insects, small birds, flying fish or bats have to move their wings in order to fly? This is a tricky question and the answer has been uncovered only recently. The main point is that insect wings move in a way to produce eddies at the front edge which in turn thrust the insect upwards. Aerodynamic studies of butterflies – shown in Figure 154 – and studies of enlarged insect models moving in oil instead of in air are exploring the precise way insects make use of vortices. At the same time, more and more 'mechanical birds' and 'model aeroplanes' that use flapping wings for their propulsion are being built around the world. The field is literally in full swing.** Researchers are especially interested in understanding how vortices allow change of flight direction at the small dimensions typical for insects. Another aim is to reduce the size of flying machines.

Ref. 228
Ref. 229

The expression (110) for the lift of fixed wings also shows what is necessary for safe take-off and landing. The lift of all wings *decreases* for smaller speeds. Thus both animals and aeroplanes *increase* their wing surface in these occasions. Many birds also vigorously increase the flapping of wings in these situations. But even strongly flapping, enlarged wings often are insufficient for take-off. Many flying animals, such as swallows, therefore avoid landing completely. For flying animals which do take off from the ground, nature most commonly makes them hit the wings against each other, over their back, so that when the wings separate again, the low pressure between them provides the first lift. This method is used by insects and many birds, including pheasants. As bird watchers

* Another part of the explanation requires some aerodynamics, which we will not study here. Aerodynamics shows that the power consumption, and thus the resistance of a wing with given mass and given cruise speed, is inversely proportional to the square of the wingspan. Large wingspans with long slender wings are thus of advantage in (subsonic) flying, especially when energy is scarce.

One issue is mentioned here only in passing: why does an aircraft fly? The correct general answer is: *because it deflects air downwards*. How does an aeroplane achieve this? It can do so with the help of a tilted plank, a rotor, flapping wings, or a fixed wing. And when does a fixed wing deflect air downwards? First of all, the wing has to be tilted with respect to the air flow; in addition, the specific cross section of the wing can increase the downward flow. The relation between wing shape and downward flow is a central topic of applied aerodynamics.

** The website www.aniprop.de presents a typical research approach and the sites ovirc.free.fr and www.ornithopter.org give introductions into the way to build such systems for hobbyists.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

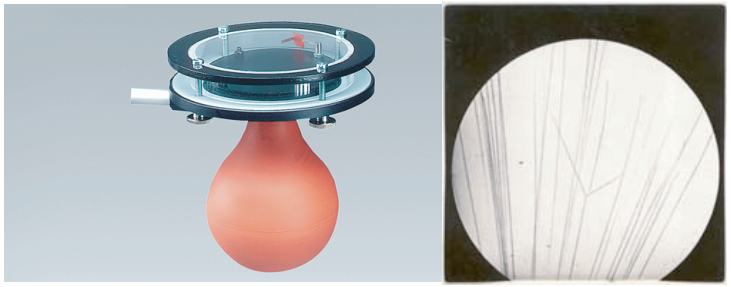


FIGURE 98 Left: a modern Wilson cloud chamber, diameter c. 100 mm. Right: one of the first pictures of α rays taken with a cloud chamber in the 1920s by Patrick Blackett, showing also a collision with an atom in the chamber (© Wiemann Lehrmittel, Royal Society)

of the reflecting entity and to estimate its *mass*. (This calculation is now a standard exercise in the study of physics at universities.) He found that the reflecting entity contains practically all of the mass of the atom in a diameter of a few fm. Rutherford named this concentrated mass the atomic *nucleus*.

Using the knowledge that atoms contain electrons, Rutherford then deduced from this experiment that atoms consist of an electron cloud that determines the size of atoms – of the order of 0.1 nm – and of a tiny but heavy nucleus at the centre. If an atom had the size of a basketball, its nucleus would have the size of a dust particle, yet contain 99.9 % of the basketball's mass. Thus

▷ Atoms resemble candy floss around a heavy dust particle.

Even though the candy floss – the electron cloud – around the nucleus is extremely thin and light, it is strong enough to avoid that two atoms interpenetrate. In solids, the candy floss, i.e., the electron cloud, keeps the neighbouring nuclei at constant distance. Figure 97 shows the more and less correct ways to picture an atom. Candy floss explains the Rutherford–Geiger experiment: for the tiny and massive α particles however, the candy floss is essentially empty space, so that they simply fly through the electron clouds until they either exit on the other side of the foil or hit a nucleus.

The density of the nucleus is impressive: about $5.5 \cdot 10^{17}$ kg/m^3. At that density, the mass of the Earth would fit in a sphere of 137 m radius and a grain of sand would have a mass larger than the largest oil tanker. (Can you confirm this?)

Challenge 124 e

> "I now know how an atom looks like!"
> Ernest Rutherford

Nuclei are composed

Magnetic resonance images also show that nuclei are *composed*. Indeed, images can also be taken using heavier nuclei instead of hydrogen, such as certain fluorine or oxygen

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

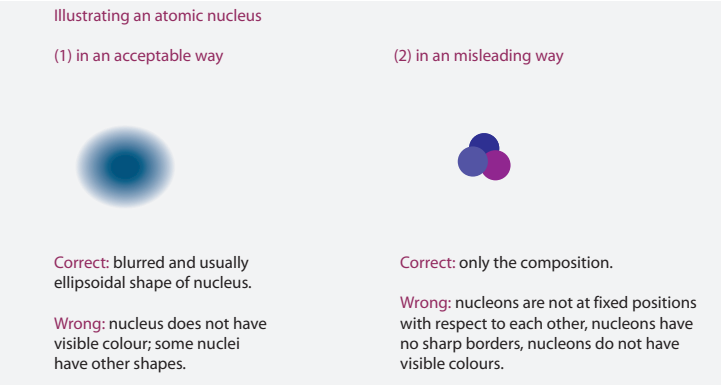


FIGURE 99 A reasonably realistic (left) and a misleading illustration of a nucleus (right) as is regularly found in school books. *Nuclei are spherical nucleon clouds.*

Vol. IV, page 106

nuclei. Also the g-factors of these nuclei depart from the value 2 characteristic of point particles; the more massive the nuclei are, the bigger the departure. Therefore, all nuclei have a finite size. The size of nuclei can actually be measured; the Rutherford–Geiger experiment and many other scattering experiments allow to do so. The measured values confirm the values predicted by the g-factor. In short, both the values of the g-factor and the non-vanishing sizes show that *nuclei are composed*.

Interestingly, the idea that nuclei are composed is older than the concept of nucleus itself. Already in 1815, after the first mass measurements of atoms by John Dalton and others, researchers noted that the mass of the various chemical elements seem to be almost perfect multiples of the weight of the hydrogen atom. William Prout then formulated the hypothesis that all elements are composed of hydrogen. When the nucleus was discovered, knowing that it contains almost all mass of the atom, it was therefore first thought that all nuclei are made of hydrogen nuclei. Being at the origin of the list of constituents, the hydrogen nucleus was named *proton*, from the greek term for 'first' and reminding the name of Prout at the same time. Protons carry a positive unit of electric charge, just the opposite of that of electrons, but are about 1836 times as heavy. More details on the proton are listed in Table 12.

However, the charge multiples and the mass multiples for the heavier nuclei do not match. On average, a nucleus that has n times the charge of a proton, has a mass that is about 2.6 n times than of the proton. Additional experiments confirmed an idea formulated by Werner Heisenberg: all nuclei heavier than hydrogen nuclei are made of positively charged *protons* and of neutral *neutrons*. Neutrons are particles a tiny bit more massive than protons (the difference is less than a part in 700, as shown in Table 12), but without any electrical charge. Since the mass is almost the same, the mass of nuclei – and thus that of atoms – is still an (almost perfect) integer multiple of the proton mass. But since neutrons are neutral, the mass and the charge number of nuclei differ. Being

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

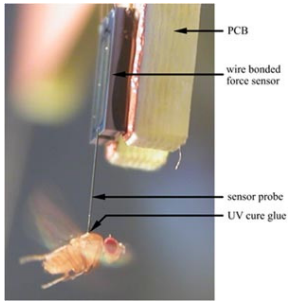


FIGURE 153 A flying fruit fly, tethered to a force-measuring microelectromechanical system (© Bradley Nelson).



FIGURE 154 Vortices around a butterfly wing (© Robert Srygley/Adrian Thomas).

two millimetres in size. Figure 153 shows a fruit fly in flight. If you have ever tried to build small model aeroplanes, or if you even only compare these insects to paper aeroplanes – possibly the smallest man-made flying thing you might have seen – you start to get a feeling for how well evolution has optimized flying insects.

Compared to paper planes, insects also have engines, flapping wings, sensors, navigation systems, gyroscopic stabilizers, landing gear and of course all the features due to life, reproduction and metabolism, built into an incredibly small volume. Evolution really is an excellent engineering team. The most incredible flyers, such as the common house fly (*Musca domestica*), can change flying direction in only 30 ms, using the stabilizers that nature has given them by reshaping the original second pair of wings. Human engineers are getting more and more interested in the technical solutions evolution has developed; many engineers are trying to achieve similar miniaturization. The topic of miniature flying systems is extremely vast, so that we will pick out only a few examples.

Ref. 226

How does a bumblebee (Bombus terrestris) fly? The lift mg generated by a *fixed* wing (as explained before) follows the empirical relation

Vol. I, page 361

$$mg = f\, A\, v^2\, \rho \tag{110}$$

where A is the surface of the wing, v is the speed of the wing in the fluid of density ρ. The factor f is a pure number, usually with a value between 0.2 and 0.4, that depends on the angle of the wing and its shape; here we use the average value 0.3. For a Boeing 747, the surface is 511 m^2, the top speed at sea level is 250 m/s; at an altitude of 12 km the

Ref. 227
Vol. I, page 38

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Chapter 11

BACTERIA, FLIES AND KNOTS

> La première et la plus belle qualité de la nature est le mouvement qui l'agite sans cesse ; mais ce mouvement n'est qu'une suite perpétuelle de crimes ; ce n'est que par des crimes qu'elle le conserve.
> Donatien de Sade, *Justine, ou les malheurs de la vertu*.**

Wobbly entities, in particular jellyfish or amoebas, open up a fresh vision of the world of motion, if we allow being led by the curiosity to study them in detail. We have missed many delightful insights by leaving them aside up to now. In fact, wobbly entities yield surprising connections between shape change and motion that will be of great use in the last part of our mountain ascent. Instead of continuing to look at the smaller and smaller, we now take a second look at everyday motion and its mathematical description.

To enjoy this chapter, we change a dear habit. So far, we always described any general example of motion as composed of the motion of *point particles*. This worked well in classical physics, in general relativity and in quantum theory; we based the approach on the silent assumption that during motion, each point of a complex system can be followed separately. We will soon discover that this assumption is *not* realized at smallest scales. Therefore the most useful description of motion of *extended* bodies uses methods that do not require that body parts be followed piece by piece. We explore these methods in this chapter; doing so is a lot of fun in its own right.

Vol. VI, page 115

If we describe elementary particles as extended entities – as we soon will have to – a particle moving through space is similar to a dolphin swimming through water, or to a bee flying through air, or to a vortex advancing in a liquid. Therefore we explore how this happens.

Bumblebees and other miniature flying systems

If a butterfly passes by during our mountain ascent, we can stop a moment to appreciate a simple fact: a butterfly flies, and it is rather small. If we leave some cut fruit in the kitchen until it rots, we observe the even smaller fruit flies (*Drosophila melanogaster*), just about

** 'The primary and most beautiful of nature's qualities is motion, which agitates her at all times; but this motion is simply a perpetual consequence of crimes; she conserves it by means of crimes only.' Donatien Alphonse François de Sade (b. 1740 Paris, d. 1814 Charenton-Saint-Maurice) is the intense writer from whom the term 'sadism' was deduced.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 12 The properties of the nucleons: proton and neutron (source: pdg.web.cern.ch).

Property	Proton	Neutron
Mass	$1.672\,621\,777(74) \cdot 10^{-27}$ kg	$1.674\,927\,351(74) \cdot 10^{-27}$ kg
	0.150 327 7484(66) nJ	0.150 534 9631(66) nJ
	938, 272 046(21) MeV	939, 565 379(21) MeV
	1.007 276 466 812(90) u	1.008 664 916 00(43) u
	1836.152 6675(39)· m_e	1838.683 6605(11)· m_e
Spin	1/2	1/2
P parity	+1	+1
Antiparticle	antiproton $\overline{p}$	antineutron $\overline{n}$
Quark content	uud	udd
Electric charge	1 e	0
Charge radius	0.88(1) fm	0.12(1) fm^2
Electric dipole moment	$< 5.4 \cdot 10^{-26}$ e · m	$< 2.9 \cdot 10^{-28}$ e · m
Electric polarizability	$1.20(6) \cdot 10^{-3}$ fm^3	$1.16(15) \cdot 10^{-3}$ fm^3
Magnetic moment	$1.410\,606\,743(33) \cdot 10^{-26}$ J/T	$-0.966\,236\,47(23) \cdot 10^{-26}$ J/T
g-factor	5.585 694 713(46)	−3.826 085 45(90)
	2.792 847 356 (23) · μ_N	−1.913 042 72(45) · μ_N
Gyromagnetic ratio	0.267 522 2005(63) 1/nsT	
Magnetic polarizability	$1.9(5) \cdot 10^{-4}$ fm^3	$3.7(2.0) \cdot 10^{-4}$ fm^3
Mean life (free particle)	$> 2.1 \cdot 10^{29}$ a	880.1(1.1) s
Shape (quadrupole moment)	oblate	oblate
Excited states	more than ten	more than ten

neutral, neutrons do not leave tracks in clouds chambers and are more difficult to detect than protons, charged hadrons or charged leptons. For this reason, the neutron was discovered later than several other, more exotic subatomic particles.

Today, it is possible to keep single neutrons suspended between suitably shaped coils, with the aid of teflon 'windows'. Such traps were proposed in 1951 by Wolfgang Paul. They work because neutrons, though they have no charge, do have a small magnetic moment. (By the way, this implies that neutrons are themselves composed of charged particles.) With a suitable arrangement of magnetic fields, neutrons can be kept in place, in other words, they can be levitated. Obviously, a trap only makes sense if the trapped particle can be observed. In case of neutrons, this is achieved by the radio waves absorbed

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

when the magnetic moment switches direction with respect to an applied magnetic field. The result of these experiments is simple: the lifetime of free neutrons is 885.7(8) s. Nevertheless, we all know that inside most nuclei we are made of, neutrons do not decay for millions of years, because the decay products do not lead to a state of lower energy. (Why not?)

Challenge 125 s

Magnetic resonance images also show that most elements have different types of atoms. These elements have atoms with the same number of protons, but with different numbers of neutrons. One says that these elements have several *isotopes*.* This result also explains why some elements radiate with a mixture of different decay times. Though chemically isotopes are (almost) indistinguishable, they can differ strongly in their nuclear properties. Some elements, such as tin, caesium, or polonium, have over thirty isotopes each. Together, the 118 known elements have over 2000 isotopes. They are shown in Figure 100. (Isotopes without electrons, i.e., specific nuclei with a given number of neutrons and protons, are called *nuclides*.)

Because nuclei are so extremely dense despite containing numerous positively charged protons, there must be a force that keeps everything together against the electrostatic repulsion. We saw that the force is not influenced by electromagnetic or gravitational fields; it must be something different. The force must be short range; otherwise nuclei would not decay by emitting high energy α rays. The additional force is called the *strong nuclear interaction*. We shall study it in detail shortly.

Page 219

The strong nuclear interaction binds protons and neutrons in the nucleus. It is essential to recall that inside a nucleus, the protons and neutrons – they are often collectively called *nucleons* – move in a similar way to the electrons moving in atoms. Figure 99 illustrates this. The motion of protons and neutrons inside nuclei allows us to understand the shape, the spin and the magnetic moment of nuclei.

Nuclei can move alone – cosmic rays

In everyday life, nuclei are mostly found inside atoms. But in some situations, they move all by themselves, without surrounding electron clouds. The first to discover an example was Rutherford; with a clever experiment he showed that the α particles emitted by many radioactive substance are helium nuclei. Like all nuclei, α particles are small, so that they are quite useful as projectiles.

Then, in 1912, Viktor Heß** made a completely unexpected discovery. Heß was intrigued by electroscopes (also called electrometers). These are the simplest possible detectors of electric charge. They mainly consist of two hanging, thin metal foils, such as two strips of aluminium foil taken from a chocolate bar. When the electroscope is

Vol. III, page 23

* The name is derived from the Greek words for 'same' and 'spot', as the atoms are on the same spot in the periodic table of the elements.

** Viktor Franz Heß, (b. 1883 Waldstein, d. 1964 Mount Vernon), nuclear physicist, received the Nobel Prize in Physics in 1936 for his discovery of cosmic radiation. Heß was one of the pioneers of research into radioactivity. Heß' discovery also explained why the atmosphere is always somewhat charged, a result important for the formation and behaviour of clouds. Twenty years after the discovery of cosmic radiation, in 1932 Carl Anderson discovered the first antiparticle, the positron, in cosmic radiation; in 1937 Seth Neddermeyer and Carl Anderson discovered the muon; in 1947 a team led by Cecil Powell discovered the pion; in 1951, the Λ^0 and the kaon K^0 are discovered. All discoveries used cosmic rays and most of these discoveries led to Nobel Prizes.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

scription of motion.

All the searches for unification that were guided by *mathematical ideas* – by mathematical theorems or by mathematical generalizations – have failed. Mathematics is not helpful in this quest. The standard model of particle physics and general relativity remain separate. In addition, the research effort has led to a much more concrete result:

▷ The search for a *higher symmetry* in nature has failed.

Despite thousands of extremely smart people exploring many possible higher symmetries of nature, their efforts have not been successful.

Symmetry considerations are not helpful in the search for unification. Symmetry *simplifies* the description of nature; but symmetry does not *specify* the description. It seems that researchers have fallen into the trap of music theory. Anybody who has learned to play an instrument has heard the statement that 'mathematics is at the basis of music'. Of course, this is nonsense; emotions are at the basis of music. But the incorrect statement about mathematics lurks in the head of every musician. Looking back to research in the twentieth century, it seems that the same has happened to researchers in the field of unification. From these failures we conclude:

▷ Unification requires to extract an underlying *physical* principle.

On the other hand, in the twentieth century, researchers have failed to find such a principle. This failure leads to two questions. In the quest for unification, is there really an alternative to the search for higher symmetry? And did researchers rely on implicit, incorrect assumptions about the structure of particles or of space-time? Before we explore these fascinating issues, we take a break to inspire us.



Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

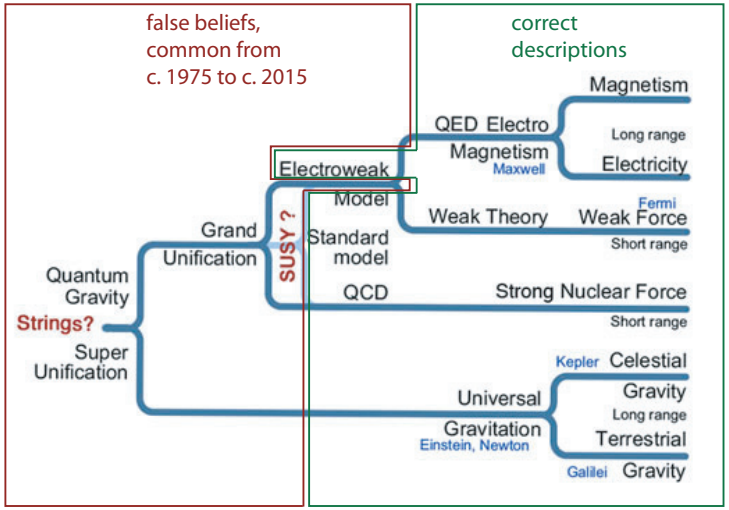


FIGURE 152 Blue and black: a typical graph on unification, as found for years in publications on the topic (© CERN). Red and green: its correct and incorrect parts.

ducing the incorrect term 'electroweak unification' instead of a correct term akin to 'electroweak compatibility' or 'electroweak mixing'.) In other words, the larger part of Figure 152 is not correct. Unfortunately, the graph and the story behind it has led most researchers along the wrong path for several decades.

* *

Over the years, the length of this chapter became shorter and shorter. This was due to the large number of unification attempts that were found to be in contradiction with experiment. It is hard to describe the vast amount of effort that has been invested, usually in vain, in the quest for unification of the description of motion.

* *

For a professional and up-to-date introduction into modern particle research, see the summer student lectures that are given at CERN every year. They can be found at cdsweb.cern.ch/collection/SummerStudentLectures?ln=en.

A summary on unification, mathematics and higher symmetries

The decades of theoretical research since the 1970s have shown:

▷ Mathematical physics is *not* the way to search for unification of the de-

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

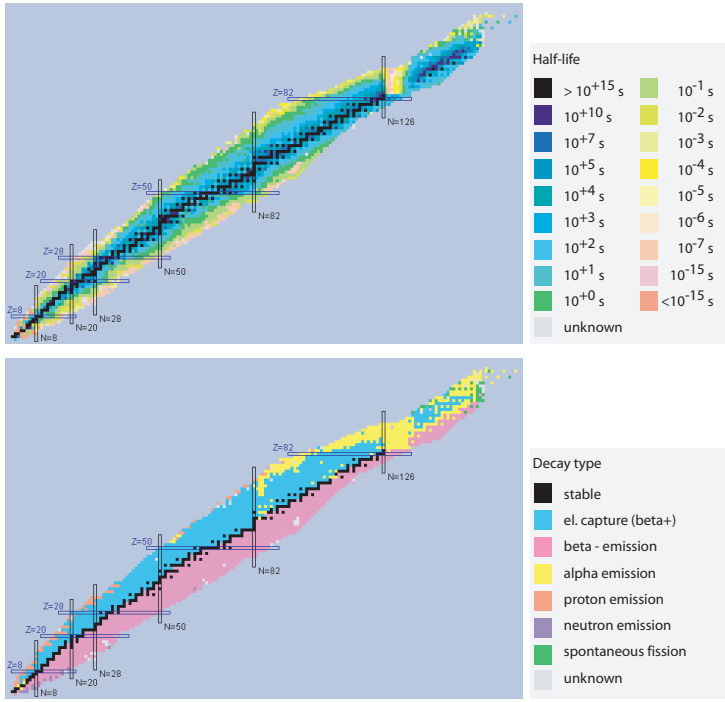


FIGURE 100 All known nuclides with their lifetimes (above) and main decay modes (below). The data are from www.nndc.bnl.gov/nudat2.

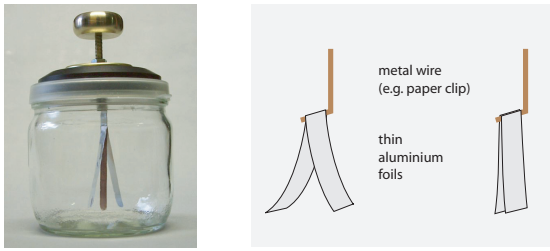


FIGURE 101 An electroscope (or electrometer) (© Harald Chmela) and its charged (middle) and uncharged state (right).

charged, the strips repel each other and move apart, as shown in Figure 101. (You can

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 102 Viktor Heß (1883–1964)

build one easily yourself by covering an empty glass with some transparent cellophane foil and suspending a paper clip and the aluminium strips from the foil. You can charge the electroscope with the help of a rubber balloon and a woollen pullover.) An electroscope thus measures electrical charge. Like many before him, Heß noted that even for a completely isolated electroscope, the charge disappears after a while. He asked: why? By careful study he eliminated one explanation after the other. Heß (and others) were left with only one possibility: that the discharge could be due to charged rays, such as those of the recently discovered radioactivity, emitted from the environment. To increase the distance to the environment, Heß prepared a sensitive electrometer and took it with him on a balloon flight.

Challenge 126 e

As expected, the balloon flight showed that the discharge effect diminished with height, due to the larger distance from the radioactive substances on the Earth's surface. But above about 1000 m of height, the discharge effect increased again, and the higher he flew, the stronger it became. Risking his health and life, he continued upwards to more than 5000 m; there the discharge was several times faster than on the surface of the Earth. This result is exactly what is expected from a radiation coming from outer space and absorbed by the atmosphere. In one of his most important flights, performed during an (almost total) solar eclipse, Heß showed that most of the 'height radiation' did not come from the Sun, but from further away. He thus called the radiation *cosmic rays*. One also speaks of *cosmic radiation*. During the last few centuries, many people have drunk from a glass and eaten chocolate covered by aluminium foil; but only Heß combined these activities with such careful observation and deduction that he earned a Nobel Prize.*

Today, the most common detectors for cosmic rays are *Geiger–Müller counters* and *spark chambers*. Both share the same idea; a high voltage is applied between two metal parts kept in a thin and suitably chosen gas (a wire and a cylindrical mesh for the Geiger-Müller counter, two plates or wire meshes in the spark chambers). When a high energy ionizing particle crosses the counter, a spark is generated, which can either be observed through the generated spark (as you can do yourself by watching the spark chamber in the entrance hall of the CERN main building), or detected by the sudden current flow. Historically, the current was first amplified and sent to a loudspeaker, so that the particles can be heard by a 'click' noise. In short, with a Geiger counter one cannot see ions or particles, but one can hear them. Later on, with the advances in electronics, ionized

* In fact, Hess used gold foils in his electrometer, not aluminium foils.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

way to say that it is approximate, or more bluntly, that it is wrong. But let us put these issues aside for the time being.

The second, still partly unknown half of the answer would specify which (mathematical) conditions a physical system, i.e., a Lagrangian, actually needs to realize in order to become a quantum field theory. Despite the work of many mathematicians, no complete list of conditions is known yet. But it is known that the list includes at least two conditions. First of all, a quantum field theory must be *renormalizable*. Secondly, a quantum field theory must be *asymptotically free*; in other words, the coupling must go to zero when the energy goes to infinity. This condition ensures that interactions are defined properly. Only a subset of renormalizable Lagrangians obey this condition.

In four dimensions, the *only* known quantum field theories with these two properties are the non-Abelian gauge theories. These Lagrangians have several general aspects which are not directly evident when we arrive at them through the usual way, i.e., by generalizing naive wave quantum mechanics. This standard approach, the historical one, emphasizes the *perturbative* aspects: we think of elementary fermions as field quanta and of interactions as exchanges of virtual bosons, to various orders of perturbation.

On the other hand, all field theory Lagrangians also show two other configurations, apart from particles, which play an important role. These mathematical solutions appear when a non-perturbative point of view is taken; they are *collective* configurations.

Vol. I, page 315

— Quantum field theories show solutions which are static and of finite energy, created by non-local field combinations, called *solitons*. In quantum field theories, solitons are usually magnetic monopoles and dyons; also the famous *skyrmions* are solitons. In this approach to quantum field theory, it is assumed that the actual equations of nature are non-linear at high energy. Like in liquids, one then expects stable, localized and propagating solutions, the solitons. These solitons could be related to the observed particles.
— Quantum field theories show self-dual or anti-self dual solutions, called *instantons*. Instantons play a role in QCD, and could also play a role in the fundamental Lagrangian of nature.
— Quantum field theory defines particles and interactions using perturbation expansions. Do particles exist non-perturbatively? When does the perturbation expansion break down? What happens in this case? Despite these pressing issues, no answer has ever been found.

Ref. 225

All these fascinating topics have been explored in great detail by mathematical physicists. This research has deepened the understanding of gauge theories. However, none of the available results has yet helped to approach unification.

CURIOSITIES ABOUT UNIFICATION

From the 1970s onwards, it became popular to draw graphs such as the one of Figure 152. They are found in many books. This approach towards the final theory of motion was inspired by the experimental success of electroweak unification and to the success among theoreticians of the idea of grand unification.

Page 252

Unfortunately, grand unification contradicts experiment. In fact, as explained above, not even the electromagnetic and the weak interactions have been unified. (It took about a decade to brainwash people into believing the contrary; this was achieved by intro-

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

and puts them on equal footing. In other words, the transformation exchanges

$$\alpha \leftrightarrow \frac{1}{\alpha} \quad \text{or} \quad \frac{1}{137.04} \leftrightarrow 137.04\,, \tag{109}$$

and thus exchanges weak and strong coupling. In other words, electromagnetic duality relates a regime where particles make sense (the low coupling regime) with one where particles do not make sense (the strong coupling regime). It is the most mind-boggling symmetry ever conceived.

Dualities are among the deepest connections of physics. They contain $\hbar$ and are thus intrinsically quantum. They do not exist in classical physics and thus confirm that quantum theory is more fundamental than classical physics. More clearly stated, dualities are intrinsically non-classical symmetries. Dualities confirm that quantum theory stands on its own.

If one wants to understand the values of unexplained parameters such as coupling constants, an obvious thing to do is to study *all* possible symmetries in parameter space, thus all possible symmetries of the second class, possibly combining them with those of the first symmetry class. Indeed, the combination of duality with supersymmetry is studied in superstring theory.

Vol. VI, page 139

These investigations showed that there are several types of dualities, which all are *non-perturbative* symmetries:

Ref. 224

— S duality, the generalization of electromagnetic duality for all interactions;
— T duality, also called space-time duality, a mapping between small and large lengths and times following $l \leftrightarrow l_{\text{Pl}}^2/l$;*
— infrared dualities.

Despite the fascination of the idea, research into dualities has not led to any experimental prediction. However, the results highlighted a different way to approach quantum field theory. Dualities play an important role in superstring theory, which we will explore later on.

Vol. VI, page 139

Collective aspects of quantum field theory

For many decades, mathematicians asked physicists: What is the essence of quantum field theory? Despite intensive research, this question has yet to be answered precisely.

Half of the answer is given by the usual definition found in physics textbooks: QFT is the most general known way to describe quantum mechanically continuous systems with a *finite* number of types of quanta but with an *infinite* number of degrees of freedom. For example, this definition implies that the Lagrangian must be relativistically invariant and must be described by a gauge theory. However, this half of the answer is already sufficient to spell trouble. We will show in the next part of our ascent that space and time have a minimal distance scale and that nature does not have infinite numbers of degrees of freedom. In other words, *quantum field theory is an effective theory*; this is the modern

Vol. VI, page 39

* Space-time duality, the transformation between large and small sizes, leads one to ask whether there is an inside and an outside to particles. We encountered this question already in our study of gloves. We will encounter the issue again below, when we explore eversion and inversion. The issue will be fully clarified only in the last volume of our adventure.

Vol. IV, page 111
Page 292

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 13 The main types of cosmic radiation.

PARTICLE	ENERGY	ORIGIN	DETECTOR	SHIELD
At high altitude, the primary particles:				
Protons (90 %)	10^9 to 10^{22} eV	stars, supernovae, extragalactic, unknown	scintillator	in mines
α rays (9 %)	typ. $5 \cdot 10^6$ eV	stars, galaxy	ZnS, counters	1 mm of any material
Other nuclei, such as Le, Be, B, Fe (1 %)	10^9 to 10^{19} eV	stars, novae	1 mm of any material	counters, films
Neutrinos	MeV, GeV	Sun, stars	chlorine, gallium, water	none
Electrons (0.1 %)	10^6 to $> 10^{12}$ eV	supernova remnants		
Gammas (10^{-6})	1 eV to 50 TeV	stars, pulsars, galactic, extragalactic	semiconductor detectors	in mines
At sea level, secondary particles are produced in the atmosphere:				
Muons	3 GeV, 150/ m^2s	protons hit atmosphere, produce pions which decay into muons	drift chamber, bubble chamber, scintillation detector	15 m of water or 2.5 m of soil
Oxygen, radiocarbon and other nuclei	varies	e.g., $n + {}^{16}\text{O} \to \text{p} + {}^{14}\text{C}$	counters	soil
Positrons	varies		counters	soil
Neutrons	varies	reaction product when proton hits ^{16}O nucleus	counters	soil
Pions	varies	reaction product when proton hits ^{16}O nucleus	counters	soil
In addition, there are slowed down primary beam particles.				

atoms or particles could be counted.

Finding the right gas mixture for a Geiger–Müller counter is tricky; it is the reason that the counter has a double name. One needs a gas that extinguishes the spark after a while, to make the detector ready for the next particle. Müller was Geiger's assistant; he made the best counters by adding the right percentage of alcohol to the gas in the chamber. Nasty rumours maintained that this was discovered when another assistant tried,

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

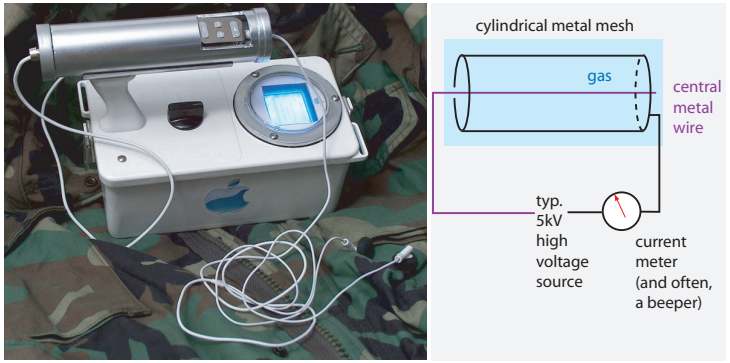


FIGURE 103 A Geiger–Müller counter with the detachable detection tube, the connection cable to the counter electronics, and, for this model, the built-in music player (© Joseph Reinhardt).

