Springer Handbook *of* Materials Data

Warlimont
Martienssen
Editors

2nd Edition

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Springer Handbook of Materials Data

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Springer Handbook of Materials Data

Hans Warlimont, Werner Martienssen (Eds.)

2nd Edition
With 1110 Figures and 1007 Tables

Springer

Editors

Hans Warlimont
Am Neuseser Weinberg 2
63579 Freigericht, Germany

Werner Martienssen †
Frankfurt am Main, Germany

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Preface to the First Edition

The Springer Handbook of Condensed Matter and Materials Data is the realization of a new concept in reference literature, which combines introductory and explanatory texts with a compilation of selected data and functional relationships from the fields of solid-state physics and materials in a single volume. The data have been extracted from various specialized and more comprehensive data sources, in particular the Landolt–Börnstein data collection, as well as more recent publications. This Handbook is designed to be used as a desktop reference book for fast and easy finding of essential information and reliable key data. References to more extensive data sources are provided in each section. The main users of this new Handbook are envisaged to be students, scientists, engineers, and other knowledge-seeking persons interested and engaged in the fields of solid-state sciences and materials technologies.

The editors have striven to find authors for the individual sections who were experienced in the full breadth of their subject field and ready to provide succinct accounts in the form of both descriptive text and representative data. It goes without saying that the sections represent the individual approaches of the authors to their subject and their understanding of this task. Accordingly, the sections vary somewhat in character. While some editorial influence was exercised, the flexibility that we have shown is deliberate. The editors are grateful to all of the authors for their readiness to provide a contribution, and to cooperate in delivering their manuscripts and by accepting essentially all alterations which the editors requested to achieve a reasonably coherent presentation.

An onerous task such as this could not have been completed without encouragement and support from the publisher. Springer has entrusted us with this novel project, and Dr. Hubertus von Riedesel has been a persistent but patient reminder and promoter of our work throughout. Dr. Rainer Poerschke has accompanied and helped the editors constantly with his professional attitude and very personable style during the process of developing the concept, soliciting authors, and dealing with technical matters. In the later stages, Dr. Werner Skolaut became a relentless and hard-working member of our team with his painstaking contribution to technically editing the authors' manuscripts and linking the editors' work with the copy editing and production of the book.

We should also like to thank our families for having graciously tolerated the many hours we have spent in working on this publication.

We hope that the users of this Handbook, whose needs we have tried to anticipate, will find it helpful and informative. In view of the novelty of the approach and any possible inadvertent deficiencies which this first edition may contain, we shall be grateful for any criticisms and suggestions which could help to improve subsequent editions so that they will serve the expectations of the users even better and more completely.

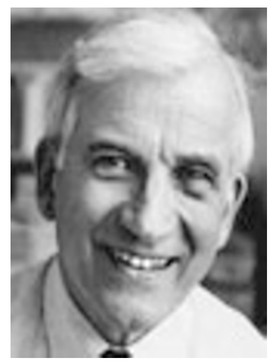
September 2004
Frankfurt am Main, Dresden

Werner Martienssen,
Hans Warlimont

About the Editors

Hans Warlimont studied Physical Metallurgy at the School of Mines in Clausthal, Germany, and received his Dr. rer. nat. Degree from the University of Stuttgart. From 1959 to 1962, he worked in the Fundamental Research Laboratory of U.S. Steel Co-operation, Monroeville, USA. From 1962 to 1974, he headed a research group at the Max-Planck-Institute for Metals Research in Stuttgart, Germany. From 1974 to 1977, he worked as Head of the Advanced Materials Division of Swiss Aluminum AG in Switzerland. From 1977 to 1991, he was Head of Research and Development of Vacuumschmelze Hanau, Germany. From 1991 to 1992, he was Authorized Representative for Corporate R & D of Metallgesellschaft Frankfurt/Main. From 1992 to 1998, he was Scientific Director of the Institute of Solid State and Materials Research Dresden and was Professor of Materials Science at the Dresden University of Technology. His main research areas were structural phase transformations and their effects on the physical and mechanical properties of metals.