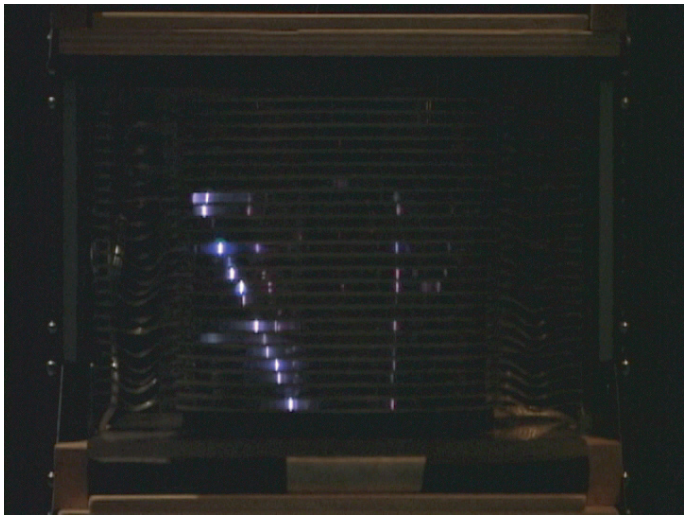


FIGURE 104 A modern spark chamber showing the cosmic rays that constantly arrive on Earth (QuickTime film © Wolfgang Rueckner).

without success, to build counters while Müller was absent. When Müller, supposedly a heavy drinker, came back, everything worked again. However, the story is apocryphal. Today, Geiger–Müller counters are used around the world to detect radioactivity; the

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

ence for supersymmetry. In particular, the Large Hadron Collider at CERN in Geneva has not found any hint of supersymmetry. In fact, experiments excluded almost all supersymmetric particle models proposed in the past.

Is supersymmetry an ingredient of the unified theory? The safe answer is: this is unclear. The optimistic answer is: there is still a small chance that supersymmetry can hold in nature. The pessimistic answer is: supersymmetry is a belief system contradicting observations and made up to correct the failings of grand unified theories. The last volume of this adventure will tell which answer is correct.

Other attempts

If supersymmetry is not successful, it might be that even higher symmetries are required for unification. Therefore, researchers have explored *quantum groups*, *non-commutative space-time*, *conformal symmetry*, *topological quantum field theory*, and other abstract symmetries. None of these approaches led to useful results; neither experimental predictions nor progress towards unification. But two further approaches deserve special mention: duality symmetries and extensions to renormalization.

Dualities – the most incredible symmetries of nature

An important discovery of mathematical physics took place in 1977, when Claus Montonen and David Olive proved that the standard concept of symmetry could be expanded dramatically in a different and new way.

The standard class of symmetry transformations, which turns out to be only the first class, acts on fields. This class encompasses gauge symmetries, space-time symmetries, motion reversal, parities, flavour symmetries and supersymmetry.

The second, new class is quite different. If we take the coupling constants of nature, we can imagine that they are members of a continuous space of all possible coupling constants, called the *parameter space*.* Montonen and Olive showed that there are transformations in parameter space that leave nature invariant. These transformations thus form a new, second class of symmetries of nature.

In fact, we already encountered a member of this class: renormalization symmetry. But Olive and Montonen expanded the symmetry class considerably by the discovery of *electromagnetic duality*. Electromagnetic duality is a discrete symmetry exchanging

Vol. III, page 90

$$e \leftrightarrow \frac{4\pi\hbar c}{e} \tag{107}$$

where the right hand side turns out to be the unit of magnetic charge. Electro-magnetic duality thus relates the electric charge e and the magnetic charge m

$$Q_{\text{el}} = me \quad \text{and} \quad Q_{\text{mag}} = ng = 2\pi\hbar c/e \tag{108}$$

* The space of solutions for all value of the parameters is called the *moduli space*.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Ref. 223 A well-known theorem by Coleman and Mandula states that if the symmetry transformations transform fermions into fermions and bosons into bosons, no quantities other than the following can be conserved:

- the energy momentum tensor $T^{\mu\nu}$, a consequence of the *external* Poincaré space-time symmetry, and
- the internal quantum numbers, all scalars, associated with each gauge group generator – such as electric charge, colour, etc. – and consequences of the *internal* symmetries of the Lagrangian.

But, and here comes a way out, if transformations that *mix* fermions and bosons are considered, new conserved quantities become possible. This family of symmetries includes gravity and came to be known as *supersymmetry*. Its conserved quantities are not scalars but *spinors*. Therefore, *classical* supersymmetry does not exist; it is a purely quantum-mechanical symmetry. The study of supersymmetry has been a vast research field. For example, supersymmetry generalizes gauge theory to super-gauge theory. The possible super-gauge groups have been completely classified.

Supersymmetry can be extended to incorporate gravitation by changing it into a local gauge theory; in that case one speaks of *supergravity*. Supergravity is based on the idea that coordinates can be fermionic as well as bosonic. Supergravity thus makes specific statements on the behaviour of space-time at small distances. Supergravity predicts N additional conserved, spinorial charges. The number N lies between 1 and 8; each value leads to a different candidate Lagrangian. The simplest case is called $N = 1$ supergravity.

In short, supersymmetry is a conjecture to unify matter and radiation at low energies. Many researchers conjectured that supersymmetry, and in particular $N = 1$ supergravity, might be an approximation to reality.

Supersymmetric models have around 100 fundamental constants, in comparison to around 25 for the standard model of particle physics. The precise experimental predictions depend on the values of these constants. Nevertheless, a number of general predictions are possible and can be tested by experiment.

— Supersymmetry predicts partners to the usual elementary particles, called *sparticles*. Fermions are predicted to have boson partners, and vice versa. For example, supersymmetry predicts a *photino* as fermionic partner of the photon, *gluinos* as partner of the gluons, a *selectron* as partner of the electron, etc. However, none of these particles have been observed yet.
— Supersymmetry allows for the unification of the coupling constants in a way compat-
Page 270 ible with the data, as shown already above.
— Supersymmetry slows down the proton decay rates predicted by grand unified theories. The slowed-down rates are compatible with observation.
— Supersymmetry predicts electric dipole moments for the neutron and other elementary particles. The largest predicted values for the neutron, $10^{-30} e$ m, are in contradiction with observations; the smallest predictions have not yet been reached by experiment. In comparison, the values expected from the standard model are at most $10^{-33} e$ m. This is a vibrant experimental research field that can save tax payers from financing an additional large particle accelerator.

However, up to the time of this writing, the year 2016, there was *no* experimental evid-

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

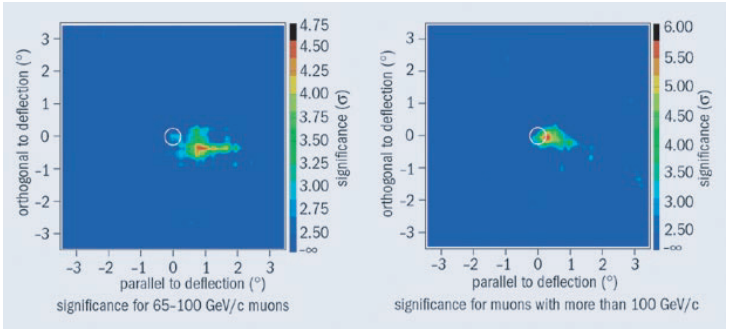


FIGURE 105 The cosmic ray moon shadow, observed with the L3 detector at CERN. The shadow is shifted with respect of the position of the moon, indicated by a white circle, because the Earth's magnetic field deflects the charged particles making up cosmic rays (© CERN Courier).

smallest versions fit in mobile phones and inside wrist watches. An example is shown in Figure 103.

If you can ever watch a working spark chamber, do so. The one in the CERN entrance hall is about 0.5 m^3 in size. A few times per minute, you can see the pink sparks showing the traces of cosmic rays. The rays appear in groups, called *showers*. And they hit us all the time.

Various particle detectors also allow measuring the energy of particles. The particle energy in cosmic rays spans a range between 10^3 eV and at least 10^{20} eV; the latter is the same energy as a tennis ball after serve, but for a single ion. This is a huge range in energy. Understanding the origin of cosmic rays is a research field on its own. Some cosmic rays are galactic in origin, some are extragalactic. For most energies, supernova remnants – pulsars and the like – seem the best candidates. However, the source of the highest energy particles is still unknown; black holes might be involved in their formation.

Cosmic rays are probably the only type of radiation discovered without the help of shadows. But in the meantime, such shadows have been found. In a beautiful experiment performed in 1994, the shadow thrown by the Moon on high energy cosmic rays (about 10 TeV) was measured, as shown in Figure 105. When the position of the shadow is compared with the actual position of the Moon, a shift is found. And indeed, due to the magnetic field of the Earth, the cosmic ray Moon shadow is expected to be shifted westwards for protons and eastwards for antiprotons. The data are consistent with a ratio
Ref. 158 of antiprotons in cosmic rays between 0 % and 30 %. By studying the shadow's position, the experiment thus showed that high energy cosmic rays are mainly positively charged and thus consist mainly of matter, and only in small part, if at all, of antimatter.

Detailed observations showed that cosmic rays arrive on the surface of the Earth as
Page 175 a mixture of many types of particles, as shown in Table 13. They arrive from outside the atmosphere as a mixture of which the largest fraction are protons, followed by α particles, iron and other nuclei. And, as mentioned above, most rays do not originate from the Sun. In other words, nuclei can thus travel alone over large distances. In fact,

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 106 An aurora borealis, produced by charged particles in the night sky (© Jan Curtis).

the distribution of the incoming direction of cosmic rays shows that many rays must be extragalactic in origin. Indeed, the typical nuclei of cosmic radiation are ejected from stars and accelerated by supernova explosions. When they arrive on Earth, they interact with the atmosphere before they reach the surface of the Earth. The detailed acceleration mechanisms at the origin of cosmic rays are still a topic of research.

The flux of *charged* cosmic rays arriving at the surface of the Earth depends on their energy. At the lowest energies, charged cosmic rays hit the human body many times a second. Measurements also show that the rays arrive in irregular groups, called *showers*. In fact, the *neutrino* flux is many orders of magnitude higher than the flux of charged rays, but does not have any effect on human bodies.

Page 256

Cosmic rays have several effects on everyday life. Through the charges they produce in the atmosphere, they are probably responsible for the start and for the jagged, non-straight propagation of lightning. (Lightning advances in pulses, alternating fast propagation for about 30 m with slow propagation, until they hit connect. The direction they take at the slow spots depends on the wind and the charge distribution in the atmosphere.) Cosmic rays are also important in the creation of rain drops and ice particles inside clouds, and thus indirectly in the charging of the clouds. Cosmic rays, together with ambient radioactivity, also start the Kelvin generator.

Vol. III, page 214

Vol. III, page 19

If the magnetic field of the Earth would not exist, we might get sick from cosmic rays. The magnetic field diverts most rays towards the magnetic poles. Also both the upper and lower atmosphere help animal life to survive, by shielding life from the harmful effects of cosmic rays. Indeed, aeroplane pilots and airline employees have a strong radiation exposure that is not favourable to their health. Cosmic rays are also one of several reasons that long space travel, such as a trip to Mars, is not an option for humans. When cosmonauts get too much radiation exposure, the body weakens and eventually they die. Space heroes, including those of science fiction, would not survive much longer than two or three years.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

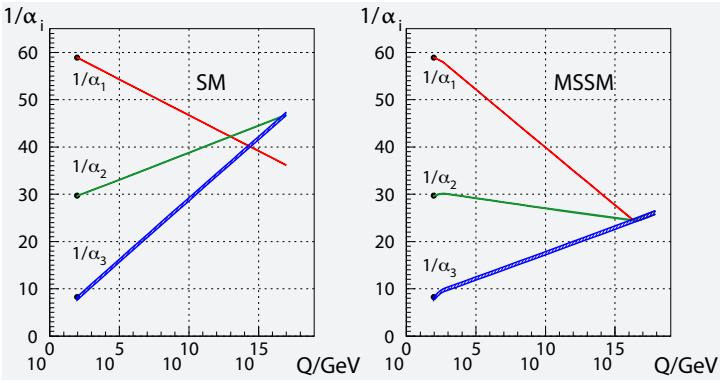


FIGURE 151 The behaviour of the three coupling constants with energy, for simple grand unification (left) and for the minimal supersymmetric model (right); the graph shows the constants $\alpha_1 = \frac{5}{3}\alpha_{em}/\cos^2\theta_W$ for the electromagnetic interaction (the factor 5/3 appears in GUTs), $\alpha_2 = \alpha_{em}/\sin^2\theta_W$ for the weak interaction and the strong coupling constant $\alpha_3 = \alpha_s$ (© W. de Boer).

which elementary particles exist in nature. In other words, grand unification only *shifts* the open questions of the standard model to the next level, while keeping most of the open questions unanswered. The name 'grand unification' was wrong from the beginning. We definitively need to continue our adventure.

Searching for higher symmetries

Since we want to reach the top of Motion Mountain, we go on. We have seen in the preceding sections that the main ingredients of the Lagrangian that describes motion are the symmetry properties. We recall that a Lagrangian is just the mathematical name for the concept that measures change. The discovery of the correct symmetry, together with mathematical consistency, usually restricts the possible choices for a Lagrangian down to a limited number, and to one in the best case. This Lagrangian then allows making experimental predictions.

The history of particle physics from 1920 to 1965 has shown that progress was always coupled to the discovery of *larger* symmetries, in the sense that the newly discovered symmetries always included the old ones as a subgroup. Therefore, in the twentieth century, researchers searched for the largest possible symmetry that is consistent with experiments on the one hand and with gauge theories on the other hand. Since grand unification failed, a better approach is to search directly for a symmetry that includes gravity.

Supersymmetry

In the search for possible symmetries of a Lagrangian describing a gauge theory and gravity, one way to proceed is to find general mathematical theorems which restrict the symmetries that a Lagrangian can possibly have.

Ref. 222

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Ref. 216 expression

$$\tau_p \approx \frac{1}{\alpha_G^2(M_X)} \frac{M_X^4}{M_p^5} \approx 10^{31\pm1}\,\mathrm{a} \qquad (105)$$

where the uncertainty is due to the uncertainty of the mass M_X of the gauge bosons involved and to the exact decay mechanism. Several large experiments have tried and are still trying to measure this lifetime. So far, the result is simple but clear. Not a single Ref. 220 proton decay has ever been observed. The data can be summarized by

$$\begin{aligned} \tau(p \to e^+ \pi^0) &> 5 \cdot 10^{33}\,\mathrm{a} \\ \tau(p \to K^+ \bar{\nu}) &> 1.6 \cdot 10^{33}\,\mathrm{a} \\ \tau(n \to e^+ \pi^-) &> 5 \cdot 10^{33}\,\mathrm{a} \\ \tau(n \to K^0 \bar{\nu}) &> 1.7 \cdot 10^{32}\,\mathrm{a} \end{aligned} \qquad (106)$$

These values are higher than the prediction by SU(5) – and SO(10) – models. For other gauge group candidates proton decay measurements require more time.

The state of grand unification

To settle the issue of grand unification definitively, one last prediction of grand unification remains to be checked: the unification of the coupling constants. Most estimates of the grand unification energy are near the Planck energy, the energy at which gravitation starts to play a role even between elementary particles. As grand unification does not take gravity into account, for a long time there was a doubt whether something was lacking in the approach. This doubt changed into certainty when the precision measure- Ref. 221 ments of the coupling constants became available, in 1991, and were put into the diagram of Figure 151. The GUT prediction of the way the constants evolve with energy implies that the three constants do *not* meet at one energy. Simple grand unification by SU(5), SU(10) or E_6 is thus ruled out by experiment.

This state of affairs is changed if *supersymmetry* is taken into account. Supersymmetry is a conjecture on the way to take into account low-energy effects of gravitation in the Page 271 particle world. Supersymmetry conjectures new elementary particles that change the curves at intermediate energies, so that they all meet at a grand unification energy of about 10^{16} GeV. (The line thicknesses in Figure 151 represent the experimental errors.) The inclusion of supersymmetry also puts the proton lifetime prediction back to a value higher (but not by much) than the present experimental bound and predicts the correct value of the mixing angle. With supersymmetry, one can thus retain the advantages of grand unification (charge quantization, one coupling constant) without being in contradiction with experiments.

In summary, pure grand unification is in contradiction with experiments. This is not a surprise, as its goal, to unify the description of matter, *cannot* been achieved in this way. Indeed, the unifying gauge group must be introduced, i.e., added, at the very beginning. Adding the group is necessary because grand unification cannot deduce the gauge group from a general principle. Neither does pure grand unification tell us completely

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

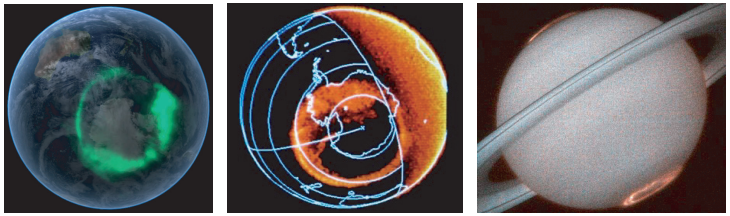


FIGURE 107 Two aurorae australes on Earth, seen from space (a composed image with superimposed UV intensity, and a view in the X-ray domain) and a double aurora on Saturn (all NASA).

Cosmic rays also produce beautifully coloured flashes inside the eyes of cosmonauts; they regularly enjoy these events in their trips. (And they all develop cataracts as a consequence.) But cosmic rays are not only dangerous and beautiful. They are also useful. If cosmic rays would not exist, we would not exist either. Cosmic rays are responsible for mutations of life forms and thus are one of the causes of biological evolution. Today, this effect is even used artificially; putting cells into a radioactive environment yields new strains. Breeders regularly derive new mutants in this way.

Cosmic rays cannot be seen directly, but their cousins, the 'solar' rays, can. This is most spectacular when they arrive in high numbers. In such cases, the particles are inevitably deviated to the poles by the magnetic field of the Earth and form a so-called *aurora borealis* (at the North Pole) or an *aurora australis* (at the South pole). These slowly moving and variously coloured curtains of light belong to the most spectacular effects in the night sky. (See Figure 106 or www.nasa.gov/mov/105423main_FUV_2005-01_v01.mov.) Visible light and X-rays are emitted at altitudes between 60 and 1000 km. Seen from space, the aurora curtains typically form a circle with a few thousand kilometres diameter around the magnetic poles. Aurorae are also seen in the rest of the solar system. Aurorae due to core magnetic fields have been observed on Jupiter, Saturn, Uranus, Neptune, Earth, Io and Ganymede. For an example, see Figure 107. Aurorae due to other mechanisms have been seen on Venus and Mars.

Cosmic rays are mainly free nuclei. With time, researchers found that nuclei appear without electron clouds also in other situations. In fact, the vast majority of nuclei in the universe have no electron clouds at all: in the inside of stars, no nucleus is surrounded by bound electrons; similarly, a large part of intergalactic matter is made of protons. It is known today that most of the matter in the universe is found as protons or α particles inside stars and as thin gas between the galaxies. In other words, in contrast to what the Greeks said, matter is not usually made of atoms; it is mostly made of bare nuclei. Our everyday environment is an exception when seen on cosmic scales. In nature, atoms are rare, bare nuclei are common.

Incidentally, nuclei are in no way forced to move; nuclei can also be stored with almost no motion. There are methods – now commonly used in research groups – to superpose electric and magnetic fields in such a way that a single nucleus can be kept floating in mid-air; we discussed this possibility in the section on levitation earlier on.

Vol. III, page 222

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Nuclei decay – more on radioactivity

Not all nuclei are stable over time. The first measurement that provided a hint was the decrease of radioactivity with time. It is observed that the number N of emitted rays *decreases*. More precisely, radioactivity follows an exponential decay with time t:

$$N(t) = N(0)\, e^{-t/\tau} \,. \tag{54}$$

The parameter τ, the so-called *life time* or *decay time*, depends on the type of nucleus emitting the rays. Life times can vary from far less than a microsecond to millions of millions of years. The expression has been checked for as long as 34 multiples of the duration τ; its validity and precision is well-established by experiments. Obviously, formula (54) is an approximation for large numbers of atoms, as it assumes that $N(t)$ is a continuous variable. Despite this approximation, deriving this expression from quantum theory is Page 48 not a simple exercise, as we saw above. Though in principle, the quantum Zeno effect could appear for small times t, for the case of radioactivity it has not yet been observed.

Instead of the life-time, often the half-life is used. The *half-life* is the time during which radioactivity decreases to *half* the starting value. Can you deduce how the two times are Challenge 127 s related?

Radioactivity is the decay of unstable nuclei. Most of all, radioactivity allows us to count the number of atoms in a given mass of material. Imagine to have measured the mass of radioactive material at the beginning of your experiment; you have chosen an element that has a lifetime of about a day. Then you put the material inside a scintillation box. After a few weeks the number of flashes has become so low that you can count them; using expression (54) you can then determine how many atoms have been in the mass to begin with. Radioactivity thus allows us to determine the number of atoms, and thus their size, in addition to the size of nuclei.

The exponential decay (54) and the release of energy is typical of *metastable* systems. In 1903, Rutherford and Soddy discovered what the state of lower energy is for α and β emitters. In these cases, radioactivity changes the emitting atom; it is a spontaneous transmutation of the atom. An atom emitting α or β rays changes its chemical nature. Radioactivity thus implies, for the case of nuclei, the same result that statistical mech- Vol. I, page 404 anics of gases implies for the case of atoms: they are quantum particles with a structure that can change over time.

— In *α decay* – or *alpha decay* – the radiating nucleus emits a (doubly charged) helium nucleus, also called an *α particle*. The kinetic energy is typically a handful of MeV. After the emission, the nucleus has changed to a nucleus situated two places earlier in the periodic system of the elements. α decay occurs mainly for nuclei that are rich in protons. An example of α decay is the decay of the ^{238}U isotope of uranium.

— In *β decay* – or *beta decay* – a neutron transforms itself into a proton, emitting an electron – also called a *β particle* – and an antineutrino. Also β decay changes the chemical nature of the atom, but to the place following the original atom in the periodic table of the elements. Example of β emitters are radiocarbon, ^{14}C, ^{38}Cl, and ^{137}Cs, the iso- Page 240 tope expelled by damaged nuclear reactors. We will explore β decay below. A variant is the β^+ decay, in which a proton changes into a neutron and emits a neutrino and

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

For each of these candidate groups, the predicted consequences of the model can be stud- Ref. 217 ied and compared with experiment.

Comparing predictions and data

Grand unification models – also incorrectly called GUTs or *grand unified theories* – make several predictions that can be matched with experiment. First of all, any grand unified model predicts relations between the quantum numbers of quarks and those of leptons. In particular, grand unification explains why the electron charge is exactly the opposite of the proton charge.

Grand unification models predict a value for the weak mixing angle θ_w; this angle is Ref. 216 not fixed by the standard model. The most frequently predicted value,

$$\sin^2 \theta_{w,th} = 0.2 \tag{103}$$

is close to the measured value of

$$\sin^2 \theta_{w,ex} = 0.231(1) \,, \tag{104}$$

which is not a good match, but might be correct, in view of the approximations in the prediction.

All grand unified models predict the existence of *magnetic monopoles*, as was shown Ref. 218 by Gerard 't Hooft. However, despite extensive searches, no such particles have been found yet. Monopoles are important even if there is only one of them in the whole uni- Ref. 219 verse: the existence of a single monopole would imply that electric charge is quantized. If monopoles were found, grand unification would explain why electric charge appears in multiples of a smallest unit.

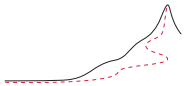
Grand unification predicts the existence of heavy intermediate vector bosons, called *X bosons*. Interactions involving these bosons do not conserve baryon or lepton number, but only the difference $B - L$ between baryon and lepton number. To be consistent with data, the X bosons must have a mass of the order of 10^{16} GeV. However, this mass is and always will be outside the range of experiments, so that the prediction cannot be tested directly.

Most spectacularly, the X bosons of grand unification imply that the *proton decays*. This prediction was first made by Pati and Abdus Salam in 1974. If protons decay, means that neither coal nor diamond* – nor any other material – would be for ever. Depending on the precise symmetry group, grand unification predicts that protons decay into pions, electrons, kaons or other particles. Obviously, we know 'in our bones' that the proton lifetime is rather high, otherwise we would die of leukaemia; in other words, the low level of cancer in the world already implies that the lifetime of the proton is larger than about 10^{16} years.

Detailed calculations for the proton lifetime τ_p using the gauge group SU(5) yield the

* As is well known, diamond is not stable, but metastable; thus diamonds are not for ever, but coal might be, as long as protons do not decay.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



Chapter 10

DREAMS OF UNIFICATION

> Materie ist geronnenes Licht.**
>
> Albertus Magnus

Is there a common origin to the three particle interactions? We have seen in the preceding chapters that the Lagrangian densities of the three gauge interactions are determined almost uniquely by two types of requirements: to possess a certain gauge symmetry, and to be consistent with space-time, through Lorentz invariance and renormalizability. The search for *unification* of the interactions thus seems to require the identification of the one, unified symmetry of nature. (Do you agree?) Challenge 149 s

Between 1970 and 2015, several conjectures have fuelled the hope to achieve unification through higher symmetry. The most popular were grand unification, supersymmetry, conformal field theory, coupling constant duality and mathematical quantum field theory. We give a short summary of these efforts; we start with the first candidate, which is conceptually the simplest.

Grand unification

At all measured energies up to the year 2016, thus below about 3 TeV, there are no contradictions between the Lagrangian of the standard model and observation. On the other hand, the Lagrangian itself can be conjectured to be a low energy approximation to the unified theory. It should thus be possible – attention, this a belief – to find a unifying symmetry that *contains* the symmetries of the electroweak and strong interactions as subgroups. In this way, the three gauge interactions would be different aspects of a single, 'unified' interaction. We can then examine the physical properties that follow from this unifying symmetry and compare them with observation. This approach, called *grand unification*, attempts the unified description of all types of matter. All known elementary particles are seen as fields which appear in a Lagrangian determined by a single gauge symmetry group.

Like for each gauge theory described so far, also the grand unified Lagrangian is fixed by the symmetry group, the representation assignments for each particle, and the corresponding coupling constant. A general search for the grand symmetry group starts with all those (semisimple) Lie groups which contain $U(1) \times SU(2) \times SU(3)$. The smallest groups with these properties are SU(5), SO(10) and E(6); they are defined in Appendix C. Ref. 216

** 'Matter is coagulated light.' Albertus Magnus (b. *c.* 1192 Lauingen, d. 1280 Cologne) was the most important thinker of his time.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

a positron. It occurs in proton-rich nuclei. An example is ^{22}Na. Another variant is electron capture; a nucleus sometimes captures an orbital electron, a proton is transformed into a neutron and a neutrino is emitted. This happens in ^{7}Be. Also bound β decay, as seen in ^{187}Re, is a variant of β decay.

- In *γ decay* – or *gamma decay* – the nucleus changes from an excited to a lower energy state by emitting a high energy photon, or *γ particle*. In this case, the chemical nature is not changed. Typical energies are in the MeV range. Due to the high energy, γ rays ionize the material they encounter; since they are not charged, they are not well absorbed by matter and penetrate deep into materials. γ radiation is thus by far the most dangerous type of (environmental) radioactivity. An example of γ decay is ^{99m}Tc. A variant of γ decay is *isomeric transition*. Still another variant is *internal conversion*, observed, for example, in ^{137m}Ba.
- In *neutron emission* the nucleus emits a neutron. The decay is rare on Earth, but occurs in the stellar explosions. Most neutron emitters have half-lives below a few seconds. Examples of neutron emitters are ^{5}He and ^{17}N.
- The process of *spontaneous fission* was discovered in 1940. The decay products vary, even for the same starting nucleus. But ^{239}Pu and ^{235}U can decay through spontaneous fission, though with a small probability.
- In *proton emission* the nucleus emits a proton. This decay is comparatively rare, and occurs only for about a hundred nuclides, for example for ^{53m}Co and ^{4}Li. The first example was discovered only in 1970. Around 2000, the simultaneous emission of two protons was also observed for the first time.
- In 1984, *cluster emission* or *heavy ion emission* was discovered. A small fraction of ^{223}Ra nuclei decay by emitting a ^{14}C nucleus. This decay occurs for half a dozen nuclides. Emission of ^{18}O has also been observed.

Many combined and mixed decays also exist. These decays are studied by nuclear physicists. Radioactivity is a common process. As an example, in every human body about nine thousand radioactive decays take place every second, mainly 4.5 kBq (0.2 mSv/a) from ^{40}K and 4 kBq from ^{14}C (0.01 mSv/a). Why is this not dangerous? Ref. 159 Challenge 128 s

All radioactivity is accompanied by emission of energy. The energy emitted by an atom through radioactive decay or reactions is regularly a million times larger than that emitted by a chemical process. More than a decay, a radioactive process is thus a microscopic explosion. A highly radioactive material thus emits a large amount of energy. That is the reason for the danger of nuclear weapons.

What distinguishes those atoms that decay from those which do not? An exponential decay law implies that the probability of decay is independent of the age of the atom. Age or time plays no role. We also know from thermodynamics, that all atoms have exactly identical properties. So how is the decaying atom singled out? It took around 30 years to discover that radioactive decays, like all decays, are quantum effects. All decays are triggered by the statistical fluctuations of the vacuum, more precisely, by the quantum fluctuations of the vacuum. Indeed, radioactivity is one of the clearest observations that classical physics is not sufficient to describe nature. Challenge 129 e Vol. IV, page 112

Radioactivity, like all decays, is a pure quantum effect. Only a finite quantum of action makes it possible that a system remains unchanged until it suddenly decays. Indeed, in 1928 George Gamow explained α decay with the tunnelling effect. He found that the

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 108 A modern accelerator mass spectrometer for radiocarbon dating, at the Hungarian Academy of Sciences (© HAS).

tunnelling effect explains the relation between the lifetime and the range of the rays, as well as the measured variation of lifetimes – between 10 ns and 10^{17} years – as the consequence of the varying potentials to be overcome in different nuclei.

Radiometric dating

As a result of the chemical effects of radioactivity, the composition ratio of certain elements in minerals allows us to determine the *age* of the mineral. Using radioactive decay to deduce the age of a sample is called *radiometric dating*. With this technique, geologists determined the age of mountains, the age of sediments and the age of the continents. They determined the time that continents moved apart, the time that mountains formed when the continents collided and the time when igneous rocks were formed. Where there surprises? No. The times found with radiometric dating are consistent with the relative time scale that geologists had defined independently for centuries before the technique appeared. Radiometric dating confirmed what had been deduced before.

Ref. 161 Page 183 Ref. 160

Radiometric dating is a science of its own. An overview of the isotopes used, together with their specific applications in dating of specimen, is given in Table 14. The table shows how the technique of radiometric dating has deeply impacted astronomy, geology, evolutionary biology, archaeology and history. (And it has reduced the number of violent believers.) Radioactive life times can usually be measured to within one or two per cent

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

speed *c*. As a result, the standard model describes the structure of the atoms, their formation in the history of the universe, the properties of matter and the mechanisms of life. Despite the prospect of fame and riches, not one deviation between experiment and the standard model has been found.

In short, the standard model realizes the dream of Leucippus and Democritus, plus a bit more: we know the bricks that compose all of matter and radiation, and in addition we know how they move, interact and transform, in flat space-time, with *perfect* accuracy.

Despite this perfect accuracy, we also know what we still do *not* know:

— We do not know the origin of the coupling constants.
— We do not know why positrons and protons have the same charge.
— We do not know the origin of the masses of the particles.
— We do not know the origin of the mixing and CP violation parameters.
— We do not know the origin of the gauge groups.
— We do not know the origin of the three particle generations.
— We do not know whether the particle concept survives at high energy.
— We do not know what happens in curved space-time.

To study these issues, the simplest way is to explore nature at particle energies that are as high as possible. There are two methods: building large experiments and exploring hypothetical models. Both are useful.



Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

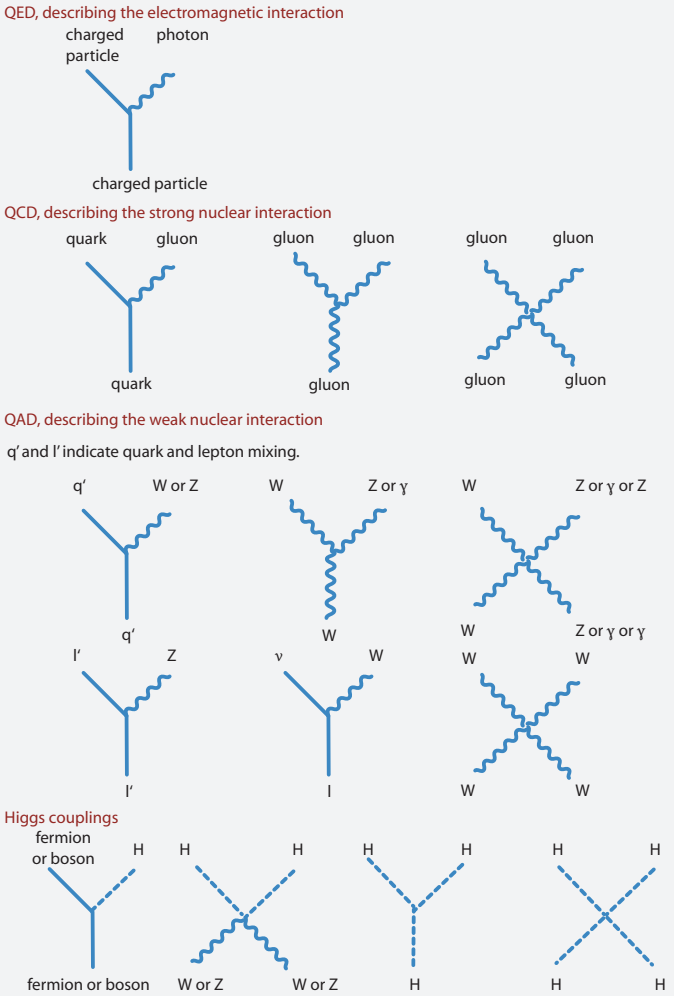


FIGURE 150 The Feynman diagrams of the standard model.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 14 The main natural isotopes used in radiometric dating.

Isotope	Decay product	Half-life	Method using it	Examples
^{147}Sm	^{143}Nd	106 Ga	samarium–neodymium method	rocks, lunar soil, meteorites
^{87}Rb	^{87}Sr	48.8 Ga	rubidium–strontium method	rocks, lunar soil, meteorites
^{187}Re	^{187}Os	42 Ga	rhenium–osmium method	rocks, lunar soil, meteorites
^{176}Lu	^{176}Hf	37 Ga	lutetium–hafnium method	rocks, lunar soil, meteorites
^{40}K	^{40}Ar	1.25 Ga	potassium–argon & argon–argon method	rocks, lunar soil, meteorites
^{40}K	^{40}Ca	1.25 Ga	potassium–calcium method	granite dating, not precise
^{232}Th	^{208}Pb	14 Ga	thorium–lead method, lead–lead method	rocks, lunar soil, meteorites
^{238}U	^{206}Pb	4.5 Ga	uranium–lead method, lead–lead method	rocks, lunar soil, meteorites
^{235}U	^{207}Pb	0.7 Ga	uranium–lead method, lead–lead method	rocks, lunar soil, meteorites
^{234}U	^{230}Th	248 ka	uranium–thorium method	corals, stalagmites, bones, teeth
^{230}Th	^{226}Ra	75.4 ka	thorium-radon method	plant dating
^{26}Al	^{26}Mg	0.72 Ma	supernova debris dating, cosmogenic	checking that nucleosynthesis still takes place in the galaxy
^{10}Be	^{10}B	1.52 Ma	cosmogenic radiometric dating	ice cores
^{60}Fe	^{60}Ni	2.6 Ma (not 1.5 Ma)	supernova debris dating	deep sea crust
^{36}Cl	^{36}Ar	0.3 Ma	cosmogenic radiometric dating	ice cores
^{53}Mn	^{53}Cr	3.7 Ma	cosmogenic radiometric dating	meteorites, K/T boundary
^{182}Hf	^{182}W	9 Ma	cosmogenic radiometric dating	meteorites, sediments
^{14}C	^{14}N	5730 a	radiocarbon method, cosmogenic	wood, clothing, bones, organic material, wine
^{137}Cs	^{137}Ba	30 a	γ-ray counting	dating food and wine after nuclear accidents
^{210}Pb		22 a	γ-ray counting	dating wine
^{3}H	^{3}He	12.3 a	γ-ray counting	dating wine

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

of accuracy, and they are known both experimentally and theoretically not to change over geological time scales. As a result, radiometric dating methods can be surprisingly precise. Can you imagine how to measure half-lives of thousands of millions of years to high precision? Challenge 130 s

Radiometric dating was even more successful in the field of ancient history. With the *radiocarbon dating method* historians determined the age of civilizations and the age of human artefacts.* Many false beliefs were shattered. In some belief communities the shock is still not over, even though over hundred years have passed since these results became known. Ref. 160

Radiocarbon dating uses the β decay of the radioactive carbon isotope ^{14}C, which has a decay time of 5730 a. This isotope is continually created in the atmosphere through the influence of cosmic rays. This happens through the reaction $^{14}N + n \to p + {}^{14}C$. As a result, the concentration of radiocarbon in air is relatively constant over time. Inside living plants, the metabolism thus (unknowingly) maintains the same concentration. In dead plants, the decay sets in. The life time value of a few thousand years is particularly useful to date historic material. Therefore, radiocarbon dating has been used to determine the age of mummies, the age of prehistoric tools and the age of religious relics. The original version of the technique measured the radiocarbon content through its radioactive decay and the scintillations it produced. A quality jump was achieved when accelerator mass spectroscopy became commonplace. It was not necessary any more to wait for decays: it is now possible to determine the ^{14}C content directly. As a result, only a tiny amount of carbon, as low as 0.2 mg, is necessary for a precise dating. Such small amounts can be detached from most specimen without big damage. Accelerator mass spectroscopy showed that numerous religious relics are forgeries, such as a cloth in Turin, and that, in addition, several of their wardens are crooks.

Researchers have even developed an additional method to date stones that uses radioactivity. Whenever an α ray is emitted, the emitting atom gets a recoil. If the atom is part of a crystal, the crystal is damaged by the recoil. In many materials, the damage can be seen under the microscope. By counting the damaged regions it is possible to date the time at which rocks have been crystallized. In this way it has been possible to determine when the liquid material from volcanic eruptions has become rock.

With the advent of radiometric dating, for the first time it became possible to reliably date the age of rocks, to compare it with the age of meteorites and, when space travel became fashionable, with the age of the Moon. The result was beyond all previous estimates and expectations: the oldest rocks and the oldest meteorites, studied independently using different dating methods, are 4570(10) million years old. From this data, the age of the Earth is estimated to be 4540(50) million years. The Earth is indeed *old*. Ref. 162

But if the Earth is so old, why did it not cool down in its core in the meantime?

Why is hell hot?

The lava seas and streams found in and around volcanoes are the origin of the imagery that many cultures ascribe to hell: fire and suffering. Because of the high temperature of lava, hell is inevitably depicted as a hot place located at the centre of the Earth. A striking

* In 1960, the developer of the radiocarbon dating technique, Willard Libby, received the Nobel Prize in Chemistry.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 23 (Continued) Basic physical constants.

Quantity	Symbol	Value in SI units	Uncert.[a]
e.m. coupling constant	$= g_{em}(m_e^2c^2)$	$= 0.007\,297\,352\,5698(24)$	$3.2 \cdot 10^{-10}$
Fermi coupling constant[d] or	$G_F/(\hbar c)^3$	$1.166\,364(5) \cdot 10^{-5}\ \mathrm{GeV}^{-2}$	$4.3 \cdot 10^{-6}$
weak coupling constant	$\alpha_w(M_Z) = g_w^2/4\pi$	1/30.1(3)	$1 \cdot 10^{-2}$
Weak mixing angle	$\sin^2\theta_W(\overline{MS})$	0.231 24(24)	$1.0 \cdot 10^{-3}$
	$\sin^2\theta_W$ (on shell)	0.2224(19)	$8.7 \cdot 10^{-3}$
	$= 1 - (m_W/m_Z)^2$		
Strong coupling constant[d]	$\alpha_s(M_Z) = g_s^2/4\pi$	0.118(3)	$25 \cdot 10^{-3}$
CKM quark mixing matrix	$\lvert V\rvert$	$\begin{pmatrix} 0.97428(15) & 0.2253(7) & 0.00347(16) \\ 0.2252(7) & 0.97345(16) & 0.0410(11) \\ 0.00862(26) & 0.0403(11) & 0.999152(45) \end{pmatrix}$	
Jarlskog invariant	J	$2.96(20) \cdot 10^{-5}$	
PMNS neutrino mixing m.	P	$\begin{pmatrix} 0.82 & 0.55 & -0.15 + 0.038i \\ -0.36 + 0.020i & 0.70 + 0.013i & 0.61 \\ 0.44 + 0.026i & -0.45 + 0.017i & 0.77 \end{pmatrix}$	
Particle masses: see previous table			

a. Uncertainty: standard deviation of measurement errors.
b. Only measured from to 10^{-19} m to 10^{26} m.
c. Defining constant.
d. All coupling constants depend on the 4-momentum transfer, as explained in the section on renormalization. *Fine-structure constant* is the traditional name for the electromagnetic coupling constant g_{em} in the case of a 4-momentum transfer of $Q^2 = m_e^2c^2$, which is the smallest one possible. At higher momentum transfers it has larger values, e.g., $g_{em}(Q^2 = M_W^2c^2) \approx 1/128$. In contrast, the strong coupling constant has lower values at higher momentum transfers; e.g., $\alpha_s(34\,\mathrm{GeV}) = 0.14(2)$. Page 131

In short, with the three tables and the figure, the standard model describes *every* observation ever made in flat space-time. In particular, the standard model includes a minimum action, a maximum speed, electric charge quantization and the least action principle.

Summary and open questions

The standard model of particle physics clearly distinguishes *elementary* from *composed* particles. The standard model provides the full list of properties that characterizes a particle – and thus any moving object and image. These properties are: mass, spin, charge, colour, weak isospin, parity, charge parity, isospin, strangeness, charm, topness, beauty, lepton number and baryon number.

The standard model describes electromagnetic and nuclear interactions as as exchanges of virtual radiation particles. In particular, the standard model describes the three types of radiation that are observed in nature with full precision, using gauge groups. The standard model is based on quantization and conservation of electric charge, weak charge and colour, as well as on a smallest action value $\hbar$ and a maximum energy

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

The table also does not mention the *weak charge* of the particles. The details on weak charge g, or, more precisely, on the *weak isospin*, a quantum number assigned to all left-handed fermions (and right-handed anti-fermions), but to no right-handed fermion (and no left-handed antifermion), are given in the section on the weak interactions.

Page 245

d. 'Beauty' is now commonly called *bottomness*; similarly, 'truth' is now commonly called *topness*. The signs of the quantum numbers S, I, C, B, T can be defined in different ways. In the standard assignment shown here, the sign of each of the non-vanishing quantum numbers is given by the sign of the charge of the corresponding quark.

e. The electron radius is observed to be less than 10^{-22} m. It is possible to store single electrons in traps for many months.

Ref. 214, Ref. 215

f. See page 233 for the precise definition and meaning of the quark masses.

The other aim that we formulated at the beginning of our adventure was to find the complete list of all *state properties*. This aim is also achieved, namely by the wave function and the field values due to the various bosons. Were it not for the possibility of space-time curvature, we would be at the end of our exploration.

The main ingredient of the standard model are the Lagrangians of the electromagnetic, the weak and the strong interactions. The combination of the Lagrangians, based on the U(1), SU(3) and broken SU(2) gauge groups, is possible only in one specific way. The Lagrangian can be summarized by the Feynman diagram of Figure 150.

To complete the standard model, we need the coupling constants of the three gauge interactions, the masses of all the particles, and the values of the mixing among quarks and among leptons. Together with all those constants of nature that define the SI system and the number of space-time dimensions, the following table therefore completes the standard model.

TABLE 23 Basic physical constants.

Quantity	Symbol	Value in SI units	Uncert.[a]
Constants that define the SI measurement units			
Vacuum speed of light[c]	c	299 792 458 m/s	0
Vacuum permeability[c]	μ_0	$4\pi \cdot 10^{-7}$ H/m	0
		= 1.256 637 061 435 ... μH/m	0
Vacuum permittivity[c]	$\varepsilon_0 = 1/\mu_0 c^2$	8.854 187 817 620 ... pF/m	0
Original Planck constant	h	$6.626\,069\,57(52) \cdot 10^{-34}$ Js	$4.4 \cdot 10^{-8}$
Reduced Planck constant, quantum of action	$\hbar$	$1.054\,571\,726(47) \cdot 10^{-34}$ Js	$4.4 \cdot 10^{-8}$
Positron charge	e	0.160 217 656 5(35) aC	$2.2 \cdot 10^{-8}$
Boltzmann constant	k	$1.380\,6488(13) \cdot 10^{-23}$ J/K	$9.1 \cdot 10^{-7}$
Gravitational constant	G	$6.673\,84(80) \cdot 10^{-11}$ Nm^2/kg^2	$1.2 \cdot 10^{-4}$
Gravitational coupling constant	$\kappa = 8\pi G/c^4$	$2.076\,50(25) \cdot 10^{-43}$ s^2/kg m	$1.2 \cdot 10^{-4}$
Fundamental constants (of unknown origin)			
Number of space-time dimensions		3 + 1	0[b]
Fine-structure constant[d] or	$\alpha = \frac{e^2}{4\pi\varepsilon_0 \hbar c}$	1/137.035 999 074(44)	$3.2 \cdot 10^{-10}$

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 109 The lava sea in the volcano Erta Ale in Ethiopia (© Marco Fulle).

example is the volcano Erta Ale, shown in Figure 109. But why is lava still hot, after so many million years?

A straightforward calculation shows that if the Earth had been a hot sphere in the beginning, it should have cooled down and solidified already long time ago. The Earth should be a solid object, like the moon: the Earth should not contain any magma nor eject any lava; hell would not be hot.

Challenge 131 ny

The solution to the riddle is provided by radioactivity: the centre of the Earth contains an oven that is fuelled with an estimated 8 to 10 TW by radioactive uranium ^{235}U and ^{238}U, with 8 to 10 TW by radioactive thorium ^{232}Th and with around 4 TW by radioactive potassium ^{40}K. The radioactivity of these elements, and a few others to a minor degree, keeps the centre of the Earth glowing. More precise investigations, taking into account the decay times and measured material concentrations, show that this mechanism indeed explains the internal heat of the Earth. (In addition, the decay of radioactive potassium is the origin for the 1 % of argon found in the Earth's atmosphere.)

Ref. 163

Page 183

In short, radioactivity keeps lava hot. Radioactivity is the reason that we depict hell as hot. This brings up a challenge: why is the radioactivity of lava and of the Earth in general not dangerous to humans?

Challenge 132 s

Nuclei can form composites

Nuclei are highly unstable when they contain more than about 280 nucleons. Nuclei with higher number of nucleons inevitably decay into smaller fragments. In short, heavy nuclei are unstable. But when the mass is above 10^{57} nucleons, they are stable again: such sys-

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

tems are called *neutron stars*. This is the most extreme example of pure nuclear matter found in nature. Neutron stars are left overs of (type II) supernova explosions. They do not run any fusion reactions any more, as other stars do; in first approximation neutron stars are simply large nuclei.

Neutron stars are made of degenerate matter. Their density of $10^{18}\,\mathrm{kg/m^3}$ is a few times that of a nucleus, as gravity compresses the star. This density value means that a tea spoon of such a star has a mass of several hundred million tons. Neutron stars are about 10 km in diameter. They are never much smaller, as such smaller stars are unstable. They are never much larger, because much larger neutron stars turn into black holes.

Nuclei have colours and shapes

In everyday life, the colour of objects is determined by the wavelength of light that is least absorbed, or, if they shine, by the wavelength that is emitted. Also nuclei can absorb photons of suitably tuned energies and get into an excited state. In this case, the photon energy is converted into a higher energy of one or several of the nucleons whirling around inside the nucleus. Many radioactive nuclei also emit high energy photons, which then are called γ rays, in the range between 1 keV (or 0.2 fJ) and more than 20 MeV (or 3.3 pJ). The emission of γ rays by nuclei is similar to the emission of light by electrons in atoms. From the energy, the number and the lifetime of the excited states – they range from 1 ps to 300 d – researchers can deduce how the nucleons move inside the nucleus.

In short, the energies of the emitted and absorbed γ ray photons define the 'colour' of the nucleus. The γ ray spectrum can be used, like all colours, to distinguish nuclei from each other and to study their motion. In particular, the spectrum of the γ rays emitted by excited nuclei can be used to determine the chemical composition of a piece of matter. Some of these transition lines are so narrow that they can been used to study the change due to the chemical environment of the nucleus, to measure nuclear motion inside solids or to detect the gravitational Doppler effect.

The study of γ-rays also allows us to determine the *shape* of nuclei. Many nuclei are spherical; but many are prolate or oblate ellipsoids. Ellipsoids are favoured if the reduction in average electrostatic repulsion is larger than the increase in surface energy. All nuclei – except the lightest ones such as helium, lithium and beryllium – have a constant mass density at their centre, given by about 0.17 nucleons per $\mathrm{fm^3}$, and a skin thickness of about 2.4 fm, where their density decreases. Nuclei are thus small clouds, as illustrated in Figure 110.

We know that molecules can be of extremely involved shape. In contrast, nuclei are mostly spheres, ellipsoids or small variations of these. The reason is the short range, or better, the fast spatial decay of nuclear interactions. To get interesting shapes like in molecules, one needs, apart from nearest neighbour interactions, also next neighbour interactions and next next neighbour interactions. The strong nuclear interaction is too short ranged to make this possible. Or does it? It might be that future studies will discover that some nuclei are of more unusual shape, such as smoothed pyramids. Some predictions have been made in this direction; however, the experiments have not been performed yet. Ref. 164

The shape of nuclei does not have to be fixed; nuclei can also *oscillate* in shape. Such oscillations have been studied in great detail. The two simplest cases, the quadrupole and

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Particle	Mass m [a]	Lifetime τ or energy width, [b] main decay modes	Isospin I, spin J, [c] parity P, charge parity C	Charge, isospin, strangeness, [c] charm, beauty, topness: $QISCBT$	Lepton & baryon numbers LB
muon μ	0.188 353 109(16) yg = 105.658 3715(35) MeV/c^2 = 0.113 428 9267(29) u gyromagnetic ratio $\mu_\mu/(e\hbar/2m_\mu) = -1.001\,165\,9209(6)$ electric dipole moment $d = (-0.1 \pm 0.9) \cdot 10^{-21} e$ m	2.196 9811(22) µs 99 % $e^- \bar{\nu}_e \nu_\mu$	$J = \frac{1}{2}$	−100000	1, 0
tau τ	1.776 82(16) GeV/c^2	290.6(1.0) fs	$J = \frac{1}{2}$	−100000	1, 0
el. neutrino ν_e	< 2 eV/c^2		$J = \frac{1}{2}$		1, 0
muon neutrino ν_μ	< 2 eV/c^2		$J = \frac{1}{2}$		1, 0
tau neutrino ν_τ	< 2 eV/c^2		$J = \frac{1}{2}$		1, 0
Elementary matter (fermions): quarks [f]					
up u	1.8 to 3.0 MeV/c^2	see proton	$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$	$+\frac{2}{3}+\frac{1}{2}0000$	$0, \frac{1}{3}$
down d	4.5 to 5.5 MeV/c^2	see proton	$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$	$-\frac{1}{3}-\frac{1}{2}0000$	$0, \frac{1}{3}$
strange s	95(5) MeV/c^2		$I(J^P) = 0(\frac{1}{2}^+)$	$-\frac{1}{3}0-1000$	$0, \frac{1}{3}$
charm c	1.275(25) GeV/c^2		$I(J^P) = 0(\frac{1}{2}^+)$	$+\frac{2}{3}00+100$	$0, \frac{1}{3}$
bottom b	4.18(17) GeV/c^2	τ = 1.33(11) ps	$I(J^P) = 0(\frac{1}{2}^+)$	$-\frac{1}{3}000-10$	$0, \frac{1}{3}$
top t	173.5(1.4) GeV/c^2		$I(J^P) = 0(\frac{1}{2}^+)$	$+\frac{2}{3}0000+1$	$0, \frac{1}{3}$
Elementary boson					
Higgs H	126(1) GeV/c^2	not measured	$J = 0$		

Notes:
a. See also the table of SI prefixes on page 326. About the eV/c^2 mass unit, see page 330.
b. The *energy width* Γ of a particle is related to its lifetime τ by the indeterminacy relation $\Gamma\tau = \hbar$. There is a difference between the *half-life* $t_{1/2}$ and the *lifetime* τ of a particle: they are related by $t_{1/2} = \tau \ln 2$, where $\ln 2 \approx 0.693\,147\,18$; the half-life is thus shorter than the lifetime. The unified *atomic mass unit* u is defined as 1/12 of the mass of a carbon 12 atom at rest and in its ground state. One has $1\,\mathrm{u} = \frac{1}{12} m(^{12}\mathrm{C}) = 1.660\,5402(10)$ yg.
c. To keep the table short, the header does not explicitly mention *colour*, the charge of the strong interactions. This has to be added to the list of basic object properties. Quantum numbers containing the word 'parity' are multiplicative; all others are additive. Time parity T (not to be confused with topness T), better called motion inversion parity, is equal to CP. The isospin I (or I_Z) is defined only for up and down quarks and their composites, such as the proton and the neutron. In the literature one also sees references to the so-called G-parity, defined as $G = (-1)^{IC}$.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

The table has not changed much since the mid-1970s, except for the Higgs boson, which has been found in 2012. Assuming that the table is complete, it contains *all* constituents that make up all matter and all radiation in nature. Thus the table lists all constituents – the real 'uncuttables' or 'atoms', as the Greek called them – of material objects and beams of radiation. The elementary particles are the basis for materials science, geology, astronomy, engineering, chemistry, biology, medicine, the neurosciences and psychology. For this reason, the table regularly features in mass tabloids, on television and on the internet.

The full list of elementary particles allows us to put together a full table of particle properties, shown in Table 22. It lists *all* properties of the elementary particles. To save space, colour and weak isospin are not mentioned explicitly. Also the decay modes of the unstable particles are not given in detail; they are found in the standard references.

Ref. 186

The Table 22 on particle properties is fascinating. It allows us to give a *complete* characterization of the intrinsic properties of *any composed object or image.* At the beginning of our study of motion, we were looking for a complete list of the permanent, *intrinsic properties* of moving entities. Now we have it.

Vol. I, page 29

TABLE 22 Elementary particle properties.

Particle	Mass m [a]	Lifetime τ or energy width, [b] main decay modes	Isospin I, spin J, [c] parity P, charge parity C	Charge, isospin, strangeness, [c] charm, beauty, topness: $QISCBT$	Lepton & baryon numbers LB
Elementary radiation (bosons)					
photon γ	0 ($< 2 \cdot 10^{-54}$ kg)	stable	$I(J^{PC}) = 0, 1(1^{--})$	000000	0, 0
$W^{\pm}$	80.385(15) GeV/c^2	2.085(42) GeV 67.60(27) % hadrons, 32.40(27) % $l^+\nu$	$J = 1$	±100000	0, 0
Z	91.1876(21) GeV/c^2	0.265(1) ys = 2.4952(23) GeV/c^2 69.91(6) % hadrons 10.0974(69) % l^+l^-	$J = 1$	000000	0, 0
gluon	0	stable	$I(J^P) = 0(1^-)$	000000	0, 0
Elementary matter (fermions): leptons					
electron e	9.109 382 91(40) · 10^{-31} kg = 81.871 0506(36) pJ/c^2 = 0.510 998 928(11) MeV/c^2 = 0.000 548 579 909 46(22) u gyromagnetic ratio $\mu_e/\mu_B = -1.001\,159\,652\,180\,76(27)$ electric dipole moment [e] $d =< 0.87 \cdot 10^{-30} e$ m	$> 13 \cdot 10^{30}$ s	$J = \frac{1}{2}$	−100 000	1, 0

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

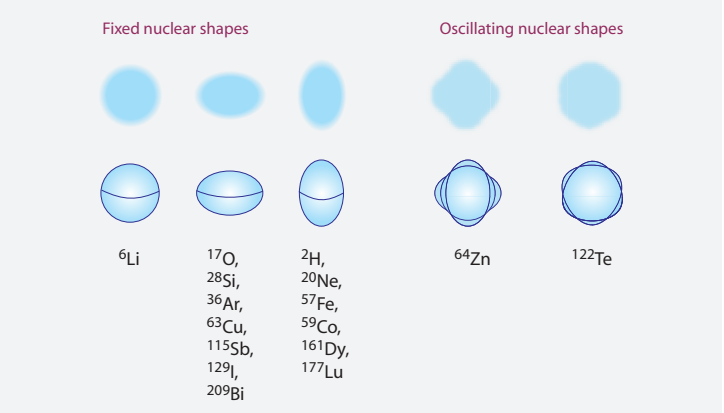


FIGURE 110 Various nuclear shapes – fixed: spherical, oblate, prolate (left) and oscillating (right), shown realistically as clouds (above) and simplified as geometric shapes (below).

octupole oscillations, are shown in Figure 110. In addition, non-spherical nuclei can also rotate. Several rapidly spinning nuclei, with a spin of up to $60\hbar$ and more, are known. They usually slow down step by step, emitting a photon and reducing their angular momentum at each step. Recently it was even discovered that nuclei can also have bulges that rotate around a fixed core, a bit like the tides that rotate around the Earth.

Ref. 165

The four types of motion in the nuclear domain

Nuclei are small because the nuclear interactions are short-ranged. Due to this short range, nuclear interactions play a role only in four types of motion:

— *scattering*,
— *bound motion*,
— *decay* and
— a combination of these three called *nuclear reactions*.

The history of nuclear physics has shown that the whole range of observed phenomena can be reduced to these four fundamental processes. Each process is a type of motion. And in each process, the main interest is the comparison of the start and the end situations; the intermediate situations are less interesting. Nuclear interactions thus lack the complex types of motion which characterize everyday life. That is also the main reason for the shortness of this chapter.

Scattering is performed in all accelerator experiments. Such experiments repeat for nuclei what we do when we look at an object. Eye observation, or seeing something, is a scattering experiment, as eye observation is the detection of scattered light. Scattering of X-rays was used to see atoms for the first time; scattering of high energy alpha particles

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

was used to discover and study the nucleus, and later the scattering of electrons with even higher energy was used to discover and study the components of the proton.

Bound motion is the motion of protons and neutrons inside nuclei or the motion of quarks inside mesons and baryons. In particular, bound motion determines shape and changes of shape of compounds: hadrons and nuclei.

Decay is obviously the basis of radioactivity. Nuclear decay can be due to the electromagnetic, the strong or the weak nuclear interaction. Decay allows studying the conserved quantities of nuclear interactions.

Nuclear reactions are combinations of scattering, decay and possibly bound motion. Nuclear reactions are for nuclei what the touching of objects is in everyday life. Touching an object we can take it apart, break it, solder two objects together, throw it away, and much more. The same can be done with nuclei. In particular, nuclear reactions are responsible for the burning of the Sun and the other stars; they also tell the history of the nuclei inside our bodies.

Quantum theory showed that all four types of nuclear motion can be described in the same way. Each type of motion is due to *the exchange of virtual particles*. For example, scattering due to charge repulsion is due to exchange of virtual photons, the bound motion inside nuclei due to the strong nuclear interaction is due to exchange of virtual gluons, β decay is due to the exchange of virtual W bosons, and neutrino reactions are due to the exchange of virtual Z bosons. The rest of this chapter explains these mechanisms in more details.

Nuclei react

Vol. IV, page 117

The first man thought to have made transuranic elements, the physics genius Enrico Fermi, received the Nobel Prize in Physics for the discovery. Shortly afterwards, Otto Hahn and his collaborators Lise Meitner and Fritz Strassmann showed that Fermi was wrong, and that his prize was based on a mistake. Fermi was allowed to keep his prize, the Nobel committee gave Hahn and Strassmann the Nobel Prize as well, and to make the matter unclear to everybody and to women physicists in particular, the prize was not given to Lise Meitner. (After her death though, a new chemical element was named after her.)

When protons or neutrons are shot into nuclei, they usually remained stuck inside them, and usually lead to the transformation of an element into a heavier one. After having done this with all elements, Fermi used uranium; he found that bombarding it with neutrons, a new element appeared, and concluded that he had created a transuranic element. Alas, Hahn and his collaborators found that the element formed was well-known: it was barium, a nucleus with less than half the mass of uranium. Instead of remaining stuck as in the previous 91 elements, the neutrons had *split* the uranium nucleus. In short, Fermi, Hahn, Meitner and Strassmann had observed reactions such as:

$$^{235}\mathrm{U} + \mathrm{n} \to {}^{143}\mathrm{Ba} + {}^{90}\mathrm{Kr} + 3n + 170\,\mathrm{MeV}\,. \tag{55}$$

Meitner called the splitting process *nuclear fission*. The amount of energy liberated in fission is unusually large, millions of times larger than in a chemical interaction of an atom. In addition, several neutrons are emitted, which in turn can lead to the same pro-

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Chapter 9

THE STANDARD MODEL OF PARTICLE PHYSICS – AS SEEN ON TELEVISION

The expression *standard model of elementary particle physics* stands for he summary of all knowledge about the motion of quantum particles in nature. he standard model can be explained in four tables: the table of the elementary particles, the table of their properties, the table of possible Feynman diagrams and the table of fundamental constants.

The following table lists the known elementary particles found in nature.

TABLE 21 The elementary particles.

Radiation	electromagnetic	weak	strong
	γ	W^+, W^-, Z^0	g_1 ... g_8
	photon	weak bosons	gluons
	Radiation particles are intermediate vector bosons, thus with spin 1. W^- is the antiparticle of W^+; the photons and the Z^0 are their own antiparticles. Only the $W^\pm$ and Z^0 are massive.		
Matter	generation 1	generation 2	generation 3
Leptons	e, ν_e	μ, ν_μ	τ, ν_τ
Quarks (each in three colours)	d, u	s, c	t, b
	Matter particles are fermions with spin 1/2; all have a corresponding antiparticle. Leptons mix among themselves; so do quarks. All fermions are massive.		
Vacuum state			
Higgs boson	H	Has spin 0 and a mass of 126 GeV.	

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

The weak interaction is described by a Lagrangian. After a century of intense research, the Lagrangian is known in all its details, including, since 2012, the Higgs boson. Theory and experiment agree whenever comparisons have been made.

All remaining limitations of the gauge theory of the weak interaction are only conceptual. Like in all of quantum field theory, also in the case of the weak interaction the mathematical form of the Lagrangian is almost uniquely defined by requiring renormalizability, Lorentz invariance, and (broken) gauge invariance – SU(2) in this case. We say again 'almost', as we did for the case of the strong interaction, because the Lagrangian of the weak and electromagnetic interactions contains a few parameters that remain unexplained:

Page 238

- The two coupling constants g and g' of the weak and the electromagnetic interaction are unexplained. (They define weak mixing angle $\theta_w = \arctan(g'/g)$.)
- The mass $M_Z = 91\,\mathrm{GeV}/c^2$ of the neutral Z boson is unexplained.
- The number $n = 3$ of generations is unexplained.
- The masses of the six leptons and the six quarks are unexplained.
- The four parameters of the Cabibbo–Kobayashi–Maskawa quark mixing matrix and the six parameters of the neutrino mixing matrix are unexplained, including the respective CP violating phases.
- The properties of space-time, in particular its Lorentz invariance, its continuity and the number of its dimensions are assumed from the outset and are obviously all unexplained.
- It is also not known how the weak interaction behaves in strong gravity, thus in strongly curved space-time.

Before exploring how to overcome these limitations, we summarize all results found so far in the so-called *standard model of particle physics*.



Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

cess; fission can thus start a *chain reaction*. Later, and (of course) against the will of the team, the discovery would be used to make nuclear bombs.

Nuclear reactions are typically triggered by neutrons, protons, deuterons or γ particles. Apart from triggering fission, neutrons are used to transform lithium into tritium, which is used as (one type of) fuel in fusion reactors; and neutrons from (secondary) cosmic rays produce radiocarbon from the nitrogen in the atmosphere. Deuterons impinging on tritium produce helium in fusion reactors. Protons can trigger the transformation of lithium into beryllium. Photons can knock alpha particles or neutrons out of nuclei.

All nuclear reactions and decays are *transformations*. In each transformation, already the ancient Greek taught us to search, first of all, for conserved quantities. Besides the well-known cases of energy, momentum, electric charge and angular momentum conservation, the results of nuclear physics lead to several new conserved quantities. The behaviour is quite constrained. Quantum field theory implies that particles and antiparticles (commonly denoted by a bar) must behave in compatible ways. Both experiment and quantum field theory show for example that every reaction of the type

$$\mathrm{A} + \mathrm{B} \to \mathrm{C} + \mathrm{D} \tag{56}$$

implies that the reactions

$$\mathrm{A} + \overline{\mathrm{C}} \to \overline{\mathrm{B}} + \mathrm{D} \tag{57}$$

or

$$\overline{\mathrm{C}} + \overline{\mathrm{D}} \to \overline{\mathrm{A}} + \overline{\mathrm{B}} \tag{58}$$

or, if energy is sufficient,

$$\mathrm{A} \to \mathrm{C} + \mathrm{D} + \overline{\mathrm{B}}\,, \tag{59}$$

are also possible. Particles thus behave like conserved mathematical entities.

Experiments show that antineutrinos differ from neutrinos. In fact, all reactions confirm that the so-called *lepton number* is conserved in nature. The lepton number L is zero for nucleons or quarks, is 1 for the electron and the neutrino, and is −1 for the positron and the antineutrino.