Werner Martienssen (1923–2010) was for many years editor-in-chief of the data collection Landolt–Börnstein, which is now part of SpringerMaterials. He studied physics and chemistry at the Universities of Würzburg and Göttingen, and obtained his Ph.D. in physics with R.W. Pohl, Gottingen. Before joining the University of Frankfurt/Main in 1961 as a full professor, he was visiting professor at the Cornell University, Ithaca, USA, and taught physics at the University of Stuttgart. His research focused on condensed matter physics, quantum optics and chaotic dynamics. Two of his former students and coworkers, Gerd K. Binnig and Horst L. Stormer, became Nobel laureates in physics. Werner Martienssen was a member of the German Academy of Sciences Leopoldina, Halle and of the Academy of Sciences in Göttingen.



List of Authors

Peter Albers
Evonik Technology & Infrastructure GmbH
Hanau, Germany
peter.albers@evonik.com

Wolf Assmus
Johann Wolfgang Goethe-University
Department of Physics
Max-von-Laue-Str. 1
60438 Frankfurt am Main, Germany
assmus@physik.uni-frankfurt.de

Fabrice Charra
Commissariat à l'Énergie Atomique, Saclay
Département de Recherche sur l'État Condensé, les Atomes et les Molécules DRECAM-SPCSI, Centre d'Études de Saclay
91191 Gif-sur-Yvette, France
fabrice.charra@cea.fr

Gianfranco Chiarotti (deceased)

Hajo Dieringa
Helmholtz-Zentrum Geesthacht
Magnesium Technology at MagIC
Geesthacht, Germany
hajo.dieringa@hzg.de

Claus Fischer
formerly Institute for Solid State and Materials Research (IFW)
Georg-Schumann-Str. 20
01187 Dresden, Germany
a_c.fischerdd@t-online.de

Jens Freudenberger
formely Leibniz-Institute for Solid State and Materials Research Dresden
Dept. of Metal Physics
Dresden, Germany
j.freudenberger@ifw-dresden.de

Günter Fuchs
formely Leibniz-Institute for Solid State and Materials Research Dresden
Dept. of Metal Physics
Dresden, Germany
fuchs@ifw-dresden.de

Frank E. Goodwin
International Zinc Association
Dept. of Technology & Market Development
Durham, NC, USA
fgoodwin@zinc.org

Susana Gota-Goldmann
Commissariat à l'Energie Atomique (CEA)
Direction de la Recherche Technologique (DRT)
Centre de Fontenay aux Roses BP 6
92265 Fontenay aux Roses Cédex, France
susana.gota-goldmann@cea.fr

Sivaraman Guruswamy
Salt Lake City, UT, USA
s.guruswamy@utah.edu

Gagik G. Gurzadyan
Garching, Germany
gurzadyan@dlut.edu.cn

Hideki Harada
Fukaya, Japan
khb16457@nifty.com

Bernhard Holzapfel
Karlsruhe Institute for Technology (KIT)
Institute for Technical Physics
Hermann-von Helmholtz-Platz 1
76344 Eggenstein-Leopoldshafen, Germany
bernhard.holzapfel@kit.edu

Karl Ulrich Kainer
Helmholtz-Zentrum Geesthacht
Magnesium Technology at MagIC
Geesthacht, Germany
karl.kainer@hzg.de

Catrin Kammer
Goslar, Germany
kammer@t-online.de

Wolfram Knabl
Plansee SE
Dept. of Development Business Unit Industries
Reutte, Austria
wolfram.knabl@plansee.com

Alfred Koethe
formely Leibniz-Institute for Solid State and Materials Research Dresden
Dept. of Metal Physics
Dresden, Germany
alfred.koethe@web.de

Dieter Krause
Mainz, Germany

Manfred Dieter Lechner
Universität Osnabrück
Institut für Chemie – Physikalische Chemie
Osnabrück, Germany
lechner@uni-osnabrueck.de

Gerhard Leichtfried
University of Innsbruck
Innsbruck, Austria
gerhard.leichtfried@uibk.ac.at

Werner Martienssen (deceased)

Toshio Mitsui
Takarazuka, Japan
t-mitsui@jttk.zaq.ne.jp

Manfred Müller
formely Leibniz-Institute for Solid State and Materials Research Dresden
Dept. of Metal Physics
Dresden, Germany
m.mueller331@googlemail.com

Sergei Pestov
Moscow Technological University
Institute of Fine Chemical Technologies,
Department of Physical Chemistry
Moskau, Russian Federation
pestovsm@yandex.ru