In addition, all reactions conserve the so-called *baryon number*. The baryon number B for protons and neutrons is 1 (and 1/3 for quarks), and −1 for antiprotons and antineutrons (and thus −1/3 for antiquarks). So far, no process with baryon number violation has ever been observed. Baryon number conservation is one reason for the danger of radioactivity, fission and fusion. The concept of baryon number was introduced by Ernst Stückelberg (b. 1905 Basel, d. 1984 Geneva), an important physicist who discovered several other concepts of particle physics, including Feynman diagrams before Feynman himself. Baryon number was renamed when Abraham Pais (b. 1918 Amsterdam, d. 2000 Copenhagen) introduced the terms 'lepton' and 'baryon'.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 111 The destruction of four nuclear reactors in 2011 in Fukushima, in Japan, which rendered life impossible at a distance of 30 km around it (courtesy Digital Globe).



FIGURE 112 The explosion of a nuclear bomb: an involved method of killing many children in the country where it explodes and ruining the economic future of many children in the country that built it.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

> Difficile est saturam non scribere.*
> Juvenal, *Saturae* 1, 30.

* *

There is no generally accepted name for the quantum field theory of the weak interaction. The expression *quantum asthenodynamics* (QAD) – from the Greek word for 'weak' – has not been universally adopted.

* *

Do ruminating *cows* move their jaws equally often in clockwise and anticlockwise direction? In 1927, the theoretical physicists Pascual Jordan and Ralph de Laer Kronig published a study showing that in Denmark the two directions are almost equally distributed. The rumination direction of cows is thus not related to the weak interaction.

Ref. 212

* *

Of course, the weak interaction is responsible for radioactive β decay, and thus for part of the radiation background that leads to mutations and thus to biological evolution.

* *

Due to the large toll it placed on society, research in nuclear physics, has almost disappeared from the planet, like poliomyelitis has. Like poliomyelitis, nuclear research is kept alive only in a few highly guarded laboratories around the world, mostly by questionable figures, in order to build dangerous weapons. Only a small number of experiments carried on by a few researchers are able to avoid this involvement and continue to advance the topic.

* *

Interesting aspects of nuclear physics appear when powerful lasers are used. In 1999, a British team led by Ken Ledingham observed laser induced uranium fission in ^{238}U nuclei. In the meantime, this has even be achieved with table-top lasers. The latest feat, in 2003, was the transmutation of ^{129}I to ^{128}I with a laser. This was achieved by focussing a 360 J laser pulse onto a gold foil; the ensuing plasma accelerates electrons to relativistic speed, which hit the gold and produce high energy γ rays that can be used for the transmutation.

Ref. 213

A summary of the weak interaction

The weak interaction is described by a non-Abelian gauge theory based on a broken SU(2) gauge group for weak processes. The weak interaction mixes with the unbroken U(1) gauge group of the electrodynamic interaction. This description matches the observed properties of β decay, of particle transformations, of neutrinos and their mixing, of the massive intermediate W and Z bosons, of maximal parity violation, of the heat production inside the Earth, of several important reactions in the Sun and of the origin of matter in the universe. Even though the weak interaction is weak, it is a bit everywhere.

* 'It is hard not to be satirical.'

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

electric charge, no colour charge and almost no gravitational charge (mass). To get an impression of the weakness of the weak interaction, it is usually said that the probability of a neutrino to be absorbed by a lead screen of the thickness of one light-year is less than 50 %. The universe is thus essentially empty for neutrinos. Is there room for bound states of neutrinos circling masses? How large would such a bound state be? Can we imagine bound states, which would be called neutrinium, of neutrinos and antineutrinos circling each other? The answer depends on the mass of the neutrino. Bound states of massless particles do not exist. They could and would decay into two free massless particles.*

Since neutrinos are massive, a neutrino–antineutrino bound state is possible in principle. How large would it be? Does it have excited states? Can they ever be detected? These issues are still open.

Challenge 148 ny

The weak interaction is so weak that a neutrino–antineutrino annihilation – which is only possible by producing a massive intermediate Z boson – has never been observed up to this day.

* *

Exploring the mixing of the weak and the electromagnetic interaction led to the prediction of the *Higgs boson*. The fascination of the Higgs boson is underlined by the fact that it is the only fundamental particle that bears the name of a physicist. By the way, the paper by Peter Higgs on the boson named after him is only 79 lines long, and has only five equations.

Ref. 210

* *

In the years 1993 and 1994 an intense marketing campaign was carried out across the United States of America by numerous particle physicists. They sought funding for the 'superconducting supercollider', a particle accelerator with a circumference of 80 km. This should have been the largest machine ever built, with a planned cost of more than twelve thousand million dollars, aiming at finding the Higgs boson before the Europeans would do so at a fraction of that cost. The central argument brought forward was the following: since the Higgs boson is the basis of particle masses, it was central to US science to know about it first. Apart from the issue of the relevance of the conclusion, the worst is that the premise is wrong.

We have seen above that 99 % of the mass of protons, and thus of the universe, is due to quark confinement; this part of mass appears even if the quarks are approximated as massless. The Higgs boson is *not* responsible for the origin of mass itself; it just might shed some light on the issue. In particular, the Higgs boson does not allow calculating or understanding the mass of any particle. The whole campaign was a classic case of disinformation, and many people involved have shown their lack of honesty.** In the end, the project was stopped, mainly for financial reasons.

Page 233

Ref. 195

* In particular, this is valid for photons bound by gravitation; this state is not possible.

** We should not be hypocrites. The supercollider lie is negligible when compared to other lies. The biggest lie in the world is probably the one that states that to ensure its survival, the USA government need to spend more on the military than all other countries in the world combined. This lie is, every single year, around 40 times as big as the once-only supercollider lie. Many other governments devote even larger percentages of their gross national product to their own version of this lie. As a result, the defence spending lie is directly responsible for most of the poverty in all the countries that use it.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Bombs and nuclear reactors

Uranium fission is triggered by a neutron, liberates energy and produces several additional neutrons. Therefore, uranium fission can trigger a *chain reaction* that can lead either to an explosion or to a controlled generation of heat. Once upon a time, in the middle of the twentieth century, these processes were studied by quite a number of researchers. Most of them were interested in making weapons or in using nuclear energy, despite the high toll these activities place on the economy, on human health and on the environment.

Most stories around the development of nuclear weapons are almost incredibly absurd. The first such weapons were built during the Second World War, with the help of the smartest physicists that could be found. Everything was ready, including the most complex physical models, several huge factories and an organization of incredible size. There was just one little problem: there was no uranium of sufficient quality. The mighty United States thus had to go around the world to shop for good uranium. They found it in the (then) Belgian colony of Congo, in central Africa. In short, without the support of Belgium, which sold the Congolese uranium to the USA, there would have been no nuclear bomb, no early war end and no superpower status.

Congo paid a high price for this important status. It was ruled by a long chain of military dictators up to this day. But the highest price was paid by the countries that actually built nuclear weapons. Some went bankrupt, others remained underdeveloped; even the richest countries have amassed huge debts and a large underprivileged population. There is *no* exception. The price of nuclear weapons has also been that some regions of our planet became uninhabitable, such as numerous islands, deserts, rivers, lakes and marine environments. But it could have been worse. When the most violent physicist ever, Edward Teller, made his first calculations about the hydrogen bomb, he predicted that the bomb would set the atmosphere into fire. Nobel Prize winner Hans Bethe* corrected the mistake and showed that nothing of this sort would happen. Nevertheless, the military preferred to explode the hydrogen bomb in the Bikini atoll, the most distant place from their homeland they could find. The place is so radioactive that today it is even dangerous simply to fly over that island!

Ref. 166

It was then noticed that nuclear test explosions increased ambient radioactivity in the atmosphere all over the world. Of the produced radioactive elements, ^{3}H is absorbed by humans in drinking water, ^{14}C and ^{90}Sr through food, and ^{137}Cs in both ways. Fortunately, in the meantime, all countries have agreed to perform their nuclear tests underground.

Radioactivity is dangerous to humans, because it disrupts the processes inside living cells. Details on how radioactivity is measured and what effects on health it produces are provided below.

Page 194

Not only nuclear bombs, also peaceful nuclear reactors are dangerous. The reason was

* Hans Bethe (b. 1906 Strasbourg, d. 2005) was one of the great physicists of the twentieth century, even though he was head of the theory department that lead to the construction of the first atomic bombs. He worked on nuclear physics and astrophysics, helped Richard Feynman in developing quantum electrodynamics, and worked on solid state physics. When he got older and wiser, he became a strong advocate of arms control; he also was essential in persuading the world to stop atmospheric nuclear test explosions and saved many humans from cancer in doing so.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 15 Some radioactivity measurements.

MATERIAL	ACTIVITY IN BQ/KG
Air	*c.* 10^{-2}
Sea water	10^{1}
Human body	*c.* 10^{2}
Cow milk	max. 10^{3}
Pure ^{238}U metal	*c.* 10^{7}
Highly radioactive α emitters	$> 10^{7}$
Radiocarbon: ^{14}C (β emitter)	10^{8}
Highly radioactive β and γ emitters	$> 10^{9}$
Main nuclear fallout: ^{137}Cs, ^{90}Sr (α emitter)	$2 \cdot 10^{9}$
Polonium, one of the most radioactive materials (α)	10^{24}

discovered in 1934 by Frédéric Joliot and his wife Irène, the daughter of Pierre and Marie Curie: *artificial radioactivity*. The Joliot–Curies discovered that materials irradiated by α rays become radioactive in turn. They found that α rays transformed aluminium into radioactive phosphorus:

$$^{27}_{13}\mathrm{Al} + {}^{4}_{2}\alpha \rightarrow {}^{30}_{15}\mathrm{P} + {}^{30}_{15}\mathrm{n}\,. \qquad (60)$$

In fact, almost all materials become radioactive when irradiated with alpha particles, neutrons or γ rays. As a result, radioactivity itself can only be contained with difficulty. After a time span that depends on the material and the radiation, any box that contains radioactive material has itself become radioactive. The 'contagion' stops only for very small amounts of radioactive material.

The dangers of natural and artificial radioactivity are the reason for the high costs of nuclear reactors. After about thirty years of operation, reactors have to be dismantled. The radioactive pieces have to be stored in specially chosen, inaccessible places, and at the same time the workers' health must not be put in danger. The world over, many reactors now need to be dismantled. The companies performing the job sell the service at high price. All operate in a region not far from the border to criminal activity, and since radioactivity cannot be detected by the human senses, many companies cross that border.

In fact, one important nuclear reactor is (usually) not dangerous to humans: the Sun. Page 200 We explore it shortly.

CURIOSITIES AND CHALLENGES ON NUCLEI AND RADIOACTIVITY

Nowadays, nuclear magnetic resonance is also used to check the quality of food. For example, modern machines can detect whether orange juice is contaminated with juice from other fruit and can check whether the fruit were ripe when pressed. Other machines can check whether wine was made from the correct grapes and how it aged.

* *

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

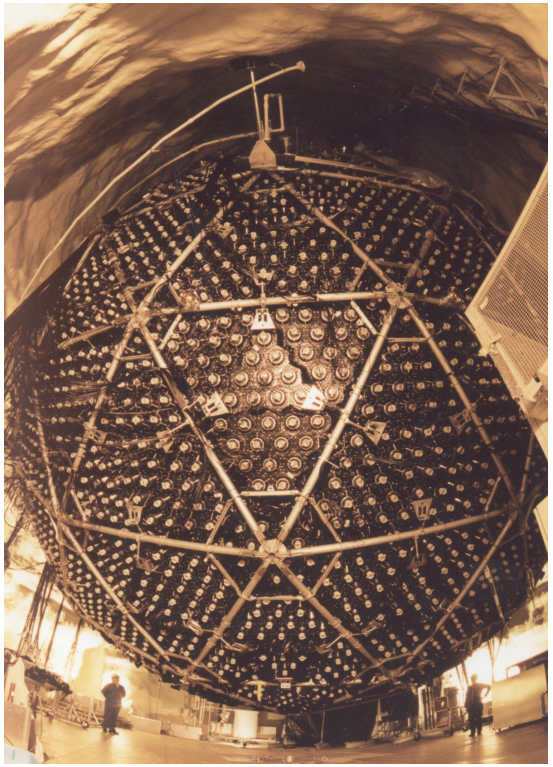


FIGURE 149 A typical underground experiment to observe neutrino oscillations: the Sudbury Neutrino Observatory in Canada (© Sudbury Neutrino Observatory)

indeed weak.

* *

Already in 1957, the great physicist Bruno Pontecorvo imagined that travelling neutrinos could spontaneously change into their own antiparticles. Today, it is known experimentally that travelling neutrinos can change generation, and one speaks of *neutrino oscillations*. Such experiments are carried out in large deep underground caves; the most famous one is shown in Figure 149. In short, experiments show that the weak interaction mixes neutrino types in the same way that it mixes quark types.

* *

Only one type of particles interacts (almost) only weakly: neutrinos. Neutrinos carry no

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Glashow and Abdus Salam. They received the 1979 Nobel Prize in physics for their work.

Abdus Salam (b. 1926 Santokdas, d. 1996 Oxford) was an example to many scientists across the world and a deeply spiritual man. In his Nobel banquet speech he explained: 'This, in effect, is the faith of all physicists: the deeper we seek, the more is our wonder excited, the more is the dazzlement for our gaze.' Salam often connected his research to the spiritual aspects of Islam. Once he was asked in Pakistani television why he believed in unification of physics; he answered: 'Because god is one!' When the parliament of Pakistan, in one of the great injustices of the twentieth century, declared Ahmadi Muslims to be non-Muslims and thus effectively started a religious persecution, Salam left Pakistan and never returned. The religious persecution continues to this day: on his tombstone in Pakistan, the word 'muslim' has been hammered away, and the internet is full of offensive comments about him by other muslims. Salam was also an important science manager. With support of UNESCO, Salam founded the International Centre for Theoretical Physics and the Third World Academy of Sciences, both in Trieste, in Italy, and attracted there the best scientists of developing countries.

* *

β decay, due to the weak interaction, separates electrons and protons. Finally, in 2005, people have proposed to use this effect to build long-life batteries that could be used in satellites. Future will tell whether the proposals will be successful.

* *

Ref. 211 Every second around 10^{16} neutrinos fly through our body. They have five sources:

— *Solar neutrinos* arrive on Earth at $6 \cdot 10^{14}\,/\mathrm{m}^2\mathrm{s}$, with an energy from 0 to 0.42 MeV; they are due to the p-p reaction in the sun; a tiny is due to the ^{8}B reaction and has energies up to 15 MeV.

— *Atmospheric neutrinos* are products of cosmic rays hitting the atmosphere, consist of 2/3 of muon neutrinos and one third of electron neutrinos, and have energies mainly between 100 MeV and 5 GeV.

Page 184 — *Earth neutrinos* from the radioactivity that keeps the Earth warm form a flux of $6 \cdot 10^{10}\,/\mathrm{m}^2\mathrm{s}$.

— *Fossil neutrinos* from the big bang, with a temperature of 1.95 K are found in the universe with a density of $300\,\mathrm{cm}^{-3}$, corresponding to a flux of $10^{15}\,/\mathrm{m}^2\mathrm{s}$.

— *Man-made neutrinos* are produced in nuclear reactors (at 4 MeV) and as neutrino beams in accelerators, using pion and kaon decay. A standard nuclear plant produces $5 \cdot 10^{20}$ neutrinos per second. Neutrino beams are produced, for example, at the CERN in Geneva. They are routinely sent 700 km across the Earth to the Gran Sasso laboratory in central Italy, where they are detected. (In 2011, a famous measurement error led some people to believe, incorrectly, that these neutrinos travelled faster than light.)

Neutrinos are mainly created in the atmosphere by cosmic radiation, but also coming directly from the background radiation and from the centre of the Sun. Nevertheless, during our own life – around 3 thousand million seconds – we have only a 10 % chance that one of these neutrinos interacts with one of the $3 \cdot 10^{27}$ atoms of our body. The reason is, as usual, that the weak interaction is felt only over distances less than 10^{-17} m, about 1/100th of the diameter of a proton. The weak interaction is

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 113 A machine to test fruit quality with the help of nuclear magnetic resonance (© Bruker).

Magnetic resonance machines pose no danger; but they do have some biological effects,
Ref. 171 as Peter Mansfield, one of the inventors of the technique, explains. The first effect is due to the conductivity of blood. When blood in the aorta passes through a magnetic field, a voltage is induced. This effect has been measured and it might interfere with cardiac functioning at 7 T; usual machines have 1.5 T and pose no risk. The second effect is due to the switching of the magnetic field. Some people sense the switching in the thorax and in the shoulders. Not much is known about the details of such peripheral nerve stimulation yet.

* *

The amount of radioactive radiation is called the *dose*. The unit for the radioactive dose is one *gray*: it is the amount of radioactivity that deposits the energy 1 J on 1 kg of matter: 1 Gy = 1 J/kg. A *sievert*, or 1 Sv, is the unit of radioactive dose *equivalent*; it is adjusted to humans by weighting each type of human tissue with a factor representing the impact of radiation deposition on it. Three to five sievert are a lethal dose to humans. In comparison, the natural radioactivity present inside human bodies leads to a dose of 0.2 mSv
Ref. 167 per year. An average X-ray image implies an irradiation of 1 mSv; a CAT scan 8 mSv. For other measurement examples, see Table 15.

The *amount of radioactive material* is measured by the number of nuclear decays per second. One decay per second is called one *becquerel*, or 1 Bq. An adult human body typically contains 9 kBq, the European limit for food, in 2011, varies between 370

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 16 Human exposure to radioactivity and the corresponding doses.

EXPOSURE	DOSE
Daily human exposure:	
Average exposure to cosmic radiation in Europe	
at sea level	0.3 mSv/a
at a height of 3 km	1.2 mSv/a
Average (and maximum) exposure from the soil, not counting radon effects	0.4 mSv/a (2 mSv/a)
Average (and maximum) inhalation of radon	1 mSv/a (100 mSv/a)
Average exposure due to internal radionuclides	0.3 mSv/a
natural content of ^{40}K in human muscles	10^{-4} Gy and 4500 Bq
natural content of Ra in human bones	$2 \cdot 10^{-5}$ Gy and 4000 Bq
natural content of ^{14}C in humans	10^{-5} Gy
Total average (and maximum) human exposure	2 mSv/a (100 mSv/a)
Common situations:	
Dental X-ray	*c.* 10 mSv equivalent dose
Lung X-ray	*c.* 0.5 mSv equivalent dose
Short one hour flight (see www.gsf.de/epcard)	*c.* 1 µSv
Transatlantic flight	*c.* 0.04 mSv
Maximum allowed dose at work	30 mSv/a
Smoking 60 cigarettes a day	26 to 120 mSv/a
Deadly exposures:	
Ionization	0.05 C/kg can be deadly
Dose	100 Gy=100 J/kg is deadly in 1 to 3 days
Equivalent dose	more than 3 Sv leads to death for 50 % of untreated patients

and 600 Bq/kg. The amount released by the Hiroshima bomb is estimated to have been between 4 PBq and 60 PBq, the amount released by the Chernobyl disaster was between 2 and 12 EBq, thus between 200 and 500 times larger. The numbers for the various Russian radioactive disasters in the 1960s and 1970 are similarly high. The release for the Fukushima reactor disaster in March 2011 is estimated to have been 370 to 630 PBq, which would put it at somewhere between 10 and 90 Hiroshima bombs.

The SI units for radioactivity are now common around the world; in the old days, 1 sievert was called 100 rem or 'Röntgen equivalent man'; the SI unit for dose, 1 gray, replaces what used to be called 100 rd or Rad. The SI unit for exposure, 1 C/kg, replaces the older unit 'röntgen', with the relation $1\,\mathrm{R} = 2.58 \cdot 10^{-4}\,\mathrm{C/kg}$. The SI unit becquerel replaces the curie (Ci), for which 1 Ci = 37 GBq.

* *

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

tric charge of the particle ψ_k in units of the positron charge. The number $t_{3L}(k)$ is the *weak isospin*, or *weak charge*, of fermion k, whose value is $+1/2$ for u_k and ν_k and is $-1/2$ for d_k and l_k. These two charges together define the so-called *vector coupling*

$$g_V^k = t_{3L}(k) - 2q_k \sin^2\theta_W \tag{101}$$

and the axial coupling

$$g_A^k = t_{3L}(k)\,. \tag{102}$$

The combination $g_V^k - g_A^k$, or $V - A$ for short, expresses the maximal violation of P and C parity in the weak interaction.

— The operators T^+ and T^- are the weak isospin raising and lowering operators. Their action on a field is given e.g. by $T^+ l_k^- = \nu_k$ and $T^- u_k = d_k$.

We see that the Lagrangian indeed contains all the ideas developed above. The electroweak Lagrangian is essentially *unique*: it could not have a different mathematical form, because both the electromagnetic terms and the weak terms are fixed by the requirements of Lorentz invariance, U(1) and broken SU(2) gauge invariance, permutation symmetry and renormalizability.

The Lagrangian of the weak interaction has been checked and confirmed by thousands of experiments. Many experiments have been designed specifically to probe it to the highest precision possible. In all these cases, no contradictions between observation and theory has ever been found. Even though the last three terms of the Lagrangian are not fully confirmed, this is – most probably – the exact Lagrangian of the weak interaction.

Ref. 186

CURIOSITIES ABOUT THE WEAK INTERACTION

Ref. 209

The weak interaction, with its breaking of parity and its elusive neutrino, exerts a deep fascination on all those who have explored it. Let us explore this fascination a bit more.

* *

The weak interaction is required to have an excess of matter over antimatter. Without the parity violation of the weak interactions, there would be no matter at all in the universe, because all matter and antimatter that appeared in the big bang would have annihilated. The weak interaction prevents the symmetry between matter and antimatter, which is required to have an excess of one over the other in the universe. In short, the parity violation of the weak interaction is a necessary condition for our own existence.

* *

The weak interaction is also responsible for the heat produced inside the Earth. This heat keeps the magma liquid. As a result, the weak interaction, despite its weakness, is responsible for most earthquakes, tsunamis and volcanic eruptions.

* *

The Lagrangian of the weak interaction was clarified by Steven Weinberg, Sheldon

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

2. the second term describes the well-known interaction of matter and electromagnetic radiation, and explains practically all material properties and colours observed in daily life;
3. the term is the so-called *charged weak current interaction*, due to exchange of virtual W bosons, that is responsible for the β decay and for the fact that the Sun is shining;
4. this term is the *neutral weak current interaction*, the '$V - A$ theory' of George Sudarshan, that explains the elastic scattering of neutrinos in matter;
5. this term represents the kinetic energy of photons and yields the evolution of the electromagnetic field in vacuum, thus the basic Maxwell equations;
6. this term represents the kinetic energy of the weak radiation field and gives the evolution of the intermediate W and Z bosons of the weak interaction;
7. this term is the kinetic energy of the vector bosons;
8. this term represents the triple vertex of the self-interaction of the vector boson;
9. this term represents the quadruple vertex of the self-interaction of the vector boson;
10. this term is the kinetic energy of Higgs boson;
11. this term is the self-interaction of the Higgs boson;
12. the last term is expected to represent the interaction of the vector bosons with the Higgs boson that restore unitarity at high energies.

Let us look into the formal details. The quantities appearing in the Lagrangian are:

— The wave functions $\psi_k = (\nu'_k \; l'^-_k)$ for leptons and $(u_k \; d'_k)$ for quarks are the left-handed fermion fields of the k-th fermion generation; every component is a spinor. The index $k = 1, 2, 3$ numbers the generation: the value 1 corresponds to (u d $\nu_e e^-$), the second generation is (c s $\nu_\mu \mu^-$) and the third (t b $\nu_\tau \tau^-$). The ψ_k transform as doublets under SU(2); the right handed fields are SU(2) singlets.

In the doublets, one has

$$d'_k = \sum_l V_{kl} d_l \,, \tag{99}$$

where V_{kl} is the Cabibbo–Kobayashi–Maskawa mixing matrix, d'_k are the quark flavour eigenstates and d_k are the quark mass eigenstates. A similar expression holds for the mixing of the neutrinos:

$$\nu'_k = \sum_l P_{kl} \nu_l \,, \tag{100}$$

where P_{kl} is the Pontecorvo–Maki–Nakagawa–Sakata mixing matrix, ν'_l the neutrino flavour eigenstates and ν_l the neutrino mass eigenstates.

— For radiation, A^μ and $F^{\mu\nu}$ is the field of the massless vector boson of the electromagnetic field, the *photon* γ.

$W^\pm_\mu$ are the massive charged gauge vector bosons of the weak interaction; the corresponding particles, W^+ and W^-, are each other's antiparticles.

Z_μ is the field of the massive neutral gauge vector boson of the weak interactions; the neutral vector boson itself is usually called Z^0.

— H is the field of the neutral scalar Higgs boson H^0, the only elementary scalar particle in the standard model.

— Two charges appear, one for each interaction. The number q_k is the well-known *elec-*

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 114 A dated image of Lake Karachay and the nuclear plant that was filling it with radioactivity (© Unknown).

Not all γ-rays are due to radioactivity. In the year 2000, an Italian group discovered that thunderstorms also emit γ rays, of energies up to 10 MeV. The mechanisms are still being investigated; they seem to be related to the formation process of lightning. Ref. 168

* *

Chain reactions are quite common in nature, and are not limited to the nuclear domain. *Fire* is a chemical chain reaction, as are exploding fireworks. In both cases, material needs heat to burn; this heat is supplied by a neighbouring region that is already burning.

* *

Radioactivity can be extremely dangerous to humans. The best example is plutonium. Only 1 μg of this α emitter inside the human body are sufficient to cause lung cancer. Another example is polonium. Polonium 210 is present in tobacco leaves that were grown with artificial fertilizers. In addition, tobacco leaves filter other radioactive substances from the air. Polonium, lead, potassium and the other radioactive nuclei found in tobacco are the main reason that *smoking produces cancer*. Table 16 shows that the dose is considerable and that it is by far the largest dose absorbed in everyday life.

* *

Why is nuclear power a dangerous endeavour? The best argument is Lake Karachay near Mayak, in the Urals in Russia. In less than a decade, the nuclear plants of the region have transformed it into the most radioactive place on Earth. In the 1970s, walking on the

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

shore of the lake for an hour led to death on the shore. The radioactive material in the lake was distributed over large areas in several catastrophic explosions in the 1950s and 1960s, leading to widespread death and illness. Several of these accidents were comparable to the Chernobyl accident of 1986; they were kept secret. Today, in contrast to Figure 114, the lake is partly filled with concrete – but not covered with it, as is often assumed. Ref. 169

* *

All lead is slightly radioactive, because it contains the ^{210}Pb isotope, a β emitter. This lead isotope is produced by the uranium and thorium contained in the rock from where the lead is extracted. For sensitive experiments, such as for neutrino experiments, one needs radioactivity shields. The best shield material is lead, but obviously it has to be lead with a low radioactivity level. Since the isotope ^{210}Pb has a half-life of 22 years, one way to do it is to use *old* lead. In a precision neutrino experiment in the Gran Sasso in Italy, the research team uses lead mined during Roman times, thus 2000 years old, in order to reduce spurious signals.

* *

Not all nuclear reactors are human made. The occurrence of *natural* nuclear reactors have been predicted in 1956 by Paul Kuroda. In 1972, the first such example was found. In Oklo, in the African country of Gabon, there is a now famous geological formation where uranium is so common that two thousand million years ago a *natural* nuclear reactor has formed spontaneously – albeit a small one, with an estimated power generation of 100 kW. It has been burning for over 150 000 years, during the time when the uranium 235 percentage was 3 % or more, as required for chain reaction. (Nowadays, the uranium 235 content on Earth is 0.7 %.) The water of a nearby river was periodically heated to steam during an estimated 30 minutes; then the reactor cooled down again for an estimated 2.5 hours, since water is necessary to moderate the neutrons and sustain the chain reaction. The system has been studied in great detail, from its geological history up to the statements it makes about the constancy of the 'laws' of nature. The studies showed that 2000 million years ago the mechanisms were the same as those used today.

* *

Nuclear reactors exist in many sizes. The largest are used in power plants and can produce over 1000 MW in electrical power; the smallest are used in satellites, and usually produce around 10 kW. All work without refuelling for between one and thirty years.

* *

Radioactivity also has forensic uses. On many surfaces, it is hard to make finger prints visible. One method is to put the object in question in an atmosphere of radioactive iodine or radioactive sulphur dioxide. The gases react with the substances in finger prints. The fingerprints have thus become radioactive. Looking at the scintillation signals of the prints – a method called *autoradiography* – then allows imaging the fingerprint simply by laying a photographic film or an equivalent detector over the object in question.

* *

In contrast to massive particles, massless particles cannot decay at all. There is a simple

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

of the SU(2) symmetry imply that the electromagnetic coupling e, the weak coupling g and the intermediate boson masses by the impressive relation

$$\left(\frac{m_W}{m_Z}\right)^2 + \left(\frac{e}{g}\right)^2 = 1\,. \tag{97}$$

The relation is well verified by experiments.

The mixing of the electromagnetic and weak interactions also suggests the existence of a scalar, elementary *Higgs boson*. This prediction, from the year 1963, was made by Peter Higgs and a number of other particles physicists, who borrowed ideas that Yoichiro Nambu and, above all, Philip Anderson introduced in solid state physics. The Higgs boson maintains the unitarity of longitudinal boson scattering at energies of a few TeV and influences the mass of all other elementary particles. In 2012, the Higgs boson has finally been observed in two large experiments at CERN. Ref. 208

The Lagrangian of the weak and electromagnetic interactions

If we combine the observed properties of the weak interaction mentioned above, namely its observed Feynman diagrams, its particle transforming ability, P and C violation, quark mixing, neutrino mixing and symmetry breaking, we arrive at the full Lagrangian density. It is given by:

$$\begin{aligned}
\mathcal{L}_{\text{E\&W}} = \;& \textstyle\sum_k \overline{\psi}_k (i\partial\!\!\!/ - m_k - \frac{g m_k H}{2 m_W})\psi_k && \text{1. fermion mass terms}\\
& -e \textstyle\sum_k q_k \overline{\psi}_k \gamma^\mu \psi_k A_\mu && \text{2. e.m. interaction}\\
& -\frac{g}{2\sqrt{2}} \textstyle\sum_k \overline{\psi}_k \gamma^\mu (1-\gamma^5)(T^+ W^+_\mu + T^- W^-_\mu)\psi_k && \text{3. charged weak currents}\\
& -\frac{g}{2\cos\theta_W} \textstyle\sum_k \overline{\psi}_k \gamma^\mu (g_V^k - g_A^k \gamma^5)\psi_k Z_\mu && \text{4. neutral weak currents}\\
& -\tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} && \text{5. electromagnetic field}\\
& -\tfrac{1}{2} W^+_{\mu\nu} W^{-\mu\nu} - \tfrac{1}{4} Z_{\mu\nu} Z^{\mu\nu} && \text{6. weak W and Z fields}\\
& +m_W^2 W^+ W^- + \tfrac{1}{2} m_Z^2 Z^2 && \text{7. W and Z mass terms}\\
& -gWWA - gWWZ && \text{8. cubic interaction}\\
& -\tfrac{g^2}{4}(W^4 + Z^4 + W^2 F^2 + Z^2 F^2) && \text{9. quartic interaction}\\
& +\tfrac{1}{2}(\partial^\mu H)(\partial_\mu H) - \tfrac{1}{2} m_H^2 H^2 && \text{10. Higgs boson mass}\\
& -\tfrac{g m_H^2}{4 m_W} H^3 - \tfrac{g^2 m_H^2}{32 m_W^2} H^4 && \text{11. Higgs self-interaction}\\
& +(g m_W H + \tfrac{g^2}{4} H^2)(W^+_\mu W^{-\mu} + \tfrac{1}{2\cos^2\theta_w} Z_\mu Z^\mu) && \text{12. Higgs–W and Z int.}
\end{aligned} \tag{98}$$

The terms in the Lagrangian are easily associated to the Feynman diagrams of Figure 148:

1. this term describes the inertia of every object around us, yields the motion of fermions, and represents the kinetic energy of the quarks and leptons, as it appears in the usual Dirac equation, modified by the so-called *Yukawa coupling* to the Higgs field H and possibly by a Majorana term for the neutrinos (not shown);

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Sakata mixing matrix or *PMNS mixing matrix*, with 4 angles for massive neutrinos (it would have 6 angles if neutrinos were massless). In 2012, the measured matrix values were

$$P = \begin{pmatrix} 0.82 & 0.55 & -0.15 + 0.038i \\ -0.36 + 0.020i & 0.70 + 0.013i & 0.61 \\ 0.44 + 0.026i & -0.45 + 0.017i & 0.77 \end{pmatrix} . \quad (94)$$

Many experiments are trying to measure these parameters with higher precision.

Symmetry breaking – and the lack of electroweak unification

The intermediate W and Z bosons are massive and their masses differ. Thus, the weak interaction does not show a SU(2) symmetry. In addition, electromagnetic and weak processes *mix*.

Beautiful research in the 1960s showed that the mixing of the electromagnetic and the weak interactions can be described by an *'electroweak' coupling constant* g and a *weak mixing angle* θ_W. The mixing angle describes the strength of the breaking of the SU(2) symmetry.

Ref. 186

It needs to be stressed that in contrast to what is usually said and written, the weak and the electromagnetic interactions do *not* unify. They have *never* been unified. Despite the incessant use of the term '*electroweak* unification' since several decades, the term is *wrong*. The electromagnetic and the weak interactions are two independent interactions, with two coupling constants, that *mix*. But they do not unify. Even though the Nobel Prize committee used the term 'unification', the relevant Nobel Prize winners confirm that the term is *not correct*.

▷ The electromagnetic and the weak interaction have *not* been unified. Their mixing has been elucidated.

The usual electromagnetic coupling constant e is related to the 'electroweak' coupling g and the mixing angle θ_w by

$$e = g \sin \theta_w \,, \quad (95)$$

which at low four-momentum transfers is the fine structure constant with the value 1/137.036. The electroweak coupling constant g also defines the historically defined *Fermi constant* G_F by

$$G_F = \frac{g^2 \sqrt{2}}{8 M_W^2} \,. \quad (96)$$

The broken SU(2) symmetry implies that in the *real* world, in contrast to the *ideal* SU(2) world, the intermediate vector bosons are

— the massless, neutral photon, given as $A = B \cos\theta_W + W^3 \sin\theta_W$;
— the massive neutral Z boson, given as $Z = -B \sin\theta_W + W^3 \cos\theta_W$;
— the massive charged W bosons, given as $W^\pm = (W^1 \mp iW^2)/\sqrt{2}$.

Together, the mixing of the electromagnetic and weak interactions as well as the breaking

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

reason for it: massless particles do not experience time, as their paths are 'null'. A particle that does not experience time cannot have a half-life. (Can you find another argument?)

Challenge 133 s

* *

High energy radiation is dangerous to humans. In the 1950s, when nuclear tests were still made above ground by the large armies in the world, the generals overruled the orders of the medical doctors. They positioned many soldiers nearby to watch the explosion, and worse, even ordered them to walk to the explosion site as soon as possible after the explosion. One does not need to comment on the orders of these generals. Several of these unlucky soldiers made a strange observation: during the flash of the explosion, they were able to see the bones in their own hand and arms. How can this be?

Challenge 134 s

* *

In 1958, six nuclear bombs were made to explode in the stratosphere by a vast group of criminals. A competing criminal group performed similar experiments in 1961, followed by even more explosions by both groups in 1962. (For reports and films, see en.wikipedia.org/wiki/High_altitude_nuclear_explosion.) As a result of most of these explosions, an *artificial aurora* was triggered the night following each of them. In addition, the electromagnetic pulse from the blasts destroyed satellites, destroyed electronics on Earth, disturbed radio communications, injured people on the surface of the Earth, caused problems with power plants, and distributed large amounts of radioactive material over the Earth – during at least 14 years following the blasts. The van Allen radiation belts around the Earth were strongly affected; it is expected that the lower van Allen belt will recover from the blasts only in a few hundred years. Fortunately for the human race, after 1962, this activity was stopped by international treaties.

* *

Nuclear bombs are terrible weapons. To experience their violence but also the criminal actions of many military people during the tests, have a look at the pictures of explosions. In the 1950s and 60s, nuclear tests were performed by generals who refused to listen to doctors and scientists. Generals ordered to explode these weapons in the air, making the complete atmosphere of the world radioactive, hurting all mankind in doing so; worse, they even obliged soldiers to visit the radioactive explosion site a few minutes after the explosion, thus doing their best to let their own soldiers die from cancer and leukaemia. Generals are people to avoid.

Ref. 170

* *

Several radioactive dating methods are used to date wine, and more are in development. A few are included in Table 14.

Page 183

* *

A few rare radioactive decay times can be changed by external influence. Electron capture, as observed in beryllium-7, is one of the rare examples were the decay time can change, by up to 1.5 %, depending on the chemical environment. The decay time for the same isotope has also been found to change by a fraction of a per cent under pressures

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

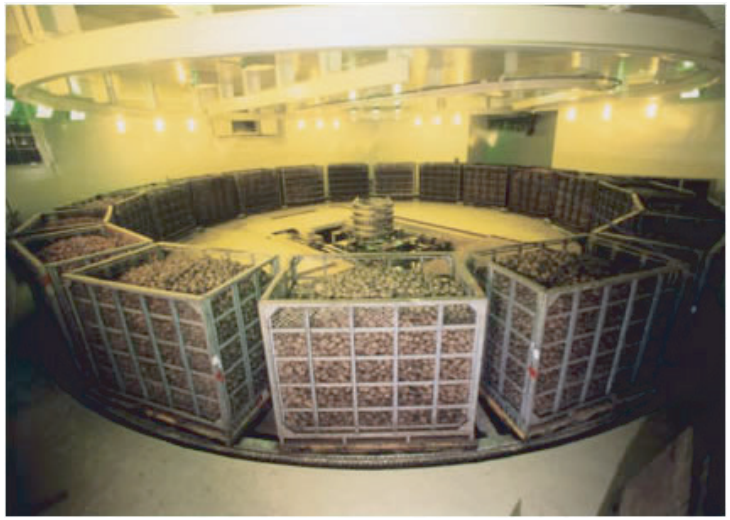


FIGURE 115 Potatoes being irradiated at the Shihorocho Agricultural Cooperative Isotope Irradiation Center in Japan. Good appetite!

of 27 GPa. On the other hand, these effects are predicted (and measured) to be negligible for nuclei of larger mass. A few additional nuclides show similar, but smaller effects. Ref. 159

The most interesting effect on nuclei is laser-induced fissioning of ^{238}U, which occurs for very high laser intensities. Page 259

* *

Both γ radiation and neutron radiation can be used to image objects without destroying them. γ rays have been used to image the interior of the Tutankhamun mask. Neutron radiation, which penetrates metals as easily as other materials, has been used to image, even at film speed, the processes inside car engines.

* *

γ rays are used in Asia to irradiate food. This is forbidden other countries, such as Germany. For example, γ rays are used to irradiate potatoes, in order to prevent sprouting. An example is given in Figure 115. It is better not to work there. In fact, over 30 countries allowed the food industry to irradiate food. For example, almost all spice in the world are treated with γ rays, to increase their shelf life. However, the consumer is rarely informed about such treatments.

* *

β rays with 10 MeV and γ rays are used in many large factories across the world to sterilize

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

First of all, it turns out that the quarks appearing in Figure 148 are not those of the strong interaction: there is a slight difference, due to *quark mixing*. Secondly, also *neutrinos mix*. And thirdly, the vector bosons are massive and break the SU(2) symmetry of the imagined idealized world; the Lie group SU(2) is not an exact symmetry of the weak interaction, and the famous Higgs boson has mass. We now explore these aspects in this order.

Surprisingly, the weak interaction eigenstates of the quarks are not the same as the mass eigenstates. This discovery by Nicola Cabibbo is described by the so-called Cabibbo–Kobayashi–Maskawa or CKM mixing matrix. The matrix is defined by

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = (V_{ij}) \begin{pmatrix} d \\ s \\ b \end{pmatrix} . \tag{91}$$

where, by convention, the states of the +2/3 quarks (u, c, t) are unmixed. In its standard parametrization, the CKM matrix reads

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \tag{92}$$

where $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ and i and j label the generation ($1 \leqslant i, j \leqslant 3$). In the limit $\theta_{23} = \theta_{13} = 0$, i.e., when only two generations mix, the only remaining parameter is the angle θ_{12}, called the *Cabibbo angle*, which was introduced when only the first two generations of fermions were known. The phase δ_{13}, lying between 0 and 2π, is different from zero in nature, and expresses the fact that CP invariance is violated in the case of the weak interactions. It appears in the third column and shows that CP violation is related to the existence of (at least) three generations.

The CP violating phase δ_{13} is usually expressed with the *Jarlskog invariant*, defined as $J = \sin\theta_{12}\sin\theta_{13}\sin\theta_{23}^2\cos\theta_{12}\cos\theta_{13}\cos\theta_{23}\sin\delta_{13}$. This expression is independent of the definition of the phase angles; it was discovered by Cecilia Jarlskog, an important Swedish particle physicist. Its measured value is $J = 2.96(20) \cdot 10^{-5}$. Ref. 207

The CKM mixing matrix is predicted to be unitary. The unitarity has been confirmed by all experiments so far. The 90 % confidence upper and lower limits for the *magnitude* of the complex CKM matrix V are given by Ref. 186

$$|V| = \begin{pmatrix} 0.97428(15) & 0.2253(7) & 0.00347(16) \\ 0.2252(7) & 0.97345(16) & 0.0410(11) \\ 0.00862(26) & 0.0403(11) & 0.999152(45) \end{pmatrix} . \tag{93}$$

The values have been determined in dozens of experiments by thousands of physicists.

Also neutrinos mix, in the same way as the d, s and b quarks. The determination of the matrix elements is not as complete as for the quark case. This is an intense research field. Like for quarks, also for neutrinos the mass eigenstates and the flavour eigenstates differ. There is a dedicated neutrino mixing matrix, called the *Pontecorvo–Maki–Nakagawa–*

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

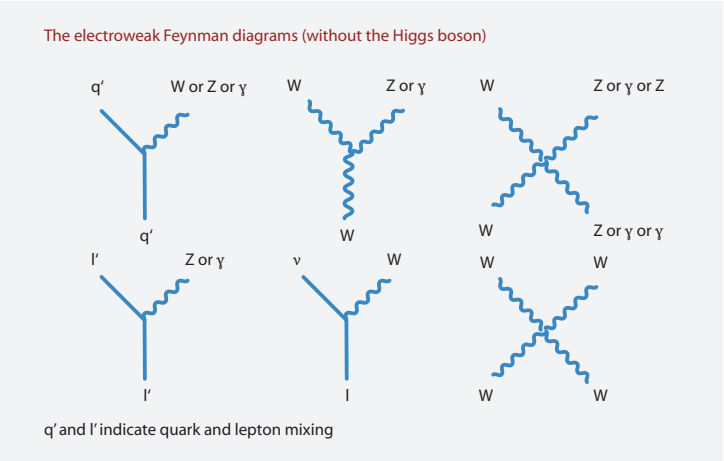


FIGURE 148 The essence of the electroweak interaction Lagrangian.

has also been observed in neutral B mesons, in several different processes and reactions. The search for other manifestations of CP violation, such as in non-vanishing electric dipole moments of elementary particles, is an intense research field. The search is not simple because CP violation is a small effect in an already very weak interaction; this tends to makes experiments large and expensive.

Since the weak interaction violates CP invariance, it also violates motion (or time) reversal T.

▷ But like all gauge theories, the weak interaction does not violate the combined CPT symmetry: it is CPT invariant.

If CPT would be violated, the masses, lifetimes and magnetic moments of particles and antiparticles would differ. That is not observed.

Weak charge and mixings

All weak interaction processes can be described by the Feynman diagrams of Figure 148. But a few remarks are necessary. First of all, the W and Z act only on left-handed fermion and on right-handed anti-fermions. Secondly, the weak interaction conserves a so-called *weak charge* T_3, also called *weak isospin*. The three quarks u, c and t, as well as the three neutrinos, have weak isospin $T_3 = 1/2$; the other three quarks and the charged leptons have weak isospin $T_3 = -1/2$. In an idealized, SU(2)-symmetric world, the three vector bosons W^+, W^0, W^- would have weak isospin values $1, 0$ and -1 and be massless. However, a few aspects complicate the issue.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

medical equipment, medical devices, toys, furniture and also to kill moulds in books and in animal food. (See www.bgs.eu for an example.)

* *

The non-radioactive isotopes ^{2}H – often written simply D – and ^{18}O can be used for measuring energy production in humans in an easy way. Give a person a glass of doubly labelled water to drink and collect his urine samples for a few weeks. Using a mass spectrometer one can determine his energy consumption. Why? Doubly labelled water $^2H_2{}^{18}O$ is processed by the body in three main ways. The oxygen isotope is expired as $C^{18}O_2$ or eliminated as $H_2{}^{18}O$; the hydrogen isotope is eliminated as ^2H_2O. Measurements on the urine allow one to determine carbon dioxide production, therefore to determine how much has food been metabolized, and thus to determine energy production.

Human energy consumption is usually given in joule per day. Measurements showed that high altitude climbers with 20 000 kJ/d and bicycle riders with up to 30 000 kJ/d are the most extreme sportsmen. Average humans produce 6 000 kJ/d.

* *

The percentage of the ^{18}O isotope in the water of the Earth's oceans can be used to deduce where the water came from. This was told in the first volume of our adventure.

Vol. I, page 368

* *

Many nuclei oscillate in shape. The calculation of these shape oscillations is a research subject in itself. For example, when a spherical nucleus oscillates, it can do so in three mutually orthogonal axes. A spherical nucleus, when oscillating at small amplitudes, thus behaves like a three-dimensional harmonic oscillator. Interestingly, the symmetry of the three-dimensional harmonic oscillator is SU(3), the same symmetry that characterizes the strong nuclear interaction. However, the two symmetries are unrelated – at least following present knowledge. A relation might appear in the future, though.

Vol. VI, page 273

Summary on nuclei

Atomic nuclei are composed of protons and neutrons. Their diameter is between one and a few femtometres, and they have angular momentum. Their angular momentum, if larger than zero, allows us to produce magnetic resonance images. Nuclei can be spherical or ellipsoidal, they can be excited to higher energy states, and they can oscillate in shape. Nuclei have colours that are determined by their spectra. Nuclei can decay, can scatter, can break up and can react among each other. Nuclear reactions can be used to make bombs, power plants, generate biological mutations and to explore the human body. And as we will discover in the following, nuclear reactions are at the basis of the working of the Sun and of our own existence.



Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Chapter 6

THE SUN, THE STARS AND THE BIRTH OF MATTER

> Lernen ist Vorfreude auf sich selbst.**
>
> Peter Sloterdijk

Nuclear physics is the most violent part of physics. But despite this bad image, nuclear physics has also something fascinating to offer: by exploring nuclei, we learn to understand the Sun, the stars, the early universe, the birth of matter and our own history. Ref. 172

Nuclei consist of protons and neutrons. Since protons are positively charged, they repel each other. Inside nuclei, protons must be bound by a force strong enough to keep them together against their electromagnetic repulsion. This is the *strong nuclear interaction*; it is needed to avoid that nuclei explode. The strong nuclear interaction is the strongest of the four interactions in nature – the others being gravitation, electromagnetism and the weak nuclear interaction. Despite its strength, we do not experience the strong nuclear interaction in everyday life, because its range is limited to distances of a few femtometres, i.e., to a few proton diameters. Despite this limitation, the strong interaction tells a good story about the burning of the Sun and about the flesh and blood we are made of.

The Sun

At present, the Sun emits 385 YW of light. The amount was first measured by Claude Pouillet at the start of the nineteenth century. The power would be sufficient to melt away, every year, a volume of ice 500 times larger than the volume of the Earth. Challenge 135 e

Where does the huge energy emitted by the Sun come from? If it came from burning coal, the Sun would stop burning after a few thousands of years. When radioactivity was discovered, researchers tested the possibility that this process might be at the heart of the Sun's shining. However, even though radioactivity – or the process of fission that was discovered later – is able to release more energy than chemical burning, the composition of the Sun – mostly hydrogen and helium – makes this impossible.

The origin of the energy radiated by the Sun was clarified in 1929 by Fritz Houtermans, Carl Friedrich von Weiszäcker, and Hans Bethe: the Sun burns by *hydrogen fusion*. Fusion is the composition of a large nucleus from smaller ones. In the Sun, the central fusion reaction Ref. 173

$$4\,{}^{1}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + 2\,e^{+} + 2\,\nu + 4.4\,\mathrm{pJ} \qquad (61)$$

** 'Learning is anticipated joy about yourself.'

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

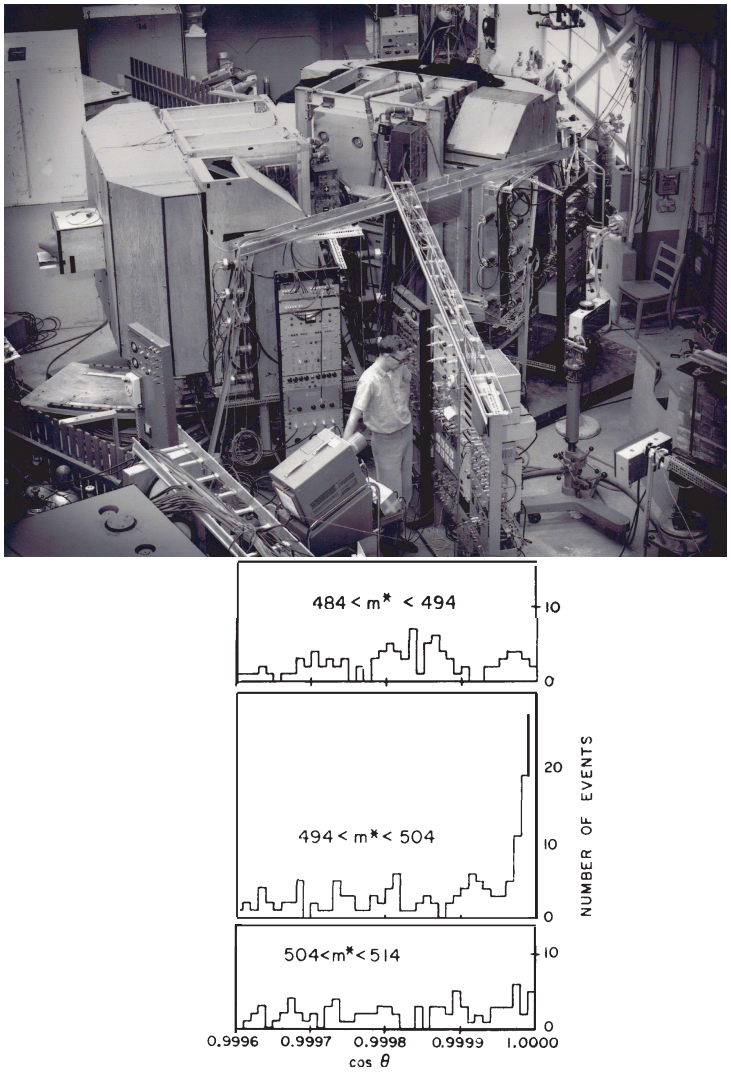


FIGURE 147 Top: the experimental set-up for measuring the behaviour of neutral K meson decay. Bottom: the measured angular dependence; the middle graph shows a peak at the right side that would not appear if CP symmetry would not be violated (© Brookhaven National Laboratory, Nobel Foundation).

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

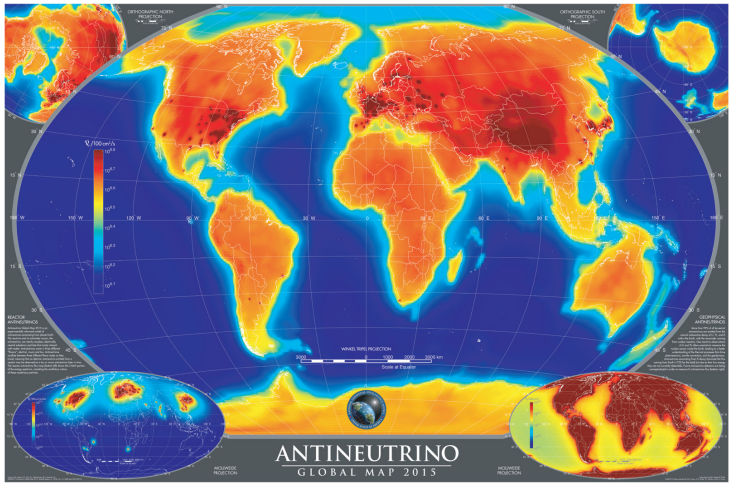


FIGURE 146 A map of the intensity distribution of the $3(2) \cdot 10^{25}$ antineutrinos between 0 and 11 MeV radiated every second from the Earth. Around 99 % of the flux is from natural sources and around 1 % from civil and military nuclear processing plants and reactors. The map is from www.nga.mil, thus cannot be completely trusted about the human sources.

Distinguishing particles and antiparticles, CP violation

In the weak interaction, the observation that only right-handed particles and left-handed antiparticles are affected has an important consequence: it implies a violation of charge conjugation parity C. Observations of muons into electrons shows this most clearly: anti-muon decay differs from muon decay. The weak interaction distinguishes particles from antiparticles.

Challenge 147 e

▷ Experiments show that C parity, like P parity, is *maximally violated* in the weak interaction.

Also this effect has been confirmed in all subsequent observations ever performed on the weak interaction. But that is not all. In 1964, a now famous observation was made by Val Fitch and James Cronin in the decay of the neutral K mesons.

▷ The weak interaction also violates the combination of parity inversion with particle-antiparticle symmetry, the so-called CP invariance. In contrast to P violation and C violation, which are maximal, CP violation is a tiny effect.

The experiment, shown in Figure 147 earned them the Nobel Prize in 1980. CP violation

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

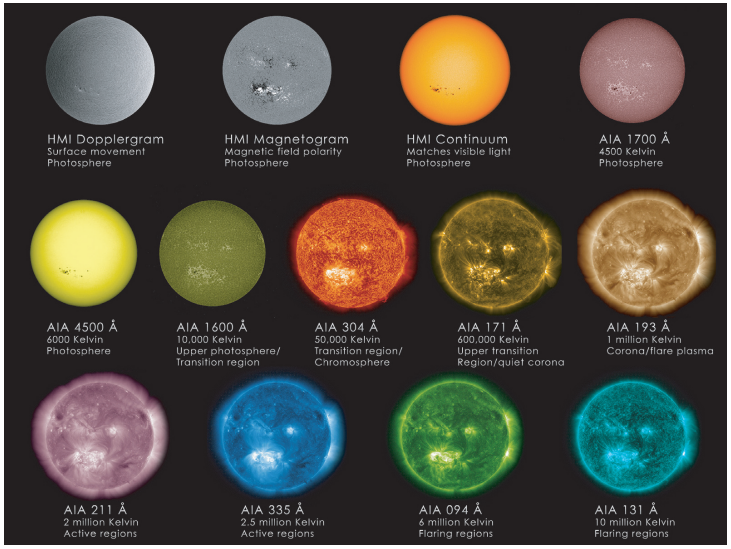


FIGURE 116 The Sun emits radiation at different wavelengths. Note that almost all images are shown in a single, false colour selected just for visual appeal. The collections does not show the radio wave images, which also show the solar spots, but with much lower resolution. (Courtesy NASA)

converts hydrogen nuclei into helium nuclei. The reaction is called the *hydrogen–hydrogen cycle* or *p–p cycle*. The hydrogen cycle is the result of a continuous cycle of three separate nuclear reactions:

$$\begin{aligned} \mathrm{p} + \mathrm{p} &\to \mathrm{d} + e^+ + \nu \quad \text{(a weak nuclear reaction involving the deuteron)} \\ \mathrm{d} + \mathrm{p} &\to {}^3\mathrm{He} + \gamma \quad \text{(a strong nuclear reaction)} \\ {}^3\mathrm{He} + {}^3\mathrm{He} &\to \alpha + 2\,\mathrm{p} + \gamma\,. \end{aligned} \tag{62}$$

We can also write the p-p cycle as

$$\begin{aligned} {}^1\mathrm{H} + {}^1\mathrm{H} &\to {}^2\mathrm{H} + e^+ + \nu \quad \text{(a weak nuclear reaction)} \\ {}^2\mathrm{H} + {}^1\mathrm{H} &\to {}^3\mathrm{He} + \gamma \quad \text{(a strong nuclear reaction)} \\ {}^3\mathrm{He} + {}^3\mathrm{He} &\to {}^4\mathrm{He} + 2\,{}^1\mathrm{H} + \gamma\,. \end{aligned} \tag{63}$$

In total, four protons are thus fused to one helium nucleus, or alpha particle; if we include the electrons, we can say that four hydrogen atoms are fused to one helium atom. The fusion process emits neutrinos and light with a total energy of 4.4 pJ (26.7 MeV). This is

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

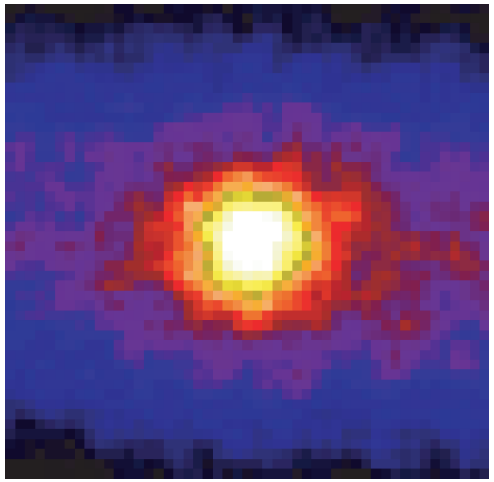


FIGURE 117 The Sun also emits neutrinos. Their intensities are shown here in a false colour image, taken through the whole Earth from an underground experiment, with a 503-day exposure, at energies from 7 to 25 MeV. However, due to scattering processes, the bright spot is several times the size of the Sun. (© Robert Svoboda)

the energy that makes the Sun shine. Most of the energy is emitted as light; around 10 % is carried away by neutrinos. The latter part is illustrated in Figure 117.

The first of the three reactions of equation (62) is due to the weak nuclear interaction. This transmutation and the normal β decay have the same first-order Feynman diagram.

Challenge 136 e The weak interaction avoids that fusion happens too rapidly and ensures that the Sun will shine still for some time. Indeed, in the Sun, with a luminosity of 385 YW, there are

Ref. 174 thus only 10^{38} fusions per second. This allows us to deduce that the Sun will last another handful of Ga (Gigayears) before it runs out of fuel.

The simplicity of the hydrogen-hydrogen cycle does not fully purvey the fascination of the process. On average, protons in the Sun's centre move with 600 km/s. Only if they hit each other precisely head-on can a nuclear reaction occur; in all other cases, the electrostatic repulsion between the protons keeps them apart. For an average proton, a head-on collision happens once every 7 thousand million years! Nevertheless, there are so many proton collisions in the Sun that every second four million tons of hydrogen are burned to helium. The second reaction of the proton cycle takes a few seconds and the third about one million years.

The fusion reaction (62) takes place in the centre of the Sun, in the so-called *core*. Fortunately for us, the high energy γ photons generated in the Sun's centre are 'slowed' down by the outer layers of the Sun, namely the *radiation zone*, the *convection zone* with its involved internal motion, and the so-called *photosphere*, the thin layer we actually see. The last layer, the atmosphere, is not visible during a day, but only during an eclipse, as shown in Figure 120. More precisely, the solar atmosphere consists of the *temperature minimum*, the *chromosphere*, the *transition region*, the *corona* and the *heliosphere*.

During the elaborate slowing-down process inside the Sun, the γ photons are pro-

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

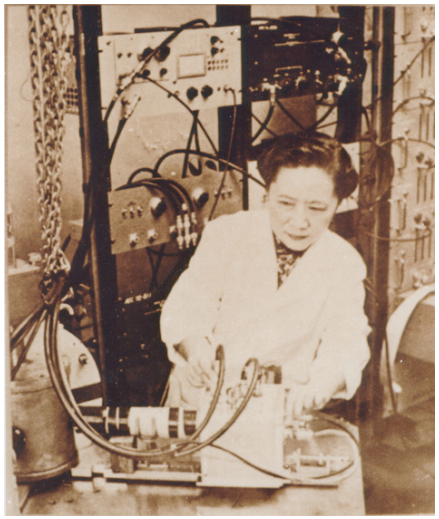


FIGURE 145 Wu Chien-Shiung (1912–1997) at her parity-violation experiment.

process allows electron transitions which are impossible by purely electromagnetic effects. In 1984, measurements confirmed that certain optical transitions of caesium atoms that are impossible via the electromagnetic interaction, are allowed when the weak interaction is taken into account. Several groups have improved these results and have been

Ref. 205 able to confirm the calculations based on the weak interaction properties, including the

Ref. 206 weak charge of the nucleus, to within a few per cent.

The weak interaction thus allows one to distinguish left from right. Nature contains processes that differ from their mirror version. In short, particle physics has shown that nature is (weakly) left-handed.

The left-handedness of nature is to be taken literally. All experiments confirmed two

Challenge 146 e central statements on the weak interaction that can be already guessed from Figure 144.

- ▷ The weak interaction only couples to left-handed particles and to right-handed antiparticles. Parity is *maximally violated* in the weak interaction.

- ▷ All neutrinos observed so far are left-handed, and all antineutrinos are right-handed.

This result can only hold if neutrino masses vanish or are negligibly small. These two experimental results fix several aspects of the Lagrangian of the weak interaction.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

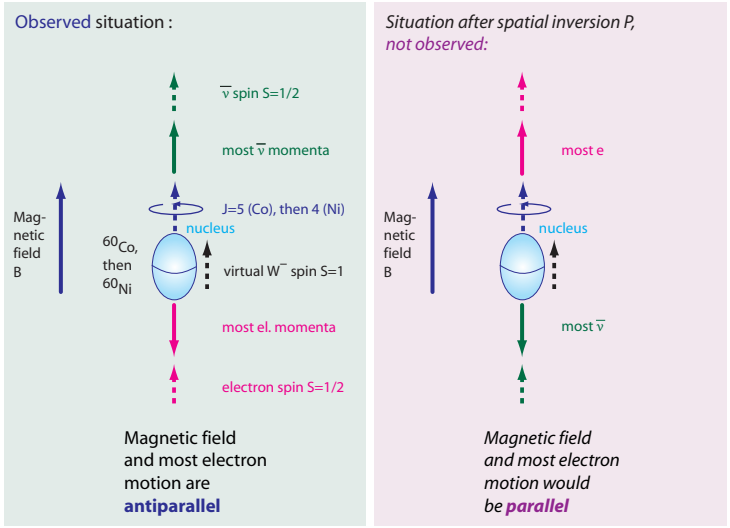


FIGURE 144 The measured behaviour of β decay, and its imagined, but unobserved behaviour under spatial inversion P (corresponding to a mirror reflection plus subsequent rotation by π around an axis perpendicular to the mirror plane).

nuclei aligned along a magnetic field, the electrons are emitted mostly *against* the spin of the nuclei. In the experiment with inversed parity, the electrons would be emitted *along* the spin direction; however, this case is not observed. Parity is violated. This earned Lee and Yang a Nobel Prize in 1957.

Parity is thus violated in the weak interaction. Parity violation does not only occur in β decay. Parity violation has been found in muon decay and in every other weak process studied so far. In particular, when two electrons collide, those collisions that are mediated by the weak interaction behave differently in a mirror experiment. The number of
Ref. 203 experiments showing this increases from year to year. In 2004, two polarized beams of electrons – one left-handed and one right-handed – were shot at a matter target and the reflected electrons were counted. The difference was 0.175 parts per million – small, but measurable. The experiment also confirmed the predicted weak charge of −0.046 of the electron.

Ref. 204 A beautiful consequence of parity violation is its influence on the *colour* of certain atoms. This prediction was made in 1974 by Bouchiat and Bouchiat. The weak interaction is triggered by the weak charge of electrons and nuclei; therefore, electrons in atoms do not exchange only virtual photons with the nucleus, but also virtual Z particles. The chance for this latter process is extremely small, around 10^{-11} times smaller than for exchange of virtual photons. But since the weak interaction is not parity conserving, this

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 118 A photograph of the Sun at a visible wavelength of around 677 nm, by the SOHO space probe, showing a few sunspots (ESA and NASA).

gressively converted to visible photons, mainly through scattering. Scattering takes time. In the Sun, it takes along time: the sunlight of today was in fact generated at the time of
Ref. 175 the Neandertals: a typical estimate is about 170 000 years ago. In other words, the average effective speed of light inside the Sun is estimated to be around 300 km/year! After these one hundred and seventy thousand years, the photons take another 8.3 minutes to reach the Earth and to sustain the life of all plants and animals.

Motion in and on the Sun

Vol. III, page 146 In its core, the Sun has a temperature of around 15 MK. At its surface, the temperature is around 5.8 kK. (Why is it cooler?) Since the Sun is cooler on its surface than in its centre, the Sun is not a homogeneous ball, but an inhomogeneous structure. If you want to experience the majestic beauty of the Sun, watch the stunning video www.youtube.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

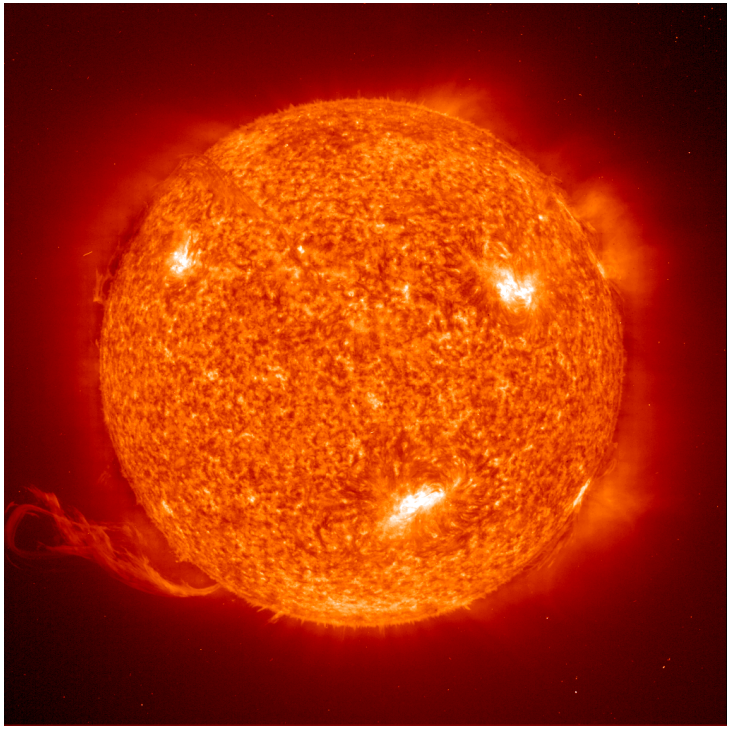


FIGURE 119 A photograph of the Sun at the extreme ultraviolet wavelength of 30.4 nm, thus in false colour, again by the SOHO space probe, showing solar prominences (ESA and NASA).

com/watch?v=ipvfwPqh3V4 that shows the Sun's surface over a two-week period. The inhomogeneity of the Sun's structure and surface is due to the convection processes induced by the temperature gradient. The convection, together with the rotation of the Sun around its axis, leads to fascinating structures that are shown in Figure 119 and the following ones: *solar eruptions*, including flares and coronal mass ejections, and *solar spots*.