Udo W. Pohl
Technical University of Berlin
Institute of Solid State Physics
Berlin, Germany
pohl@physik.tu-berlin.de

Karsten Ruth
Umicore AG & Co. KG
Hanau, Germany
karsten.ruth@eu.umicore.com

Günther Schlamp
Steinbach, Germany

Barbara Schüpp-Niewa
MINT-Kolleg Baden-Württemberg
University of Stuttgart
Stuttgart, Germany
barbara.schuepp-niewa@mint-kolleg.de

Roland Stickler
Vienna, Austria
roland.stickler@univie.ac.at

Pancho Tzankov
Technical University of Berlin
Institute of Solid State Physics
Berlin, Germany
tzankov@mbi-berlin.de

Volkmar Vill
Helmholtz-Zentrum Geesthacht
Magnesium Technology at MagIC
Geesthacht, Germany
vill@chemie.uni-hamburg.de

Hans Warlimont
formely Leibniz-Institute for Solid State and Materials Research Dresden
Dept. of Metal Physics
Dresden, Germany
warlimont.dsl@t-online.de

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Part B Metals

Part D Functional Materials

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List of Abbreviations

0-D	zero-dimensional
1-D	one-dimensional
1D-LPS	one-dimensional long-period superstructure
2-D	two-dimensional
2D-LPS	two-dimensional long-period superstructure
3-D	three-dimensional
4-D	four-dimensional
5-D	five-dimensional
6-D	six-dimensional

A

ABS	poly(acrylonitrile-co-butadiene-co-styrene)
AFM	atomic force microscopy
ARUPS	angle-resolved ultraviolet photoemission spectroscopy
ASA	poly(acrylonitrile-co-styrene-co-acrylester)
ASW	acoustic surface wave
A-TEM	analytical transmission electron microscopy
a.u.	atomic unit

B

BBO	beta barium borate
bcc	body-centered cubic
BCS	Bardeen–Cooper–Schrieffer
BET	Brunauer–Emmett–Teller
BGB	basal grain boundary
BMC	bulk molding compound
BP	band pass

C

CA	cellulose acetate
CAB	cellulose acetobutyrate
CAS	chemically active species
CBN	cubic boron nitride
CBO	cesium borate
CCT	continuous-cooling-transformation
CE	carbon equivalent
CG	compacted graphite
CGO	conventional grain-oriented
CIGS	copper indium gallium diselenide
CLBO	cesium lithium borate
CMOS	complementary metal–oxide–semiconductor
COC	cycloolefine copolymer
CP	cellulose propionate
CP	cross polarization
cp-Ti	commercially pure titanium
CT	computed tomography
CVD	chemical vapor deposition

D

DAP	diallylphthalate
DAS	dimer–adatom–stacking fault
DB	dangling bond
DBR	distributed Bragg reflector
DBTT	ductile–brittle transition temperature
DDT	dichloro diphenyl trichloroethane
DFB	distributed feedback
DFG	difference frequency generation
DFT	density functional theory
DLAP	deuterated L-arginine phosphate
DMC	dough molding compound
DOP	dioctyl phthalate
DOS	density of states
DP	depth profiling
DSC	differential scanning calorimetry
DTA	differential thermal analysis

E

EAA	poly(ethylene-co-acrylic acid)
EB	electron-beam melting
EC	ethyl cellulose
ECB	edge colony boundary
ECS	electron capture spectroscopy
ECTFE	poly(ethylene-co-chlorotrifluoroethylene)
EDTA	ethylenediaminetetraacetic acid
EDX	energy-dispersive X-ray microanalysis
EELS	electron-energy loss spectroscopy
EFP	explosively formed penetrator
EGB	edge crystal grain boundary
EIM	polyethylene ionomer
ELC	extra low carbon
EP	epoxide, epoxy
EPDM	ethylene/propylene/diene-rubber
ERD	elastic recoil detection
ESA	electrokinetic sonic amplitude
ESCA	electron spectroscopy for chemical analysis
ETFE	poly(ethylene-co-tetrafluoroethylene)
EVA	poly(ethylene-co-vinylacetate)
EXAFS	extended x-ray absorption fine structure

F

fcc	face-centered cubic
FEP	poly(tetrafluoroethylene-co-hexafluoropropylene)