In short, the Sun is not a static object. The matter in the Sun is in constant motion. An impressive way to experience the violent processes it contains is to watch the film shown in Figure 122, which shows the evolution of a so-called *solar flare*. Many solar eruptions, such as those shown in the lower left corner in Figure 119 or in Figure 123, eject matter far into space. When this matter reaches the Earth,* after being diluted by the journey, it affects our everyday environment. Such *solar storms* can deplete the higher atmosphere

* It might also be that the planets affect the solar wind; the issue is not settled and is still under study.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

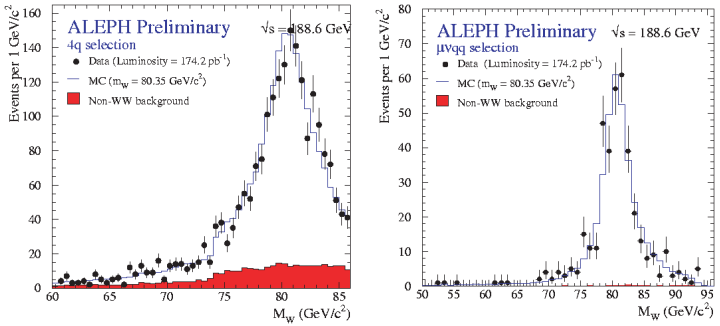


FIGURE 143 A measurement of the W boson mass at LEP (© CERN)

temper made his secretaries leave, on average, after three weeks, and the chief technologist, Simon van der Meer, received the 1984 Nobel Prize in Physics for the discovery. This again confirmed the 'law' of nature that bosons are discovered in Europe and fermions in America. The simplest data that show the Z and W bosons is shown in Figure 142 and Figure 143; both results are deduced from the cross section of electron-positron collisions at LEP, a decade after the original discovery.

In the same way that photons are emitted by accelerated electric charges, W and Z bosons are emitted by accelerated weak charges. Due to the high mass of the W and Z bosons, the required accelerations are very high, so that they are only found in certain nuclear decays and in particle collisions. Nevertheless, the W and Z bosons are, apart from their mass and their weak charge, similar to the photon in most other aspects. In particular, the W and the Z are observed to be elementary. For example, the W gyromagnetic ratio has the value predicted for elementary particles.

Ref. 186

Distinguishing left from right

Another weird characteristic of the weak interaction is the non-conservation of parity P under spatial inversion. The weak interaction distinguishes between mirror systems; this is in contrast to everyday life, to gravitation, to electromagnetism, and to the strong interaction. The non-conservation of parity by the weak interaction had been predicted by 1956 by Lee Tsung-Dao and Yang Chen Ning in order to explain the ability of K^0 mesons to decay sometimes into 2 pions, which have even parity, and sometimes into 3 pions, which have odd parity.

Ref. 202

Lee and Yang suggested an experiment to Wu Chien-Shiung* The experiment she performed with her team is shown schematically in Figure 144. A few months after the first meetings with Lee and Yang, Wu and her team found that in the β decay of cobalt

* Wu Chien-Shiung (b. 1912 Shanghai, d. 1997 New York) was called 'madame Wu' by her colleagues. She was a bright and driven physicist born in China. She worked also on nuclear weapons; later in life she was president of the American Physical Society.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



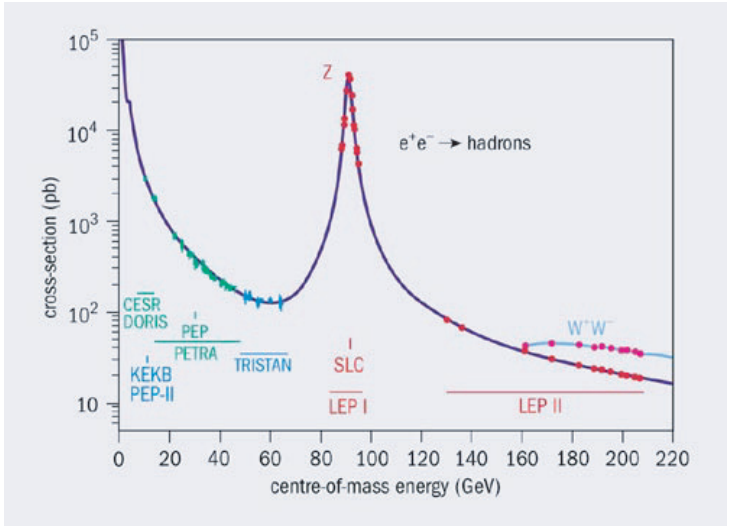
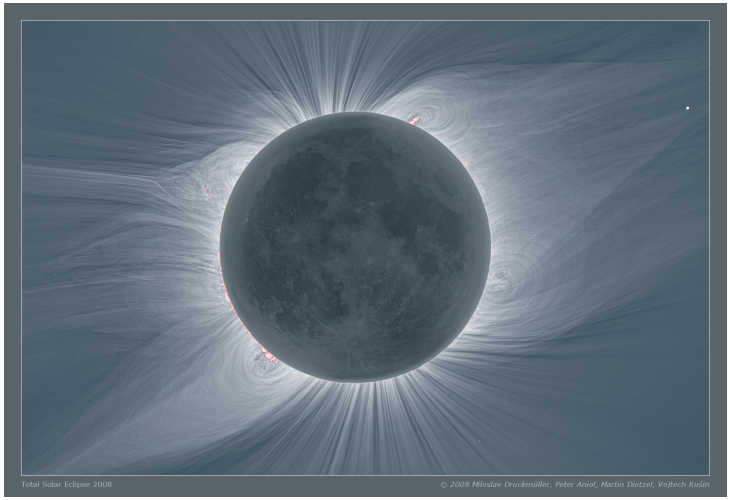


FIGURE 142 Top: the SPS, the proton–antiproton accelerator and collider at CERN, with 7 km circumference, that was used to make the first observations of real W and Z bosons. Bottom: the beautifully simple Z observation made with LEP, the successor machine (© CERN)

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



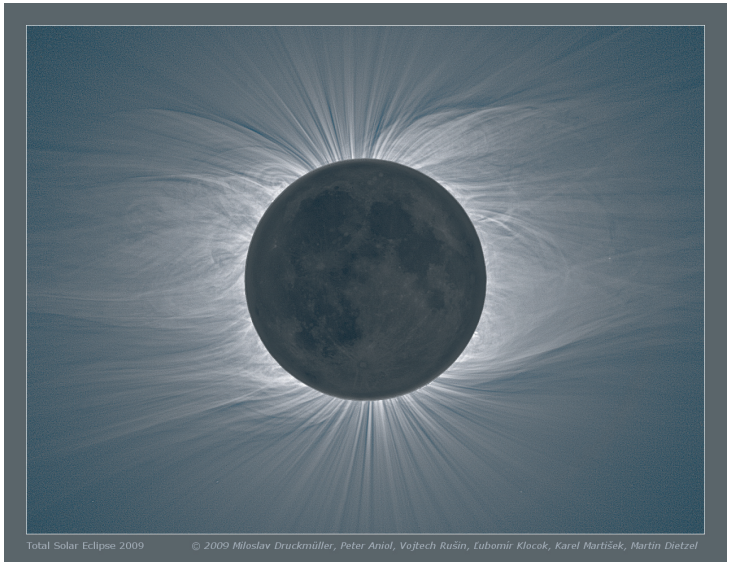


FIGURE 120 The complex details of corona of the Sun, photographed during the 2008 eclipse in Bor Udzuur in Mongolia and the 2009 eclipse on the Marshall islands. The images are digital compositions of several dozen photographs chosen to reproduce as closely as possible the experience of looking at the eclipse through a small telescope. The first image includes protuberances. The structures also allow to locate the solar poles. (Top image © Miloslav Druckmüller, Martin Dietzel, Peter Aniol, Vojtech Rušin; bottom image © Miloslav Druckmüller, Peter Aniol, Vojtech Rušin, Ľubomír Klocok, Karel Martišek and Martin Dietzel)

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

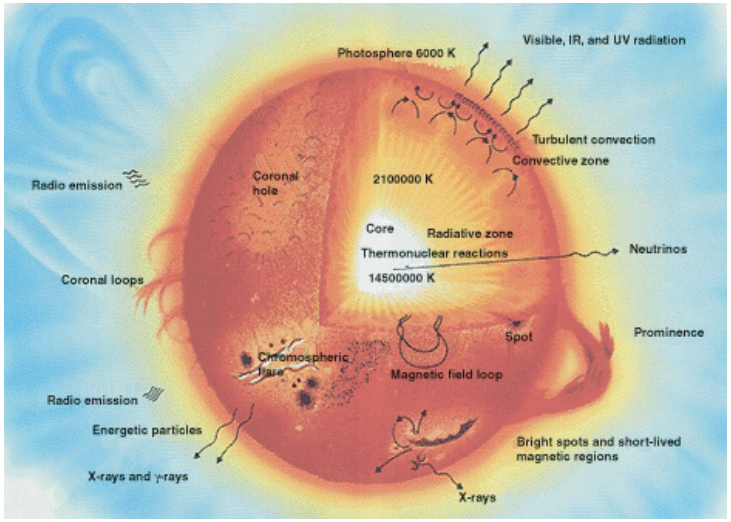


FIGURE 121 A drawing of the interior of the Sun (courtesy NASA).

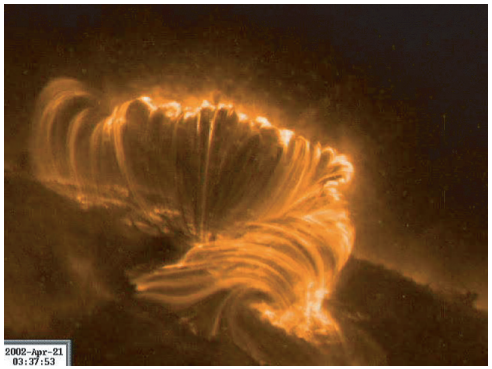


FIGURE 122 The evolution of a solar flare observed by the TRACE satellite (QuickTime film courtesy NASA).

and can thus possibly even trigger usual Earth storms. Other effects of solar storms are the formation of auroras and the loss of orientation of birds during their migration; this happens during exceptionally strong solar storms, because the magnetic field of the Earth

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 20 The intermediate vector bosons of the weak interaction (the Z boson is its own antiparticle; the W boson has an antiparticle of opposite charge).

BOSON	MASS m	SPIN J	COLOUR; WEAK BEHAVIOUR	CHARGE Q, ISOSPIN I, STRANGENESS S, CHARM C, BEAUTY B', TOPNESS T	LEPTON NUMBER L, BARYON NUMBER B
Z boson	91.1876(21) GeV/c^2	1	white; 'triplet'	0, 0, 0, 0, 0, 0	0, 0
W boson	80.398(25) GeV/c^2	1	white; 'triplet'	1, 0, 0, 0, 0, 0	0, 0

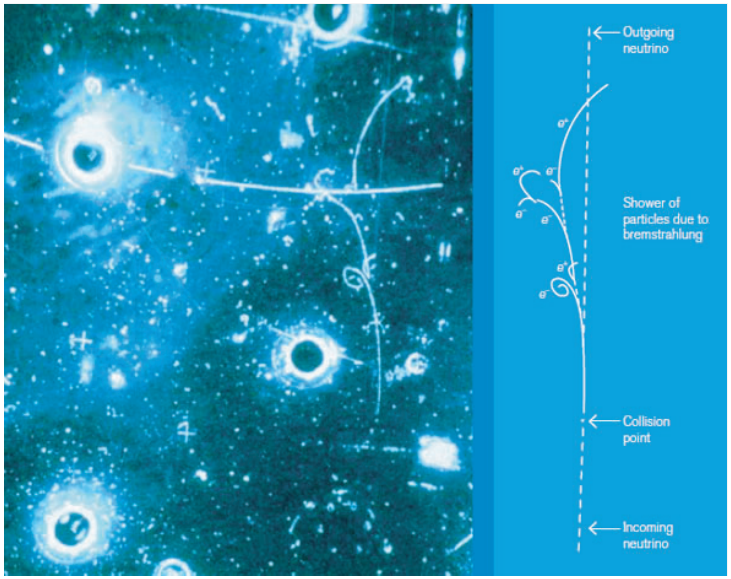


FIGURE 141 The first observation of a virtual Z boson: only neutral weak currents allow that a neutrino collides with an electron in the bubble chamber and leaves again (© CERN).

famous one is shown in Figure 141.

In 1983, CERN groups produced and detected the first *real* W and Z bosons. This experiment was a five-year effort by thousands of people working together. The results are summarized in Table 20. The energetic manager of the project, Carlo Rubbia, whose bad

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 19 The leptons: the three neutrinos and the three charged leptons (antiparticles have opposite charge Q and parity P).

NEUTRINO	MASS m AND DECAY (SEE TEXT)	SPIN J PARITY P	COLOUR; POSSIBLE WEAK BEHAVIOUR	CHARGE Q, ISOSPIN I, STRANGENESS S, CHARM C, BEAUTY B', TOPNESS T	LEPTON NUMBER L, BARYON NUMBER B
Electron neutrino ν_e	$< 2\,\mathrm{eV}/c^2$, oscillates	$\frac{1}{2}^+$	white; singlet, doublet	0, 0, 0, 0, 0, 0	1, 0
Muon neutrino ν_e	$< 2\,\mathrm{eV}/c^2$, oscillates	$\frac{1}{2}^+$	white; singlet, doublet	0, 0, 0, 0, 0, 0	1, 0
Tau neutrino ν_e	$< 2\,\mathrm{eV}/c^2$, oscillates	$\frac{1}{2}^+$	white; singlet, doublet	0, 0, 0, 0, 0, 0	1, 0
Electron e	0.510 998 928(11) MeV/c^2, stable	$\frac{1}{2}^+$	white; singlet, doublet	−1, 0, 0, 0, 0, 0	1, 0
Muon μ	105.658 3715(35) MeV/c^2, *c.* 99 % $e\overline{\nu}_e\nu_\mu$	$\frac{1}{2}^+$	white; singlet, doublet	−1, 0, 0, 0, 0, 0	1, 0
Tau τ	1.776 82(16) GeV/c^2, *c.* 17 % $\mu\overline{\nu}_\mu\nu_\tau$, *c.* 18 % $e\overline{\nu}_e\nu_\tau$	$\frac{1}{2}^+$	white; singlet, doublet	−1, 0, 0, 0, 0, 0	1, 0

Together, the W and Z bosons are also called the *weak vector bosons*, or the *weak intermediate bosons*.

The masses of the weak vector bosons are so large that free weak radiation exists only for an extremely short time, about 0.1 ys; then the bosons decay. The large mass is the reason that the weak interaction is extremely short range and thus extremely weak. Indeed, any exchange of virtual carrier particles scales with the negative exponential of the intermediate particle's mass. A few additional properties are given in Table 20. In fact, the weak interaction is so weak that neutrinos, particles which interact *only* weakly, have a large probability to fly through the Sun without any interaction.

The existence of a massive charged intermediate vector boson, today called the W, was already deduced and predicted in the 1940s; but theoretical physicists did not accept the idea until the Dutch physicists Martin Veltman and Gerard 't Hooft proved that it was possible to have such a mass without having problems in the rest of the theory. For this proof they later received the Nobel Prize in Physics – after experiments confirmed their prediction.

The existence of an additional massive *neutral* intermediate vector boson, the Z boson, was predicted only much after the W boson, by Salam, Weinberg and Glashow. Experimentally, the Z boson was first observed as a *virtual* particle in 1973 at CERN in Geneva. The discovery was made by looking, one by one, at over 700 000 photographs made at the Gargamelle bubble chamber. Only a few interesting pictures were found; the most

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

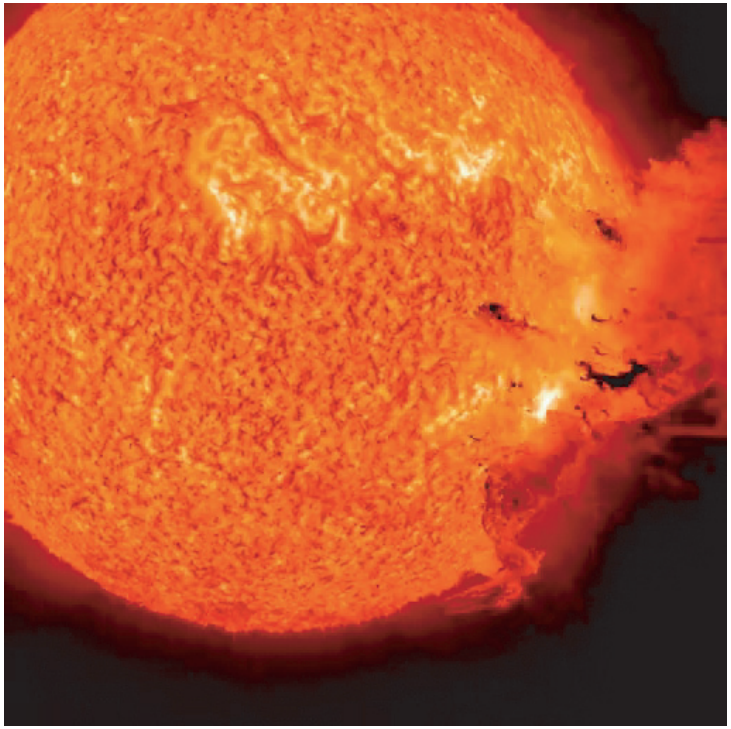


FIGURE 123 A spectacular coronal mass ejection observed on June 7, 2011 by the Solar Dynamic Observatory satellite (QuickTime film courtesy NASA).

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

is disturbed in these situations. A famous effect of a solar storm was the loss of electricity in large parts of Canada in March of 1989. The flow of charged solar particles triggered large induced currents in the power lines, blew fuses and destroyed parts of the network, shutting down the power system. Millions of Canadians had no electricity, and in the most remote places it took two weeks to restore the electricity supply. Due to the coldness of the winter and a train accident resulting from the power loss, over 80 people died. In the meantime, the power network has been redesigned to withstand such events.

How can the Sun's surface have a temperature of 6 kK, whereas the Sun's *corona* – the thin gas emanating from and surrounding the Sun that is visible during a total solar eclipse, as shown in Figure 120 – reaches one to three million Kelvin on average, with localized peaks inside a flare of up to 100 MK? In the latter part of the twentieth century it was shown, using satellites, that the magnetic field of the Sun is the cause; through the violent flows in the Sun's matter, magnetic energy is transferred to the corona in those places were flux tubes form knots, above the bright spots in the left of Figure 119 or above the dark spots in Figure 118. As a result, the particles of the corona are accelerated and heat the corona to temperatures that are a thousand times higher than those at the surface of the Sun.

Why do the stars shine?

> "Don't the stars shine beautifully? I am the only person in the world who knows why they do."
> Friedrich (Fritz) Houtermans *

All stars shine because of fusion. When two light nuclei are fused to a heavier one, some energy is set free, as the average nucleon is bound more strongly. This energy gain is possible until nuclei of iron ^{56}Fe are produced. For nuclei beyond this nucleus, as shown in Figure 124, the binding energies per nucleon then decrease again; thus fusion is not energetically possible. It turns out that the heavier nuclei found on Earth and across the universe were formed through *neutron capture*. In short, nuclei below iron are made through fusion, nuclei above iron are made through neutron capture. And for the same reason, nuclei release energy through *fusion* when the result is lighter than iron, and release energy through *fission* when the starting point is above iron.

The different stars observed in the sky** can be distinguished by the type of fusion nuclear reaction that dominates them. Most stars, in particular young or light stars, run hydrogen fusion. But that is not all. There are several types of hydrogen fusion: the direct hydrogen–hydrogen (p–p) cycle, as found in the Sun and in many other stars, and the various CNO cycle(s) or Bethe-Weizsäcker cycle(s).

Page 200

The hydrogen cycle was described above and can be summarized as

$$4\,{}^{1}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + 2\,e^{+} + 2\,\nu + 4.4\,\mathrm{pJ} \qquad (64)$$

* Friedrich Houtermans (1903–1966) was one of the most colourful physicists of his time. He lived in Austria, England, the Soviet Union, Germany and the United States. He was analyzed by Sigmund Freud, imprisoned and tortured by the NKWD in Russia, then imprisoned by the Gestapo in Germany, then worked on nuclear fission. He worked with George Gamow and Robert Atkinson.

** To find out which stars are in the sky above you at present, see the www.surveyor.in-berlin.de/himmel website.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

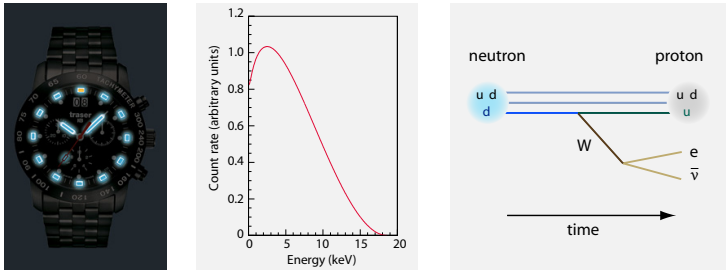


FIGURE 140 β decay (beta decay) in tritium: a modern, tritium-powered illuminated watch, the measured continuous energy spectrum of the emitted electrons from tritium, and the process occurring in the tritium nucleus (© Traser, Katrin collaboration).

teraction. Chemical transformations are also rare, otherwise we would not be running around with a constant chemical composition. The fourth interaction is therefore *weak*. Since the transformation processes were observed in the nucleus first, the interaction was named the *weak nuclear interaction*.

In β decay, the weak nuclear interaction transforms quarks into each other. In fact, the weak nuclear interaction can also transform leptons into each other, such as muons into electrons. But where does the energy released in β decay go to? Measurements in 1911 showed that the energy spectrum of the emitted electron is *continuous*. This is illustrated in Figure 140. How can this be? In 1930, Wolfgang Pauli had the courage and genius to explain this observation with a daring hypothesis: the energy of the decay is split between the electron and a new, truly astonishing particle, the *neutrino* – more precisely, the electron anti-neutrino $\bar{\nu}_e$. In order to agree with data, the neutrino must be uncharged, cannot interact strongly, and must be of very low mass. As a result, neutrinos interact with ordinary matter only extremely rarely, and usually fly through the Earth without being affected. This property makes their detection very difficult, but not impossible; the first neutrino was finally detected in 1952. Later on, it was discovered that there are three types of neutrinos, now called the electron neutrino, the muon neutrino and the tau neutrino, each with its own antiparticle. For the summary of these experimental efforts, see Table 19.

Page 242

The weakness of the weak nuclear interaction

From the observation of β decay, and helped by the quark model, physicists quickly concluded that there must be an intermediate particle that carries the weak nuclear interaction, similar to the photon that carries the electromagnetic interaction. This 'weak radiation', in contrast to all other types of radiation, consists of *massive* particles.

▷ There are two types of weak radiation particles: the neutral Z boson with a mass of 91.2 GeV – that is the roughly mass of a silver atom – and the electrically charged W boson with a mass of 80.4 GeV.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Chapter 8

THE WEAK NUCLEAR INTERACTION AND THE HANDEDNESS OF NATURE

The weirdest interaction in nature is the weak interaction. The weak interaction ransforms elementary particles into each other, has radiation particles hat have mass, violates parity and treats right and left differently. Fortunately, we do not experience the weak interaction in our everyday life, as its properties violate much of what we normally experience. This contrast makes the weak interaction the most fascinating of the four interactions in nature.

Transformation of elementary particles

Radioactivity, in particular the so-called β decay, is a bizarre phenomenon. Experiments in the 1910s showed that when β sources emit electrons, atoms are *transformed* from one chemical element to another. For example, experiments such as those of Figure 140 show that tritium, an isotope of hydrogen, decays into helium as

$$ {}^{3}_{1}\mathrm{H} \to {}^{3}_{2}\mathrm{He} + e^- + \overline{\nu}_e \,. \tag{88}$$

In fact, new elements appear in all β decays. In the 1930s it became clear that the transformation process is due to a neutron in the nucleus changing into a proton (and more):

$$ n \to p + e^- + \overline{\nu}_e \,. \tag{89}$$

This reaction explains all β decays. In the 1960s, the quark model showed that β decay is in fact due to a down quark changing to an up quark:

$$ d \to u + e^- + \overline{\nu}_e \,. \tag{90}$$

This reaction explains the transformation of a neutron – a *udd* state – into a proton – a *uud* state. In short, matter particles can transform into each other. We note that this transformation differs from what occurs in other nuclear processes. In fusion, fission or α decay, even though nuclei change, every neutron and every proton retains its nature. In β decay, elementary particles are not immutable. The dream of Democritus and Leucippus about immutable basic building blocks is definitely *not* realized in nature.

Experiments show that quark transformations cannot be achieved with the help of electromagnetic fields, nor with the help of gluon fields, nor with the help of gravitation. There must be another type of radiation in nature, and thus another, fourth in-

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

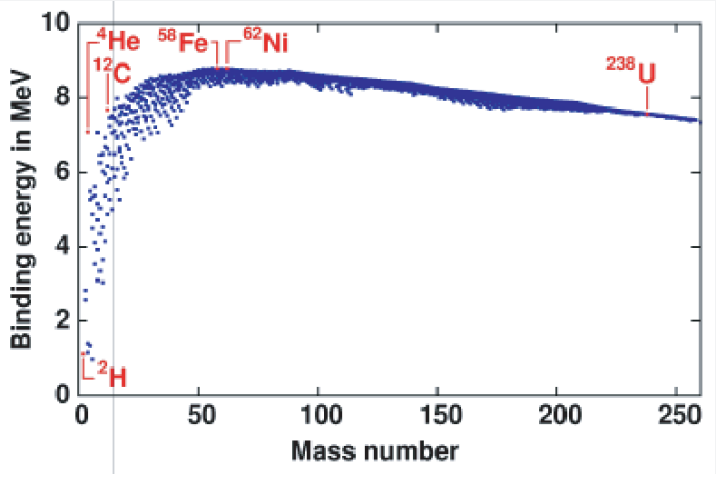


FIGURE 124 Measured values of the binding energy *per nucleon* in nuclei. The region on the left of the maximum, located at ^{58}Fe, is the region where *fusion* is energetically possible; the right region is where *fission* is possible (© Max Planck Institute for Gravitational Physics).

or, equivalently,

$$ 4\,\mathrm{p} \to \alpha + 2\,e^+ + 2\,\nu + 26.7\,\mathrm{MeV} \,. \tag{65}$$

But this is not the only way for a star to burn. If a star has heavier elements inside it, the hydrogen fusion uses these elements as catalysts. This happens through the so-called Bethe-Weizsäcker cycle or CNO cycle, which runs as

$$\begin{aligned} {}^{12}\mathrm{C} + {}^{1}\mathrm{H} &\to {}^{13}\mathrm{N} + \gamma \\ {}^{13}\mathrm{N} &\to {}^{13}\mathrm{C} + \mathrm{e}^+ + \nu \\ {}^{13}\mathrm{C} + {}^{1}\mathrm{H} &\to {}^{14}\mathrm{N} + \gamma \\ {}^{14}\mathrm{N} + {}^{1}\mathrm{H} &\to {}^{15}\mathrm{O} + \gamma \\ {}^{15}\mathrm{O} &\to {}^{15}\mathrm{N} + \mathrm{e}^+ + \nu \\ {}^{15}\mathrm{N} + {}^{1}\mathrm{H} &\to {}^{12}\mathrm{C} + {}^{4}\mathrm{He} \end{aligned} \tag{66}$$

The end result of the cycle is the *same* as that of the hydrogen cycle, both in nuclei and in energy. The Bethe-Weizsäcker cycle is faster than hydrogen fusion, but requires higher temperatures, as the protons must overcome a higher energy barrier before reacting with carbon or nitrogen than when they react with another proton. (Why?) Inside the Sun, due to the comparatively low temperature of a few tens of million kelvin, the Bethe-Weizsäcker cycle (and its variations) is not as important as the hydrogen cycle.

Challenge 138 s

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

The proton cycle and the Bethe-Weizsäcker cycle are not the only options for the burning of stars. Heavier and older stars than the Sun can also shine through other fusion reactions. In particular, when no hydrogen is available any more, stars run *helium burning*:

$$3\,{}^4\mathrm{He} \to {}^{12}\mathrm{C}\,. \tag{67}$$

This fusion reaction, also called the *triple-α process*, is of low probability, since it depends on three particles being at the same point in space at the same time. In addition, small amounts of carbon disappear rapidly via the reaction $\alpha + {}^{12}\mathrm{C} \to {}^{16}\mathrm{O}$. Nevertheless, since ${}^8\mathrm{Be}$ is unstable, the reaction with 3 alpha particles is the only way for the universe to produce carbon. All these negative odds are countered only by one feature: carbon has an excited state at 7.65 MeV, which is 0.3 MeV above the sum of the alpha particle masses; the excited state *resonantly enhances* the low probability of the three particle reaction. Only in this way the universe is able to produce the atoms necessary for apes, pigs and people. The prediction of this resonance by Fred Hoyle is one of the few predictions in physics made from the simple experimental observation that humans exist. The story has lead to a huge outflow of metaphysical speculations, most of which are unworthy of being even mentioned.

Vol. III, page 333

The studies of star burning processes also explain why the Sun and the stars do not collapse. In fact, the Sun and most stars are balls of hot gas, and the *gas pressure* due to the high temperature of its constituents prevents their concentration into a small volume. For other types of stars – especially those of high mass such as red giants – the *radiation pressure* of the emitted photons prevents collapse; for still other stars, such as neutron stars, the role is taken by the *Pauli pressure*.

The nuclear reaction rates at the interior of a star are extremely sensitive to its temperature T. The carbon cycle reaction rate is proportional to between T^{13} for hot massive O stars and T^{20} for stars like the Sun. In red giants and supergiants, the triple-α reaction rate is proportional to T^{40}; these strong dependencies imply that stars usually shine with constancy over long times, often thousands and millions of years, because any change in temperature would be damped by a very efficient feedback mechanism. Of course, there are exceptions: variable stars get brighter and darker with periods of a few days; some stars change in brightness every few years. And even the Sun shows such effects. In the 1960s, it was discovered that the Sun pulsates with a frequency of 5 minutes. The amplitude is small, only 3 kilometres out of 1.4 million; nevertheless, it is measurable. In the meantime, helioseismologists have discovered numerous additional oscillations of the Sun, and in 1993, even on other stars. Such oscillations allow studying what is happening inside stars, even separately in each of the layers they consist of.

By the way, it is still not clear how much the radiation of the Sun changes over long time scales. There is an 11 year periodicity, the famous *solar cycle*, but the long term trend is still unknown. Precise measurements cover only the years from 1978 onwards, which makes only about 3 cycles. A possible variation of the intensity of the Suns, the so-called *solar constant* might have important consequences for climate research; however, the issue is still open.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

— It is also not known how QCD has to be modified in strong gravity, thus in strongly curved space-time.

We will explore ways to overcome these limits in the last part of our adventure. Before we do that, we have a look at the other nuclear interaction observed in nature.



Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

* *

Historically, nuclear reactions provided the first test of the relation $E = c^2\gamma m$. This was achieved in 1932 by Cockcroft and Walton. They showed that by shooting protons into lithium one gets the reaction

$$ {}^{7}_{3}\mathrm{Li} + {}^{1}_{1}\mathrm{H} \to {}^{8}_{4}\mathrm{Be} \to {}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} + 17\,\mathrm{MeV}\,. \qquad (87) $$

The measured energy on the right is exactly the same value that is derived from the differences in total mass of the nuclei on both sides.

* *

A large fraction of researchers say that QCD is defined by *two* parameters. Apart from the coupling constant, they count also the strong CP parameter. Indeed, it might be that the strong interaction violates CP invariance. This violation would be described by a second term in the Lagrangian; its strength would be described by a second parameter, a phase usually called θ_{CP}. However, many high-precision experiments have been performed to search for this effect, and no CP violation in the strong interaction has ever been detected.

A summary of QCD and its open issues

Quantum chromodynamics, the non-Abelian gauge theory based on the Lagrangian with SU(3) symmetry, describes the properties of gluons and quarks, the properties of the proton, the neutron and all other hadrons, the properties of atomic nuclei, the working of the stars and the origin of the atoms inside us and around us. Without the strong interaction, we would not have flesh and blood. And all these aspects of nature follow from a single number, the strong coupling constant, and the SU(3) gauge symmetry.

The strong interaction acts only on quarks and gluons. It conserves particle type, colour, electric charge, weak charge, spin, as well as C, P and T parity.

QCD and experiment agree wherever comparisons have been made. QCD is a perfect description of the strong interaction. The limitations of QCD are only conceptual. Like in all of quantum field theory, also in the case of QCD the mathematical form of the Lagrangian is almost uniquely defined by requiring renormalizability, Lorentz invariance and gauge invariance – SU(3) in this case. We say 'almost', because the Lagrangian, despite describing correctly all experiments, contains a few parameters that remain unexplained:

- The number, 6, and the masses m_q of the quarks are not explained by QCD.
- The coupling constant of the strong interaction g_s, or equivalently, α_s or Λ, is unexplained. QCD predicts its energy dependence, but not its absolute value.
- Experimentally, the strong interaction is found to be CP conserving. This is not obvious; the QCD Lagrangian assumes that any possible CP-violating term vanishes, even though there exist CP-violating Lagrangian terms that are Lorentz-invariant, gauge-invariant and renormalizable.
- The properties of space-time, in particular its Lorentz invariance, its continuity and the number of its dimensions are assumed from the outset and are obviously all unexplained in QCD.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

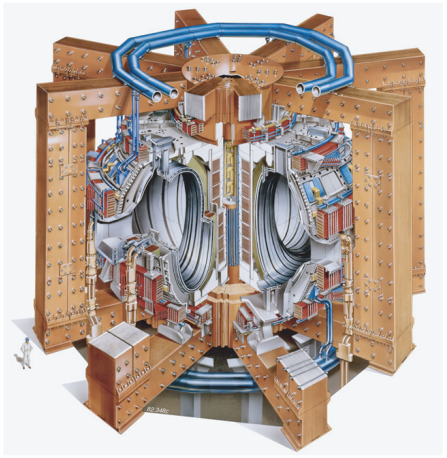


FIGURE 125 A simplified drawing of the Joint European Torus in operation at Culham, showing the large toroidal chamber and the magnets for the plasma confinement (© EFDA-JET).

Why are fusion reactors not common yet?

Across the world, for over 50 years, a large number of physicists and engineers have tried to build fusion reactors. Fusion reactors try to copy the mechanism of energy release used by the Sun. The first machine that realized macroscopic energy production through fusion was, in 1991, the Joint European Torus* (JET for short) located in Culham in the United Kingdom. Despite this success, the produced power was still somewhat smaller than the power needed for heating.

Ref. 176 The idea of JET is to produce an extremely hot plasma that is as dense as possible. At high enough temperature and density, fusion takes place; the energy is released as a particle flux that is transformed (like in a fission reactor) into heat and then into electricity. To achieve ignition, JET used the fusion between deuterium and tritium, because this reaction has the largest cross section and energy gain:

$$ \mathrm{D} + \mathrm{T} \to \mathrm{He}^4 + \mathrm{n} + 17.6\,\mathrm{MeV}\,. \qquad (68) $$

Because tritium is radioactive, most research experiments are performed with the far less efficient deuterium–deuterium reactions, which have a lower cross section and a lower energy gain:

$$ \mathrm{D} + \mathrm{D} \to \mathrm{T} + \mathrm{H} + 4\,\mathrm{MeV} $$
$$ \mathrm{D} + \mathrm{D} \to \mathrm{He}^3 + \mathrm{n} + 3.3\,\mathrm{MeV}\,. \qquad (69) $$

* See www.jet.edfa.org.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Fusion takes place when deuterium and tritium (or deuterium) collide at high energy. The high energy is necessary to overcome the electrostatic repulsion of the nuclei. In other words, the material has to be hot. To release energy from deuterium and tritium, one therefore first needs energy to heat it up. This is akin to the ignition of wood: in order to use wood as a fuel, one first has to heat it with a match.

Following the so-called *Lawson criterion*, rediscovered in 1957 by the English engineer John Lawson, after its discovery by Russian researchers, a fusion reaction releases energy only if the triple product of density n, reaction (or containment) time τ and temperature T exceeds a certain value. Nowadays this criterion is written as

Ref. 177

$$n\tau T > 3 \cdot 10^{28}\,\mathrm{s\,K/m^3}\,. \tag{70}$$

In order to realize the Lawson criterion, JET uses temperatures of 100 to 200 MK, particle densities of 2 to $3 \cdot 10^{20}\,\mathrm{m^{-3}}$, and confinement times of 1 s. The temperature in JET is thus much higher than the 15 MK at the centre of the Sun, because the densities and the confinement times are much lower.

Matter at these temperatures is in form of a *plasma*: nuclei and electrons are completely separated. Obviously, it is impossible to pour a 100 MK plasma into a container: the walls would instantaneously evaporate. The only option is to make the plasma float in a vacuum, and to avoid that the plasma touches the container wall. The main challenge of fusion research in the past has been to find a way to keep a hot gas mixture of deuterium and tritium suspended in a chamber so that the gas never touches the chamber walls. The best way is to suspend the gas using a magnetic field. This works because in the fusion plasma, charges are separated, so that they react to magnetic fields. The most successful geometric arrangement was invented by the famous Russian physicists Igor Tamm and Andrei Sakharov: the *tokamak*. Of the numerous tokamaks around the world, JET is the largest and most successful. Its concrete realization is shown in Figure 125. JET manages to keep the plasma from touching the walls for about a second; then the situation becomes unstable: the plasma touches the wall and is absorbed there. After such a *disruption*, the cycle consisting of gas injection, plasma heating and fusion has to be restarted. As mentioned, JET has already achieved ignition, that is the state were more energy is released than is added for plasma heating. However, so far, no sustained commercial energy production is planned or possible, because JET has no attached electrical power generator.

The successor project, *ITER*, an international tokamak built with European, Japanese, US-American and Russian funding, aims to pave the way for commercial energy generation. Its linear reactor size will be twice that of JET; more importantly, ITER plans to achieve 30 s containment time. ITER will use superconducting magnets, so that it will have extremely cold matter at 4 K only a few metres from extremely hot matter at 100 MK. In other words, ITER will be a high point of engineering. The facility is being built in Cadarache in France. Due to its lack of economic sense, ITER has a good chance to be a modern version of the tower of Babylon; but maybe one day, it will start operation.

Like many large projects, fusion started with a dream: scientists spread the idea that fusion energy is safe, clean and inexhaustible. These three statements are still found on every fusion website across the world. In particular, it is stated that fusion reactors are not dangerous, produce much lower radioactive contamination than fission reactors, and use

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

three-jet events. The observed rate and the other properties of these events confirmed the predictions of QCD. Experiments at PETRA also determined the spin $S = 1$ of the gluon and the running of the strong coupling constant. The hero of those times was the project manager Gustav-Adolf Voss, who completed the accelerator on budget and six months ahead of schedule.

* *

Something similar to colour radiation, but still stranger, might have been found in 1997. It might be that a scalar meson with a mass of $1.5\,\mathrm{GeV/c^2}$ is a *glueball*. This is a hypothetical meson composed of gluons only. Numerical results from lattice gauge theory seem to confirm the possibility of a glueball in that mass range. The existence of glueballs is hotly debated and still open.

Ref. 198

* *

There is a growing consensus that most light scalar mesons below $1\,\mathrm{GeV/c^2}$, are *tetraquarks*. In 2003, experiments provided also candidates for heavier tetraquarks, namely the X(3872), Ds(2317) and Ds(2460). The coming years will show whether this interpretation is correct.

Ref. 199

* *

Do particles made of five quarks, so-called *pentaquarks*, exist? So far, they seem to exist only in a few laboratories in Japan, whereas in other laboratories across the world they are not seen. Most researchers do not believe the results any more.

Ref. 200

* *

Whenever we look at a periodic table of the elements, we look at a manifestation of the strong interaction. The Lagrangian of the strong interaction describes the origin and properties of the presently known 115 elements.

Nevertheless one central aspect of nuclei is determined by the electromagnetic interaction. Why are there around 115 different elements? Because the electromagnetic coupling constant α is around 1/137.036. In more detail, the answer is the following. If the charge of a nucleus were much higher than around 137, the electric field around nuclei would lead to spontaneous electron–positron pair generation; the generated electron would fall into the nucleus and transform one proton into a neutron, thus inhibiting a larger proton number. The finite number of the elements is thus due to the electromagnetic interaction.

* *

To know more about radioactivity, its effects, its dangers and what a government can do about it, see the English and German language site of the Federal Office for Radiation Protection at www.bfs.de.

* *

From the years 1990 onwards, it has regularly been claimed that extremely poor countries are building nuclear weapons. Why is this highly unlikely?

Challenge 145 s

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 18 Correspondence between QCD and superconductivity.

QCD	Superconductivity
Quark	magnetic monopole
Colour force non-linearities	Electron–lattice interaction
Chromoelectric flux tube	magnetic flux tube
Gluon-gluon attraction	electron–electron attraction
Glueballs	Cooper pairs
Instability of bare vacuum	instability of bare Fermi surface
Discrete centre symmetry	continuous U(1) symmetry
High temperature breaks symmetry	low temperature breaks symmetry

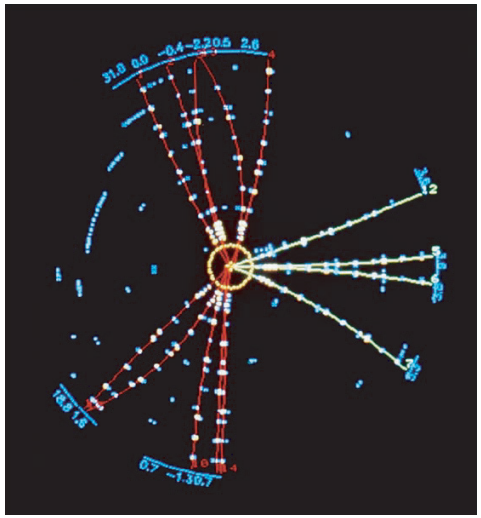


FIGURE 139 A three jet event observed at the PETRA collider in Hamburg in Germany. The event, triggered by an electron-positron collision, allowed detecting the decay of a gluon and measuring its spin (© DESY).

Nobody knows whether this will be necessary also in the future: the race for a simple approximation method for finding solutions is still open.

* *

Even though gluons are massless, like photons and gravitons are, there is *no* colour radiation in nature. Gluons carry colour and couple to themselves; as a result, free gluons were predicted to directly decay into quark–antiquark pairs.

In 1979, the first clear decays of *gluons* have been observed at the PETRA particle collider in Hamburg. The occurrence of certain events, called *gluon jets*, are due to the decay of high-energy gluons into narrow beams of particles. Gluon jets appear in coplanar

Ref. 191

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

water as basic fuel. 'Solar fusion energy would be as clean, safe and limitless as the Sun.' In reality, the only reason that we do not feel the radioactivity of the Sun is that we are far away from it. Fusion reactors, like the Sun, are highly radioactive. The management of radioactive fusion reactors is much more complex than the management of radioactive fission reactors.

It is true that fusion fuels are almost inexhaustible: deuterium is extracted from water and the tritium – a short-lived radioactive element not found in nature in large quantities – is produced from *lithium*. The lithium must be enriched, but since material is not radioactive, this is not problematic. However, the production of tritium from lithium is a dirty process that produces large amounts of radioactivity. Fusion energy is thus inexhaustible, but not safe and clean.

In summary, of all technical projects ever started by mankind, fusion is by far the most challenging and ambitious. Whether fusion will ever be successful – or whether it ever should be successful – is another issue.

Where do our atoms come from?

> The elements were made in less time than you could cook a dish of duck and roast potatoes.
> George Gamow

People consist of electrons and various nuclei. Where did the nucleosynthesis take place? Many researchers contributed to answering this question.

Ref. 178

About three minutes after the big bang, when temperature was around 0.1 MeV, protons and neutrons formed. About seven times as many protons as neutrons were formed, mainly due to their mass difference. Due to the high densities, the neutrons were captured, through the intermediate step of deuterium nuclei, in α particles. The process stopped around 20 minutes after the big bang, when temperatures became too low to allow fusion. After these seventeen minutes, the mass of the universe was split into 75 % of hydrogen, 25 % of helium (both percentages result from the factor 7 between the number of protons and neutrons), and traces of deuterium, lithium and beryllium. This process is called *primordial nucleosynthesis*. No heavier elements were formed, because the temperature fall prevented their accumulation in measurable quantities, and because there are stable nuclei with 5 or 8 nucleons.

Simulations of primordial nucleosynthesis agree well with the element abundances found in extremely distant, thus extremely old stars. The abundances are deduced from the spectra of these stars. In short, *hydrogen, helium, lithium and beryllium nuclei are formed shortly after ('during') the big bang*. These are the so-called *primordial elements*.

Vol. II, page 246

All other nuclei are formed many millions of years after the big bang. In particular, *other light nuclei are formed in stars*. Young stars run hydrogen burning or helium burning; heavier and older stars run neon-burning or even silicon-burning. These latter processes require high temperatures and pressures, which are found only in stars with a mass at least eight times that of the Sun. All these fusion processes are limited by photodissociation and thus will only lead to nuclei up to ^{56}Fe.

Ref. 179

Nuclei heavier than iron can only be made by neutron capture. There are *two* main neutron capture processes. The first process is the so-called *s-process* – for 'slow'. The process occurs inside stars, and gradually builds up heavy elements – including the most

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

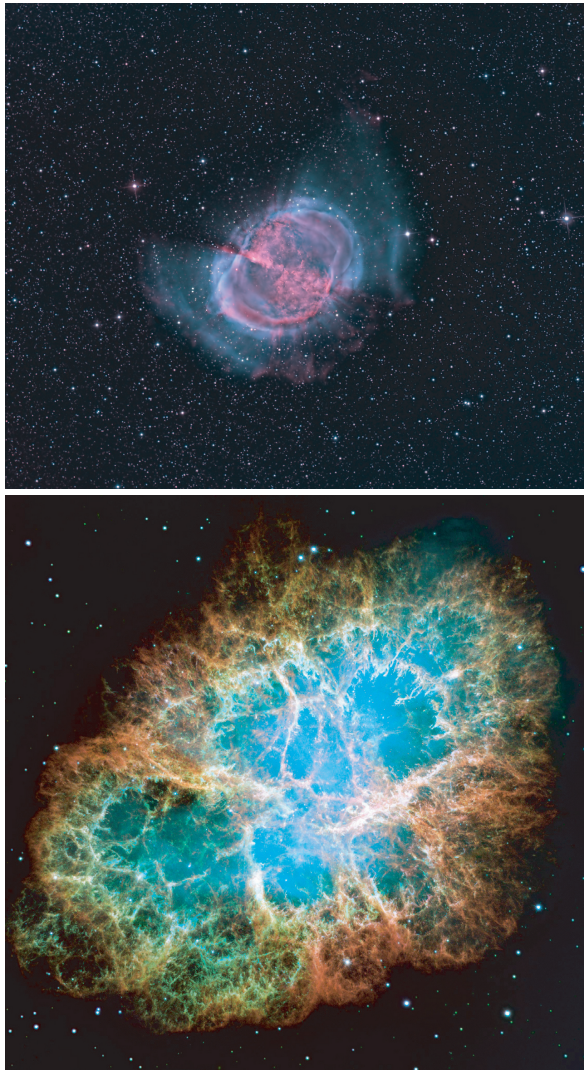


FIGURE 126 Two examples of how exploding stars shoot matter into interstellar space: the Crab nebula M1 and the Dumbbell nebula M27 (courtesy NASA and ESA, © Bill Snyder).

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

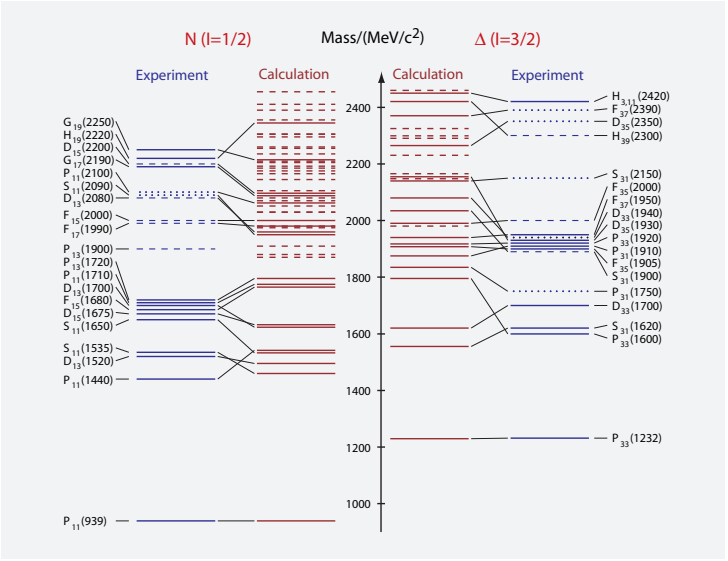


FIGURE 138 The mass spectrum of the excited states of the proton: experimental and calculated values (from Ref. 186).

Ref. 186

In the same way, protons and neutrons can be excited. In fact, their excited states have been studied in detail; a summary, also showing the limitation of the approach, is shown in Figure 138. Many excitations can be explained as excited quarks states, but many more are predicted. The calculated masses agree with observations to within 10 %. The quark model and QCD thus structure and explain a large part of the baryon spectrum; but the agreement is not yet perfect.

Obviously, in our everyday environment the energies necessary to excite nucleons do not appear – in fact, they do not even appear inside the Sun – and these excited states can be neglected. They only appear in particle accelerators and in cosmic rays. In a sense, we can say that in our corner of the universe, the colour of protons usually is not visible.

Curiosities about the strong interaction

In a well-known analogy, QCD can be compared to superconductivity. Table 18 gives an overview of the correspondence.

* *

The computer calculations necessary to extract particle data from the Lagrangian of quantum chromodynamics are among the most complex calculations ever performed. They beat weather forecasts, fluid simulations and the like by orders of magnitude.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

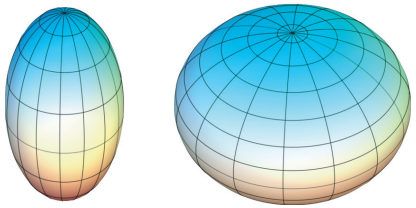


FIGURE 137 An illustration of a *prolate* (left) and an *oblate* (right) ellipsoidal shape (© Sam Derbyshire).

The mass, shape and colour of protons

Ref. 195 Frank Wilczek mentions that one of the main results of QCD, the theory of strong interactions, is to explain mass relations such as

$$m_{\text{proton}} \sim e^{-k/\alpha} m_{\text{Planck}} \quad \text{and} \quad k = 11/2\pi\,,\ \alpha_{\text{unif}} = 1/25\,. \tag{86}$$

Page 268 Here, the value of the coupling constant α_{unif} is taken at the grand unifying energy, a factor of 1000 below the Planck energy. (See the section of grand unification below.) In other words, a general understanding of masses of bound states of the strong interaction, such as the proton, requires almost purely a knowledge of the unification energy and the coupling constant at that energy. The approximate value $\alpha_{\text{unif}} = 1/25$ is an extrapolation from the low energy value, using experimental data. The proportionality factor k in expression (86) is not easy to calculate. It is usually determined on computers using lattice QCD.

But the mass is not the only property of the proton. Being a cloud of quarks and gluons, it also has a shape. Surprisingly, it took a long time before people started to become interested in this aspect. The proton, being made of two up quarks and one down quark, resembles a ionized H_2^+ molecule, where one electron forms a cloud around two protons. Obviously, the H_2^+ molecule is elongated, or *prolate*, as shown in Figure 137.

Is the proton prolate? There is no spectroscopically measurable asphericity – or quadrupole moment – of the proton. However, the proton has an *intrinsic* quadrupole moment. The quadrupole moments of the proton and of the neutron are predicted to be Ref. 196 positive in all known calculation methods, implying an *prolate* shape. Recent measurements at Jefferson Laboratories confirm this prediction. A prolate shape is predicted for all $J = 1/2$ baryons, in contrast to the oblate shape predicted for the $J = 3/2$ baryons. The spin 0 pseudoscalar mesons are predicted to be prolate, whereas the spin 1 vector mesons are expected to be oblate.

The shape of any molecule will depend on whether other molecules surround it. Recent research showed that similarly, both the size and the shape of the proton in nuclei Ref. 197 is slightly variable; both seem to depend on the nucleus in which the proton is built-in.

Apart from shapes, molecules also have a colour. The colour of a molecule, like that of any object, is due to the energy absorbed when it is irradiated. For example, the H_2^+ molecule can absorb certain light frequencies by changing to an excited state. Molecules change mass when they absorb light; the excited state is heavier than the ground state.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

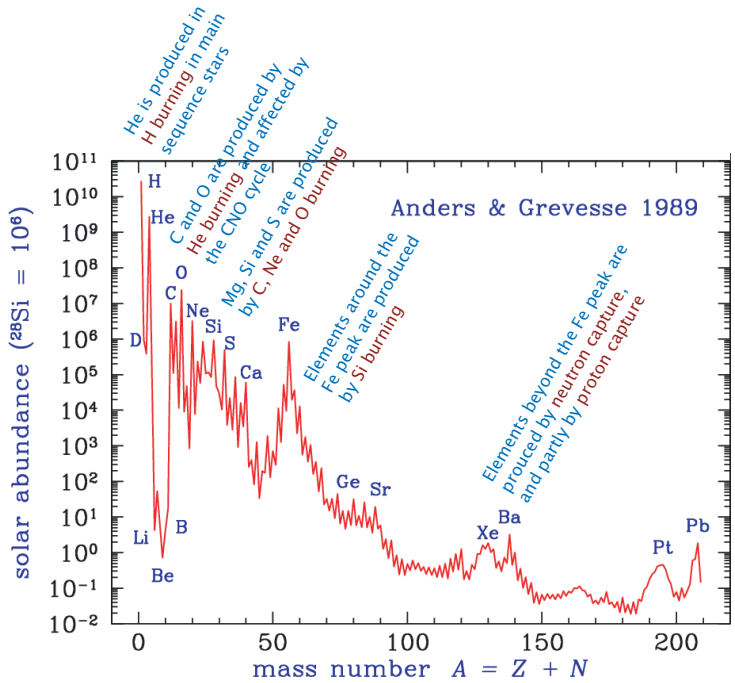


FIGURE 127 The measured nuclide abundances in the solar system and their main production processes (from Ref. 180).

Ref. 181 heavy stable nucleus, lead – from neutrons flying around. The second neutron capture process is the rapid *r-process*. For a long time, its was unknown where it occurred; for many decades, it was thought that it takes place in stellar explosions. Recent research points to *neutron star mergers* as the more likely place for the r-process. Such collisions emit material into space. The high neutron flux produces heavy elements. For example, it seems that most *gold* nuclei are synthesized in this way. (The first clear neutron star merger was observed in 2013 with the Hubble space telescope, after it had been detected as a gamma ray burst with the name GRB 130603B. Such an event is also called a *kilonova*, because the emitted energy is between that of a *nova* and of a *supernova*. In October 2017, a further, well-publicized neutron star merger was observed with the help of gravitational wave detectors, of gamma ray burst detectors and of over 70 optical telescopes. It took place at a distance of 130 million light years.) The abundances of the heavy elements in the solar system can be measured with precision, a shown in Figure 127. These data points correspond well with what is expected from the material synthesized by neutron star

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

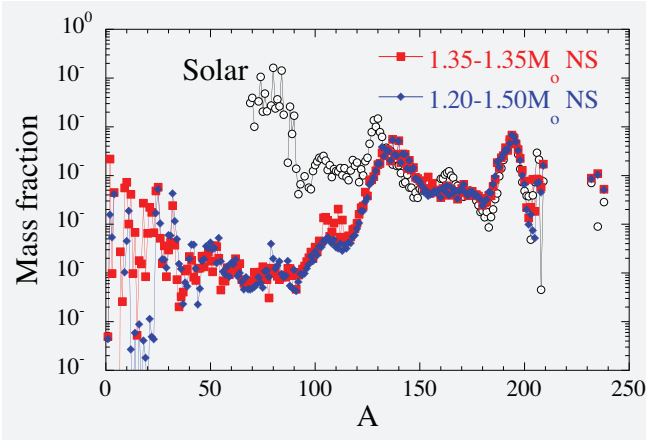


FIGURE 128 The comparison between measured nuclide abundances (dotted circles) in the solar system and the calculated values (red squares, blue diamonds) predicted by neutron star mergers (from reference Ref. 181).

mergers, the most likely candidate for the r-process at present, as illustrated by Figure 128.

A number of other processes, such as *proton capture* and the so-called *equilibrium process*, contributed to the formation of the elements.

In summary, the electrons and protons in our body were made during the big bang; the lighter nuclei, such as carbon or oxygen, in stars; the heavier nuclei in star explosions and neutron star mergers. But how did those nuclei arrive on Earth?

At a certain stage of their life, many stars explode. An exploding star is called a *supernova*. Such a supernova has an important effect: it distributes most of the matter of the star, such as carbon, nitrogen or oxygen, into space. This happens mostly in the form of neutral atoms. (Some elements are also synthesized during the explosion.) Exploding supernovae are thus essential for distributing material into space.

The Sun is a second generation star – as so-called 'population I' star. and the solar system formed from the remnants of a supernova, as did, somewhat later, life on Earth. We all are made of recycled atoms.

We are recycled stardust. This is the short summary of the extended study by astrophysicists of all the types of stars found in the universe, including their birth, growth, mergers and explosions. The exploration of how stars evolve and then move in galaxies is a fascinating research field, and many aspects are still unknown.

Vol. II, page 211

Curiosities about the Sun and the stars

What would happen if the Sun suddenly stopped shining? Obviously, temperatures would fall by several tens of degrees within a few hours. It would rain, and then all water would freeze. After four or five days, all animal life would stop. After a few weeks, the

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

the discovery of asymptotic freedom was essential to establish QCD as a theory of the strong interaction.

Asymptotic freedom can be understood qualitatively if the situation is compared to QED. The electron coupling increases at small distances, because the screening due to the virtual electron-positron pairs has less and less effect. In QCD, the effective colour coupling also changes at small distances, due to the smaller number of virtual quark-antiquark pairs. However, the gluon properties lead to the opposite effect, an *antiscreening* that is even stronger: in total, the effective strong coupling decreases at small distances.

The sizes and masses of quarks

The size of quarks, like that of all elementary particles, is predicted to vanish by QCD, as in all quantum field theory. So far, no experiment has found any effect due to a finite quark size. Measurements show that quarks are surely smaller than 10^{-19} m. No size conjecture has been given by any hypothetical theory. Quarks are assumed point-like, or at most Planck-sized, in all descriptions so far.

Ref. 194

We noted in several places that a neutral compound of charged particles is always less massive than its components. But if you look up the mass values for quarks in most tables, the masses of u and d quarks are only of the order of a few MeV/c^2, whereas the proton's mass is 938 MeV/c^2. What is the story here?

It turns out that the definition of the mass is more involved for quarks than for other particles. Quarks are never found as free particles, but only in bound states. As a result, the concept of quark mass depends on the calculation framework one is using.

Due to *asymptotic freedom*, quarks behave almost like free particles only at high energies. The mass of such a 'free' quark is called the *current quark mass*; for the light quarks it is only a few MeV/c^2, as shown in Table 17.

At low energy, for example inside a proton, quarks are *not* free, but must carry along a large amount of energy due to the confinement process. As a result, bound quarks have a much larger effective, so-called *constituent quark mass*, which takes into account this confinement energy. To give an idea of the values, take a proton; the indeterminacy relation for a particle inside a sphere of radius 0.9 fm gives a momentum indeterminacy of around 190 MeV/c. In three dimensions this gives an energy of $\sqrt{3}$ times that value, or an effective, constituent quark mass of about 330 MeV/c^2. Three confined quarks are thus heavier than a proton, whose mass is 938 MeV/c^2; we can thus still say that a compound proton is less massive than its constituents.

In short, the mass of the proton and the neutron is (almost exclusively) the kinetic energy of the quarks inside them, as their rest mass is almost negligible. As Frank Wilczek says, some people put on weight even though they never eat anything heavy.

Ref. 195

But also the small current quark mass values for the up, down, strange and charmed quarks that appear in the QCD Lagrangian depend on the calculation framework that is used. The values of Table 17 are those for a renormalization scale of 2 GeV. For half that energy, the mass values increase by 35 %. The heavy quark masses are those used in the so-called $\overline{MS}$ scheme, a particular way to perform perturbation expansions.

Ref. 186

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

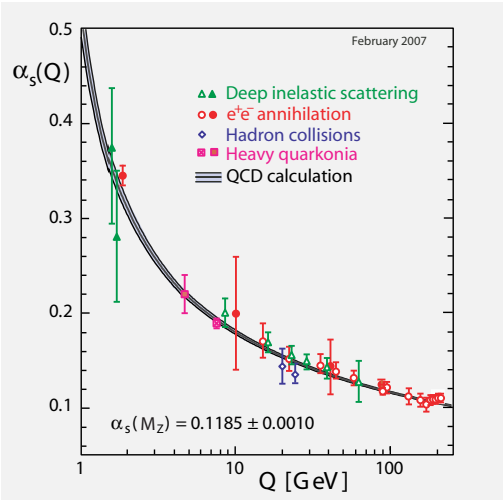


FIGURE 136 The measured and the calculated variation of the strong coupling with energy, showing the precision of the QCD Lagrangian and the asymptotic freedom of the strong interaction (© Siegfried Bethke, updated from Ref. 193).

The energy dependence of the strong coupling can be calculated with the standard renormalization procedures and is expected to be

Ref. 186, Ref. 188

$$\alpha_s(Q^2) = \frac{12\pi}{33-2n_f}\frac{1}{L}\left(1 - \frac{(918-114n_f)\ln L}{(33-2n_f)^2 L} + \ldots\right) \quad \text{where} \quad L = \ln\frac{Q^2}{\Lambda^2(n_f)} \qquad (85)$$

where n_f is the number of quarks with mass below the energy scale Q, thus a number between 3 and 6. (The expression has been expanded to many additional terms with the help of computer algebra.)

The third way to describe the strong coupling is thus the energy parameter $\Lambda(n_f)$. Experiments yield $\Lambda(3)$ =230(60) GeV, $\Lambda(4)$ =180(50) GeV and $\Lambda(5)$ =120(30) GeV.

The accelerator experiments that measure the coupling are extremely involved, and hundreds of people across the world have worked for many years to gather the relevant data. The comparison of QCD and experiment, shown in Figure 136, does not show any contradiction between the two.

Figure 136 and expression (85) illustrate what is called *asymptotic freedom*: α_s decreases at high energies. In other words, at high energies quarks are *freed* from the strong interaction; they behave as free particles.* As a result of asymptotic freedom, in QCD, a perturbation expansion can be used only at energies much larger than Λ. Historically,

* Asymptotic freedom was discovered in 1972 by Gerard 't Hooft; since he had received the Nobel Prize already, the 2004 Prize was then given to the next people who highlighted it: David Gross, David Politzer and Frank Wilczek, who studied it extensively in 1973.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

oceans would freeze; after a few months, air would liquefy. Fortunately, this will never happen.

* *

Not everything about the Sun is known. For example, the neutrino flux from the Sun oscillates with a period of 28.4 days. That is the same period with which the magnetic field of the Sun oscillates. The connection is still being explored.

* *

The Sun is a fusion reactor. But its effects are numerous. If the Sun were less brighter than it is, evolution would have taken a different course. We would not have eyelids, we would still have more hair, and would have a brighter skin. Can you find more examples?

Challenge 139 e

* *

Some stars shine like a police siren: their luminosity increases and decreases regularly. Such stars, called *Cepheids*, are important because their period depends on their average (absolute) brightness. Therefore, measuring their period and their brightness on Earth thus allows astronomers to determine their distance.

* *

The first human-made hydrogen bomb explosion took place the Bikini atoll. Fortunately, none has ever been used on people.

But nature is much better at building bombs. The most powerful nuclear explosions known take place on the surface of neutron stars in X-ray binaries. The matter falling into such a neutron star from the companion star, mostly hydrogen, will heat up until the temperature allows fusion. The resulting explosions can be observed in telescopes as light or X-ray flashes of about 10 s duration; the explosions are millions of times more powerful that those of human-made hydrogen bombs.

* *

In the 1960s, it was discovered that surface of the Sun oscillates. The surface is covered with standing waves. The amplitude is a few hundred kilometres, the wavelength can be hundred times larger; the typical frequency of the famous p-modes, or trapped acoustic waves, is between 2 and 4 mHz, thus roughly between 8 and 3 minutes. The oscillations are also visible as diameter oscillations of the Sun. This research field is now called *helioseismology*.

* *

Lithium, beryllium and boron are rare inside stars, because they like to capture protons, and thus change identity. For the same reason, these elements are rare on Earth.

* *

By chance, the composition ratios between carbon, nitrogen and oxygen inside the Sun are the same as inside the human body.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

* *

Nucleosynthesis is mainly regulated by the strong interaction. However, if the electromagnetic interaction would be much stronger or much weaker, stars would either produce too little oxygen or too little carbon, and we would not exist. This famous argument is due to Fred Hoyle. Can you fill in the details?