FE-SEM	field-emission scanning electron microscopy
FF	flux flow
FG	flake graphite
FL	fully lamellar
FOM	figure of merit

G

GAR	grain aspect ratio
GD-MS	glow discharge mass spectrometry
GMC	granulated molding compound
GMR	giant magnetoresistance
GO	grain-oriented
GP	Guinier–Preston
GSD	grain size distribution

H

HATOF	helium atom time-of-flight spectroscopy
HB	Brinell hardness number
HCN	hydrocyanic acid
hcp	hexagonal close-packed
HDPE	high density polyethylene
HEIS	high-energy ion scattering/high-energy ion scattering spectroscopy
HGO	high permeability grain-oriented
hh	heavy hole
HI	high impact (modifier)
HK	Knoop hardness
HMF	heavy-metal fluoride
HMO	heavy-metal oxide
HOPG	highly oriented pyrolytic graphite
HP	high pressure
HPDC	high-pressure die casting
HPO	hydroxylamine phosphate oxime process
HRA	Rockwell hardness A scale
HRTEM	high-resolution transmission electron microscopy
HSLA	high-strength low-alloy
HT	high temperature
HTSC	high-temperature superconductor
HV	Vickers hardness

I

IACS	International Annealed Copper Standard
IBA	ion bombardment and annealing
IBAD	ion-beam-assisted deposition
IC	ion chromatography
ICP	inductively coupled plasma
ICP-MS	inductively coupled plasma spectroscopy-mass spectrometry
ICP-OES	inductively coupled plasma spectroscopy-optical emission spectral analysis
IINS	inelastic incoherent neutron scattering
IPS	in-plane-switching
IR	infrared spectroscopy
IR-DRIFT	infrared spectroscopy diffuse reflection
iso	isotactic
ISS	ion scattering spectroscopy
IT	isothermal transformation
ITO	indium tin oxide
i-XPS	imaging x-ray photoelectron spectroscopy

J

JDOS	joint density of state

K

KE	kinetic energy
KRIPES	K-resolved inverse photoelectron spectroscopy

L

LA	longitudinal acoustic
LB	Langmuir–Blodgett
LBO	lithium triborate
LC	liquid crystal
LCD	liquid crystal display
LCM	LC materials
LCP	liquid crystal polymer
LDA	local-density approximation
LDPE	low density polyethylene
LEED	low-energy electron diffraction
LEIS	low-energy ion scattering/low-energy ion scattering spectroscopy
lh	light hole
LHPC	low-heat Portland cement
LLDPE	linear low density polyethylene
LP	long pass filter
LPE	liquid phase epitaxy
LS	laser scattering

M

MAS	magic-angle spinning
MBE	molecular-beam epitaxy
MDPE	medium density polyethylene
MEIS	medium-energy ion scattering/medium-energy ion scattering spectroscopy
MF	melamine formaldehyde
MF	multifilamentary
MFL	modified fully lamellar
MFM	magnetic force microscopy
MMT	methylcyclopentadienyl manganese tricarbonyl
MNL	modified nearly lamellar
MOCVD	metal organic chemical vapor deposition
MP	multiphase
MPC	modified Portland cement
MQW	multiple quantum well
MTJ	magnetic tunnel junction

mu	monomer unit
MVA-TFT	multidomain vertical alignment thin film transistor

N

n-D	*n*-dimensional
ND	neutron diffraction
NG	near-gamma
NL	nearly lamellar
NMR	nuclear magnetic resonance
NO	nonoriented
NOL	nano-oxide layer
NPC	normal or ordinary Portland cement
NRA	nuclear reaction analysis
NRC	new RheoCast process
n.u.	natural unit

O

OD	optical density
ODS	oxide-dispersion-strengthened
OPO	optical parametric oscillation