Challenge 140 d

Summary on stars and nucleosynthesis

> All humans are brothers. We came from the same supernova.
>
> Allan Sandage

Stars and the Sun burn because of nuclear fusion. The energy liberated in nuclear fusion is due to the strong nuclear interaction that acts between nucleons. When stars have used up their nuclear fuel, they usually explode. In such a supernova explosion, they distribute nuclei into space in the form of dust. Already in the distant past, such dust recollected because of gravity and then formed the Sun, the Earth and, later on, humans.

The nuclear reaction processes behind nucleosynthesis have been studied in great detail. Nucleosynthesis during the big bang formed hydrogen and helium, nucleosynthesis in stars formed the light nuclei, and nucleosynthesis in neutron star mergers and supernovae explosions formed the heavy nuclei.



Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

In other words, two quarks in a hadron attract each other with a force equal to the weight of two elephants: about 14 tons.

Experiments are thus clear: the observed Chew-Frautschi plots, as well as several other observations not discussed here, are best described by a quark–quark potential that grows, above 1 fm, *linearly* with distance. The slope of the linear potential, the force, has a value equal to the force with which the Earth attracts two elephants. As a result, quarks *never* appear as free particles: quarks are always *confined* in hadrons. This situation is in contrast with QED, where the force between charges goes to zero for large distances; electric charges are thus not confined, but can exist as free particles. At large distances, the electric potential *decreases* in the well-known way, with the inverse of the distance. In contrast, for the strong interaction, experiments lead to a quark potential given by

Ref. 185

$$V = -\frac{4}{3}\frac{\alpha_{sc}\hbar c}{r} + kr \tag{84}$$

where k is the mentioned 0.87 GeV/fm, α_{sc} is 0.2, and $\hbar c$ is 0.1975 GeV/fm. The quark potential is illustrated in Figure 134.

Even though experiments are clear, theoreticians face a problem. So far, neither the quark-quark potential nor the quark bound states can be deduced from the QCD Lagrangian with a *simple* approximation method. Nevertheless, complicated non-perturbative calculations show that the QCD Lagrangian does predict a force between two coloured particles that levels off at a constant value (corresponding to a linearly increasing potential). These calculations show that the old empirical approximations of hadrons as quarks connected by strings or a quarks in bags, shown in Figure 134, can indeed be deduced from the QCD Lagrangian. However, the calculations are too complex to be summarized in a few lines. Independently, the constant force value has also been reproduced in computer calculations in which one simplifies space-time to a lattice and then approximates QCD by so-called *lattice QCD* or *lattice gauge theory*. Lattice calculations have further reproduced the masses of most mesons and baryons with reasonable accuracy. Using the most powerful computers available, these calculations have given predictions of the mass of the proton and other baryons within a few per cent. Discussing these complex and fascinating calculations lies outside the scope of this text, however.

Ref. 192

In fact, the challenge of explaining confinement in simple terms is so difficult that the brightest minds have been unable to solve it yet. This is not a surprise, as its solution probably requires the unification of the interactions and, most probably, also the unification with gravity. We therefore leave this issue for the last part of our adventure.

Asymptotic freedom

QCD has another property that sets it apart form QED: the behaviour of its coupling with energy. In fact, there are three equivalent ways to describe the strong coupling strength. The first way is the quantity appearing in the QCD Lagrangian, g_s. The second way is often used to define the equivalent quantity $\alpha_s = g_s^2/4\pi$. Both α_s and g_s depend on the energy Q of the experiment. If they are known for one energy, they are known for all of them. Presently, the best experimental value is $\alpha_s(M_Z) = 0.1185 \pm 0.0010$.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

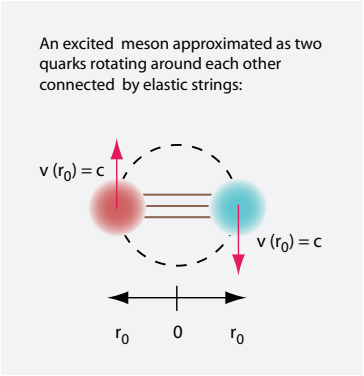


FIGURE 135 Calculating masses of excited hadrons.

The quark masses are assumed negligible. For the total energy this implies the relation

$$E = c^2 m = 2\int_0^{r_0} \frac{k}{\sqrt{1 - v(r)/c^2}} \mathrm{d}r = k r_0 \pi \tag{80}$$

and for angular momentum the relation

$$J = \frac{2}{\hbar c^2}\int_0^{r_0} \frac{k r v(r)}{\sqrt{1 - v(r)/c^2}} \mathrm{d}r = \frac{k r_0^2}{2\hbar c} \,. \tag{81}$$

Including the spin of the quarks, we thus get

$$J = \alpha_0 + \alpha' m^2 \quad \text{where} \quad \alpha' = \frac{c^3}{2\pi k \hbar} \,. \tag{82}$$

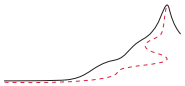
Regge thus deduced a simple expression that relates the mass m of excited hadrons to their total spin J. For bizarre historical reasons, this relation is called a *Regge trajectory*.

The value of the constant α' is predicted to be independent of the quark–antiquark pairing. A few years later, as shown in Figure 134, such linear relations were found in experiments: the *Chew-Frautschi plots*. For example, the three lowest lying states of Δ are the spin 3/2 Δ(1232) with m^2 of 1.5 GeV^2, the spin 7/2 Δ(1950) with m^2 of 3.8 GeV^2, and the spin 11/2 Δ(2420) with m^2 of 5.9 GeV^2. The value of the constant α' is found experimentally to be around 0.93 GeV^{-2} for almost all mesons and baryons, whereas the value for α_0 varies from particle to particle. The quark string tension is thus found to be

Ref. 188

$$k = 0.87\,\mathrm{GeV/fm} = 0.14\,\mathrm{MN} \,. \tag{83}$$

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



CHAPTER 7

THE STRONG INTERACTION – INSIDE NUCLEI AND NUCLEONS

Both radioactivity and medical images show that nuclei are composed systems. But quantum theory predicts even more: also protons and neutrons must be composed. There are two reasons: first, nucleons have a finite size, and second, their magnetic moments do not match the value predicted for point particles.

The prediction of components inside protons was confirmed in the late 1960s when Ref. 182 Kendall, Friedman and Taylor shot high energy electrons into hydrogen atoms. They found that a proton contains *three* constituents with spin 1/2. The experiment was able to 'see' the constituents through large angle scattering of electrons, in the same way that we see objects through large angle scattering of photons. These constituents correspond Ref. 183 in number and (most) properties to the so-called *quarks* predicted in 1964 by George Zweig and also by Murray Gell-Mann.**

Why are there three quarks inside a proton? And how do they interact? The answers are deep and fascinating.

THE FEEBLE SIDE OF THE STRONG INTERACTION

The mentioned deep inelastic scattering experiments show that the interaction keeping the protons together in a nucleus, which was first described by Yukawa Hideki,*** is

** The physicist George Zweig (b. 1937 Moscow) proposed the quark idea – he called them *aces* – in 1963, with more clarity than Gell-Mann. Zweig stressed the reality of aces, whereas Gell-Mann, in the beginning, did not believe in the existence of quarks. Zweig later moved on to a more difficult field: neurobiology.

Murray Gell-Mann (b. 1929 New York) received the Nobel Prize in Physics in 1969. He is the originator of the term 'quark'. The term has two origins: officially, it is said to be taken from *Finnegans Wake*, a novel by James Joyce; in reality, Gell-Mann took it from a Yiddish and German term meaning 'lean soft cheese' Ref. 184 and used figuratively in those languages to mean 'silly idea'.

Gell-Mann was the central figure of particle physics in the 20th century; he introduced the concept of strangeness, the renormalization group, the flavour SU(3) symmetry and quantum chromodynamics itself. A disturbing story is that he took the idea, the data, the knowledge, the concepts and even the name of the V–A theory of the weak interaction from the bright physics student George Sudarshan and published it, together with Richard Feynman, as his own. The wrong attribution is still found in many textbooks.

Gell-Mann is also known for his constant battle with Feynman about who deserved to be called the most arrogant physicist of their university. A famous anecdote is the following. Newton's once used a common saying of his time in a letter to Hooke: 'If I have seen further than you and Descartes, it is by standing upon the shoulders of giants.' Gell-Mann is known for saying: 'If I have seen further than others, it is because I am surrounded by dwarfs.'

*** Yukawa Hideki (b. 1907 Azabu, d. 1981 Kyoto), important physicist specialized in nuclear and particle physics. He received the 1949 Nobel Prize in Physics for his theory of mesons. Yukawa founded the journal

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

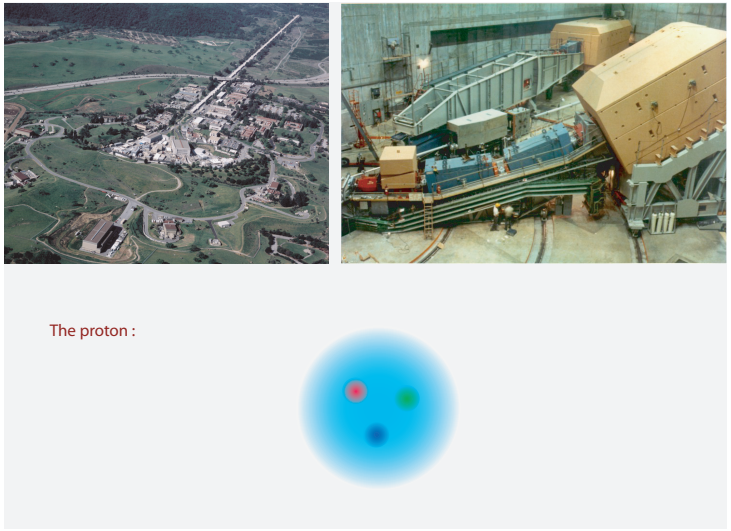


FIGURE 129 Top: SLAC, the electron linear collider, and the detectors used for the deep inelastic electron scattering experiment. Bottom: an artistic illustration of the final result, showing the three scattering centres observed inside the proton.

only a feeble shadow of the interaction that keeps quarks together in a proton. Both interactions are called by the same name. The two cases correspond somewhat to the two cases of electromagnetism found in atomic matter. The clearest example is provided by neon atoms: the strongest and 'purest' aspect of electromagnetism is responsible for the attraction of the electrons to the neon nuclei; its feeble 'shadow', the Van-der-Waals interaction, is responsible for the attraction of neon atoms in liquid neon and for processes like its evaporation and condensation. Both attractions are electromagnetic, but the strengths differ markedly. Similarly, the strongest and 'purest' aspect of the strong interaction leads to the formation of the proton and the neutron through the binding of quarks; the feeble, 'shadow' aspect leads to the formation of nuclei and to α decay. Obviously, most information can be gathered by studying the strongest and 'purest' aspect.

Bound motion, the particle zoo and the quark model

Deep electron scattering showed that protons are made of interacting constituents. How can one study these constituents?

Physicists are simple people. To understand the constituents of matter, and of protons in particular, they had no better idea than to take all particles they could get hold of and

Progress of Theoretical Physics and together with his class mate Tomonaga Shin'ichiro, who also won the prize, he was an example to many scientists in Japan.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

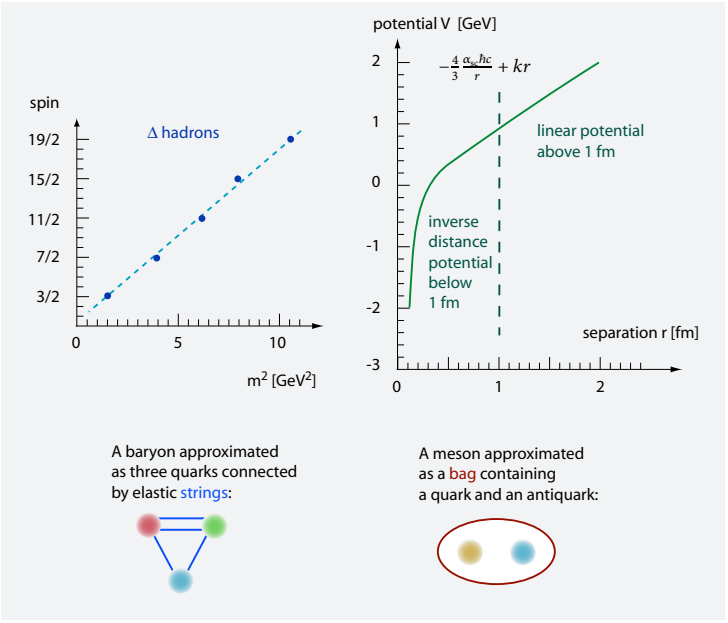


FIGURE 134 Top left: a Regge trajectory, or Chew–Frautschi plot, due to the confinement of quarks. Top right: the quark confinement potential. Bottom: two approximate ways to describe quark confinement: the string model and the bag model of hadrons.

confirming the number of colours. Many other such *branching ratios* can be calculated in this way. They agree with experiments only if the number of colours is three.

Confinement of quarks – and elephants

Many of the observed hadrons are not part of the diagrams of Figure 131 and Figure 132; these additional hadrons can be explained as *rotational excitations* of the fundamental mesons from those diagrams. As shown by Tullio Regge in 1957, the idea of rotational excitations leads to quantitative predictions. Regge assumed that mesons and baryons are quarks connected by strings, like rubber bands – illustrated in Figure 134 and Figure 135 – and that the force or tension k between the quarks is thus constant over distance.

We assume that the strings, whose length we call $2r_0$, rotate around their centre of mass as rapidly as possible, as shown in Figure 135. Then we have

$$v(r) = c\frac{r}{r_0} \,. \tag{79}$$

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

Assuming that $m_u = m_d$ and that the quark magnetic moment is proportional to their charge, the quark model predicts a ratio of the magnetic moments of the proton and the neutron of

$$\frac{\mu_p}{\mu_n} = -\frac{3}{2} \,. \tag{77}$$

This prediction differs from measurements only by 3 %. Furthermore, using the same values for the magnetic moment of the quarks, magnetic moment values of over half a dozen of other baryons can be predicted. The results typically deviate from measurements only by around 10 %. In particular, the sign of the resulting baryon magnetic moment is always correctly calculated.

* *

The quark model describes all *quantum numbers* of mesons and baryons. P-parity, C-parity, and the absence of certain meson parities are all reproduced. The observed conservation of electric charge, baryon number, isospin, strangeness etc. is reproduced. Hadron family diagrams such as those shown in Figure 131 and in Figure 132 describe all existing hadron states (of lowest angular momentum) *completely*; the states not listed are not observed. The quark model thus produces a complete and correct classification of all hadrons as bound states of quarks.

* *

The quark model also explains the *mass spectrum* of hadrons. The best predictions are made by QCD lattice calculations. With months of computer time, researchers were able
Ref. 189 to reproduce the masses of proton and neutron to within a few per cent. Interestingly, if one sets the u and d quark masses to zero, the resulting proton and neutron mass
Ref. 190 differ from experimental values only by 10 %. The mass of protons and neutrons is almost
Page 233 completely due to the binding, not to the constituents. More details are given below.

* *

The number of colours of quarks must be taken into account to get correspondence of theory and calculation. For example, the measured decay time of the neutral pion is 83 as. The calculation without colour gives 750 as; if each quark is assumed to appear in 3 colours the value must be divided by 9, and then matches the measurement.

* *

In particle colliders, collisions of electrons and positrons sometimes lead to the production of hadrons. The calculated production rates also fit experiments only if quarks have three colours. In more detail, if one compares the ratio of muon–antimuon production
Challenge 144 s and of hadron production, a simple estimate relates them to their charges:

$$R = \frac{\sum q_{\text{hadrons}}}{\sum q_{\text{muons}}} \tag{78}$$

Between 2 and 4 GeV, when only three quarks can appear, this argument thus predicts $R = 2$ if colours exist, or $R = 2/3$ if they don't. Experiments yield a value of $R = 2.2$, thus

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net



FIGURE 130 A typical experiment used to study the quark model: the Proton Synchroton at CERN in Geneva (© CERN).

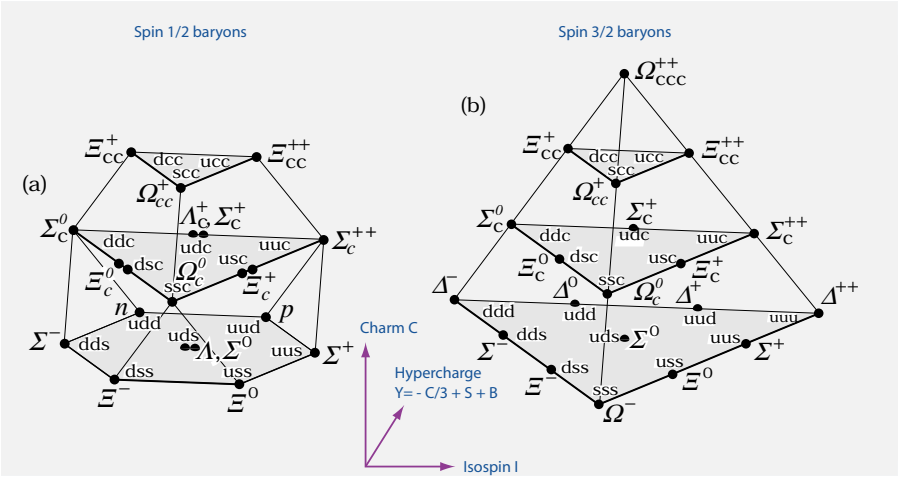


FIGURE 131 The family diagrams for the least massive baryons that can be built as qqq composites of the first four quark types (from Ref. 186).

Ref. 185 to smash them into each other. Many researchers played this game for decades. Obviously, this is a facetious comment; in fact, quantum theory forbids any other method.
Challenge 141 s Can you explain why?

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

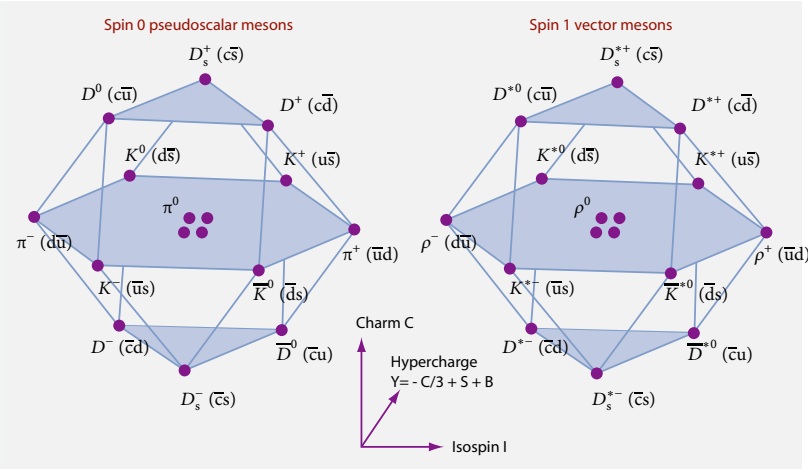


FIGURE 132 The family diagram for the least massive pseudoscalar and vector mesons that can be built as $q\bar{q}$ composites of the first four quark flavours.

Understanding the structure of particles by smashing them into each other is not simple. Imagine that you want to study how cars are built just by crashing them into each other. Before you get a list of all components, you must perform and study a non-negligible number of crashes. Most give the same result, and if you are looking for a particular part, you might have to wait for a long time. If the part is tightly attached to others, the crashes have to be especially energetic. In addition, the part most likely will be deformed. Compared to car crashes, quantum theory adds the possibility for debris to transform, to react, to bind and to get excited. Therefore the required diligence and patience is even greater for particle crashes than for car crashes. Despite these difficulties, for many decades, researchers have collected an ever increasing number of proton debris, also called *hadrons*. The list, a small part of which is given in Appendix B, is overwhelmingly long; the official full list, several hundred pages of fine print, is found at pdg.web.cern.ch and contains hundreds of hadrons. Hadrons come in two main types: integer spin hadrons are called *mesons*, half-integer spin hadrons are called *baryons*. The proton and the neutron themselves are thus baryons.

Page 342

Then came the quark model. Using the ingenuity of many experimentalists and theoreticians, the quark model explained the whole meson and baryon catalogue as a consequence of only 6 types of bound quarks. Typically, a large part of the catalogue can be structured in graphs such as the ones given in Figure 132 and Figure 131. These graphs were the beginning of the end of high energy physics. The quark model explained all quantum numbers of the debris, and allowed understanding their mass ratios as well as their decays.

The quark model explained why debris come into two types: all *mesons* consist of a

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

ing to the eight gluon types – is given, for example, by the set of the *Gell-Mann matrices*

$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \quad \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

$$\lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \quad \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix} . \quad (75)$$

There are eight matrices, one for each gluon type, with 3×3 elements, due to the 3 colours of the strong interaction. There is no ninth gluon, because that gluon would be colourless, or 'white'.

The Lagrangian is complete only when the 6 quark masses and the coupling constant g_s are included. These values, like the symmetry group SU(3), are not explained by QCD, of course.

Only quarks and gluons appear in the Lagrangian of QCD, because only quarks and gluons interact via the strong force. This can be also expressed by saying that only quarks and gluons carry colour; *colour* is the source of the strong force in the same way that electric charge is the source of the electromagnetic field. In the same way as electric charge, colour charge is *conserved* in all interactions. Electric charge comes in two types, positive and negative; in contrast, colour comes in three types, called *red*, *green* and *blue*. The neutral state, with no colour charge, is called *white*. Protons and neutrons, but also electrons or neutrinos, are thus 'white', thus *neutral* for the strong interaction.

In summary, the six quark types interact by exchanging eight gluon types. The interaction is described by the Feynman diagrams of Figure 133, or, equivalently, by the Lagrangian (71). Both descriptions follow from the requirements that the gauge group is SU(3) and that the masses and coupling constants are given. It was a huge amount of work to confirm that all experiments indeed agree with the QCD Lagrangian; various competing descriptions were discarded.

Experimental consequences of the quark model

How can we pretend that quarks and gluons exist, even though they are never found alone? There are a number of arguments in favour.

* *

The quark model explains the non-vanishing magnetic moment of the neutron and explains the magnetic moments μ of the baryons. By describing the proton as a *uud* state and the neutron a *udd* state with no orbital angular momentum and using the precise wave functions, we get

Challenge 143 e

$$\mu_u = \tfrac{1}{5}(4\mu_p + \mu_n) \quad \text{and} \quad \mu_d = \tfrac{1}{5}(4\mu_n + \mu_p) . \quad (76)$$

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

In QCD, the eight gluons are massless; also this property is taken from experiment. Therefore no gluon mass term appears in the Lagrangian. It is easy to see that massive gluons would spoil gauge invariance. As mentioned above, in contrast to electromagnetism, where the gauge group U(1) is Abelian, the gauge group SU(3) of the strong interactions is non-Abelian. As a consequence, the colour field itself is charged, i.e., carries colour, and thus the index a appears on the fields A and F. As a result, gluons can interact with each other, in contrast to photons, which pass each other undisturbed. The first two diagrams of Figure 133 are thus reflected in the somewhat complicated definition of the field $F^{(a)}_{\mu\nu}$. In contrast to electrodynamics, the definition has an extra term that is *quadratic* in the fields A; it is described by the so-called structure constants f_{abc} and the interaction strength g_s. The numbers f_{abc} are the structure constants of the SU(3).

Challenge 142 ny

Page 361

The behaviour of the gauge transformations and of the gluon field is described by the eight matrices $\lambda^a_{k,l}$. They are a fundamental, 3-dimensional representation of the *generators* of the SU(3) algebra and correspond to the eight gluon types. The matrices $\lambda_a, a = 1...8$, and the structure constants f_{abc} obey the relations

$$[\lambda_a, \lambda_b] = 2if_{abc}\lambda_c$$
$$\{\lambda_a, \lambda_b\} = 4/3\delta_{ab}I + 2d_{abc}\lambda_c \qquad (73)$$

where I is the unit matrix. The structure constants f_{abc} of SU(3), which are odd under permutation of any pair of indices, and d_{abc}, which are even, have the values

abc	f_{abc}	abc	d_{abc}	abc	d_{abc}
123	1	118	$1/\sqrt{3}$	355	1/2
147	1/2	146	1/2	366	−1/2
156	−1/2	157	1/2	377	−1/2
246	1/2	228	$1/\sqrt{3}$	448	$-1/(2\sqrt{3})$
257	1/2	247	−1/2	558	$-1/(2\sqrt{3})$
345	1/2	256	1/2	668	$-1/(2\sqrt{3})$
367	−1/2	338	$1/\sqrt{3}$	778	$-1/(2\sqrt{3})$
458	$\sqrt{3}/2$	344	1/2	888	$-1/\sqrt{3}$
678	$\sqrt{3}/2$				

(74)

All other elements vanish. Physically, the structure constants of SU(3) describe the details of the interaction between quarks and gluons and of the interaction between the gluons themselves.

A fundamental 3-dimensional representation of the eight generators λ_a – correspond-

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

TABLE 17 The quarks.

QUARK	MASS m (SEE TEXT)	SPIN J PARITY P	POSSIBLE COLOURS; POSSIBLE WEAK BEHAVIOUR	CHARGE Q, ISOSPIN I, STRANGENESS S, CHARM C, BEAUTY B', TOPNESS T	LEPTON NUMBER L, BARYON NUMBER B
Down d	4.5 to 5.5 MeV/c^2	$\frac{1}{2}^+$	red, green, blue; singlet, doublet	$-\frac{1}{3}, -\frac{1}{2}, 0, 0, 0, 0$	$0, \frac{1}{3}$
Up u	1.8 to 3.0 MeV/c^2	$\frac{1}{2}^+$	red, green, blue; singlet, doublet	$+\frac{2}{3}, +\frac{1}{2}, 0, 0, 0, 0$	$0, \frac{1}{3}$
Strange s	95(5) MeV/c^2	$\frac{1}{2}^+$	red, green, blue; singlet, doublet	$-\frac{1}{3}, 0, -1, 0, 0, 0$	$0, \frac{1}{3}$
Charm c	1.275(25) GeV/c^2	$\frac{1}{2}^+$	red, green, blue; singlet, doublet	$+\frac{2}{3}, 0, 0, +1, 0, 0$	$0, \frac{1}{3}$
Bottom b	4.18(3) GeV/c^2	$\frac{1}{2}^+$	red, green, blue; singlet, doublet	$-\frac{1}{3}, 0, 0, 0, -1, 0$	$0, \frac{1}{3}$
Top t	173.5(1.4) GeV/c^2	$\frac{1}{2}^+$	red, green, blue; singlet, doublet	$+\frac{2}{3}, 0, 0, 0, 0, +1$	$0, \frac{1}{3}$

quark and an antiquark and thus have integer spin; all *baryons* consist of three quarks, and thus have half-integer spin. In particular, the proton and the neutron are seen as combinations of two quark types, called *up* (u) and *down* (d): the proton is a *uud* state, the neutron a *udd* state. The discovery of other hadrons lead to the addition of four additional types of quarks. The quark names are somewhat confusing: they are called *strange* (s), *charm* (c), *bottom* (b) – also called 'beauty' in the old days – and *top* (t) – called 'truth' in the past. The quark types are called *flavours*; in total, there are thus 6 quark flavours in nature.

All quarks have spin one half; they are fermions. Their electric charges are multiples of 1/3 of the electron charge. In addition, quarks carry a strong charge, called, again confusingly, *colour*. In contrast to electromagnetism, which has only positive, negative, and neutral charges, the strong interaction has red, blue, green quarks on one side, and anti-red, anti-blue and anti-green on the other. The neutral state is called 'white'. All baryons, including proton and neutrons, and all mesons are white, in the same way that all atoms are neutral.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

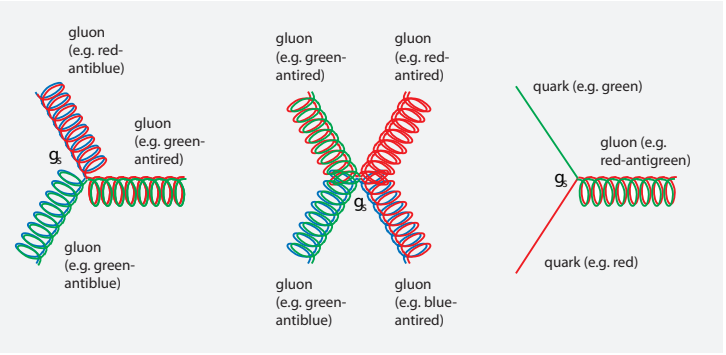


FIGURE 133 The essence of the QCD Lagrangian: the Feynman diagrams of the strong interaction.

The essence of quantum chromodynamics

The theory describing the bound states of quarks is called *quantum chromodynamics*, or QCD. It was formulated in its final form in 1973 by Fritzsch, Gell-Mann and Leutwyler. In the same way that in atoms, electrons and protons are held together by the exchange of virtual photons, in protons, quarks are held together by the exchange of virtual gluons. *Gluons* are the quanta of the strong interaction, and correspond to photons, the quanta of the electromagnetic interactions.

Ref. 187

Quantum chromodynamics describes all motion due to the strong interaction with the three fundamental processes shown in Figure 133: two gluons can scatter, a gluon can emit or absorb another, and a quark can emit or absorb a gluon. In electrodynamics, only the last diagram is possible; in the strong interaction, the first two appear as well. Among others, the first two diagrams are responsible for the confinement of quarks, and thus for the lack of free quarks in nature.

Ref. 188

QCD is a *gauge* theory: the fields of the strong interaction show gauge invariance under the Lie group SU(3). We recall that in the case of electrodynamics, the gauge group is U(1), and Abelian, or commutative. In contrast, SU(3) is non-Abelian; QCD is a non-Abelian gauge theory. Non-Abelian gauge theory was invented and popularized by Wolfgang Pauli. It is often incorrectly called *Yang–Mills theory* after the first two physicists who wrote down Pauli's ideas.

Due to the SU(3) gauge symmetry, there are 8 gluons; they are called red-antigreen, blue-antired, etc. Since SU(3) is non-Abelian, gluons interact among themselves, as shown in the first two processes in Figure 133. Out of the three combinations red-antired, blue-antiblue and green-antigreen, only two gluons are linearly independent, thus giving a total of $3^2 - 1 = 8$ gluons.

The coupling strength of the strong interaction, its three fundamental processes in Figure 133, together with its SU(3) gauge symmetry and the observed number of six quarks, completely determine the behaviour of the strong interaction. In particular, they completely determine its Lagrangian density.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net

The Lagrangian of quantum chromodynamics*

The Lagrangian density of the strong interaction can be seen as a complicated formulation of the Feynman diagrams of Figure 133. Indeed, the Lagrangian density of quantum chromodynamics is

$$\mathcal{L}_{QCD} = -\tfrac{1}{4} F^{(a)}_{\mu\nu} F^{(a)\mu\nu} - c^2 \sum_q m_q \overline{\psi}^k_q \psi_{qk} + i\hbar c \sum_q \overline{\psi}^k_q \gamma^\mu (D_\mu)_{kl} \psi^l_q \qquad (71)$$

where the gluon field strength and the gauge covariant derivative are

$$F^{(a)}_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g_s f_{abc} A^b_\mu A^c_\nu$$

$$(D_\mu)_{kl} = \delta_{kl}\partial_\mu - i\frac{g_s}{2}\sum_a \lambda^a_{k,l} A^a_\mu \,.$$

Vol. I, page 278

We remember from the section on the principle of least action that Lagrangians are always sums of scalar products; this is clearly seen in expression (71). The index $a = 1 \ldots 8$ numbers the eight types of gluons and the index $k = 1, 2, 3$ numbers the three colours, all due to SU(3). The index $q = 1 \ldots 6$ numbers the six quark flavours. The fields $A^a_\mu(x)$ are the eight gluon fields, represented by the coiled lines in Figure 133. The fields $\psi^k_q(x)$ are those of the quarks of flavour q and colour k, represented by the straight line in the figure. The six times three quark fields, like those of any elementary fermion, are 4-component Dirac spinors with masses m_q.**

The Lagrangian (71) is that of a *local* field theory: observables are functions of position. In other words, QCD is similar to quantum electrodynamics and can be compared to experiment in the same way.

The first term of the Lagrangian (71) represents the kinetic energy of the radiation (the gluons), the second or mass term the kinetic energy of the matter particles (the quarks) and the third term the interaction between the two.

The mass term in the Lagrangian is the only term that spoils or *breaks flavour symmetry*, i.e., the symmetry under exchange of quark types. (In particle physics, this symmetry is also called *chiral symmetry*, for historical reasons.) Obviously, the mass term also breaks space-time conformal symmetry.

The interaction term in the Lagrangian thus corresponds to the third diagram in Figure 133. The strength of the strong interaction is described by the *strong coupling constant* g_s. The constant is independent of flavour and colour, as observed in experiment. The Interaction term does not mix different quarks; as observed in experiments, flavour is conserved in the strong interaction, as is baryon number. The strong interaction also conserves spatial parity P and charge conjugation parity C. The strong interaction does not transform matter.

* This section can be skipped at first reading.

** In their simplest form, the matrices γ_μ can be written as

$$\gamma_0 = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix} \quad \text{and} \quad \gamma_n = \begin{pmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{pmatrix} \quad \text{for } n = 1, 2, 3 \qquad (72)$$

Vol. IV, page 230

where the σ^i are the Pauli spin matrices.

Motion Mountain – The Adventure of Physics copyright © Christoph Schiller June 1990–March 2018 free pdf file available at www.motionmountain.net