P

PA	polyamide
PA11	polyamide 11
PA12	polyamide 12
PA6	polyamide 6
PA610	polyamide 610
PA66	polyamide 66
PAI	poly(amide imide)
PB	polybutene
PBT	poly(butylene terephthalate)
PBT-GF	glasfiber reinforced poly(butylene terephthalate)
PC	polycarbonate
PCB	printed circuit board
pcr	partially crystalline
PCTFE	polychlorotrifluoroethylene
PE	polyethylene
PED	photoelectron diffraction
PEEK	polyether ether ketone
PEFC	proton-exchange fuel cell
PEI	poly(ether imide)
PEM	polymer electrolyte membrane
PES	poly(ether sulfone)
PET	poly(ethylene terephthalate)
PF	phenol formaldehyde
PGM	platinum group metal
PI	polyimide
PIB	polyisobutylene
PILC	paper insulated lead-sheathed cable
PIT	powder-in-tube
PL	photoluminescence
PLD	pulsed laser deposition
PLE	photoluminescence excitation
PLZT	La-modified PZT
P/M	powder metallurgy
PMMA	poly(methyl methacrylate)
PMP	poly(4-methyl-1-pentene)
POM	poly(oxymethylene)
POM-R	poly(oxymethylene-co-ethylene)
PP	polypropylene
PPE	poly(phenylene ether)
PPS	poly(phenylene sulfide)
PS	polystyrene
PSD	particle size distribution
PSU	polysulfone
PSZ	partially stabilized zirconia
PTFE	polytetrafluoroethylene
PUR	polyurethane
PVC-P1	plastisized polyvinyl chloride (75/25)
PVC-P2	plastisized polyvinyl chloride (60/40)
PVC-U	unplastisized polyvinyl chloride
PVK	poly(vinyl carbazole)
PZT	piezoelectric material

Q

QCSE	quantum-confined Stark effect
QENS	quasielastic neutron scattering
QW	quantum well
QWR	quantum wire

R

RABiTS	rolling assisted bi-axially textured substrate
RAS	reflectance anisotropy spectroscopy
RBA	Rutherford backscattering analysis
RD	rolling direction
RE	rare earth
RHEED	reflection high-energy electron diffraction
RHPC	rapid-hardening Portland cement
RIE	reactive ion etching
RRR	residual resistivity ratio
RT	room temperature
RTP	room temperature and standard pressure
RW	weighted sound reduction

S

SAN	poly(styrene-co-acrylonitrile)
SAW	surface acoustic wave
SB	poly(styrene-co-butadiene)
SBW	semi borosilicate Wertheim
SBZ	surface Brillouin zone
SCB	small-angle colony boundary
SCL	shaped charge liner
SCLS	surface core level shift
SCR	selective catalytic reduction
SDD	silicon drift detector
SDR	surface differential reflectivity
SE	secondary electron
SEM	scanning electron microscopy

SERS	surface-enhanced Raman scattering
SFG	sum frequency generation
SG	spheroidal graphite
SH	second harmonic
SHG	second-harmonic generation
SI	International System of Units
SIMS	secondary-ion mass spectrometry
SNMS	secondary neutral mass spectrometry
SNR	signal-to-noise ratio
SPARPES	spin-polarized angle-resolved photoemission spectroscopy
SPLEED	spin-polarized low-energy electron diffraction
SQUID	superconducting quantum interference device
SRI	sound reduction index
SRPC	sulfate-resisting Portland cement
SSMP	semi-solid metal processing
SS-XPS	small-spot x-ray photoelectron spectroscopy
STA	simultaneous thermal analysis
STC	sound transmission classification
STEM	scanning transmission electron microscopy
STM	scanning tunneling microscopy
STN	supertwisted nematic
STP	standard temperature and pressure
syn	syndiotactic

T

TA	transverse acoustic
TAFF	thermally activated flux flow
TAS	thallium arsenic selenide
TC	temperature coefficient
TCR	temperature coefficient of resistivity
TE	transverse-electric
TEC	thermal expansion coefficient
TEM	transmission electron microscopy
TFT	thin-film transistor
TG	thermogravimetry
THF	tetrahydrofuran
TM	transverse-magnetic
TMR	tunnel magnetoresistance
TMT	thermomechanical treatment
TN	twisted nematic
TO	transverse optical branch
TOW	time of wetness
TPD	thermally programmed desorption
TPO	thermally programmed oxidation
TPR	thermally programmed reduction
TPU	thermoplastic polyurethane elastomer
TrFE	trifluoroethylene
TTT	time-temperature-transformation

U

UF	urea formaldehyde
UHMWPE	ultrahigh molecular weight polyethylene
ULE	ultralow expansion
UNS	unified numbering system for metals and alloys
UP	unsaturated polyester
UTS	ultimate tensile strength
UV	ultraviolet radiation

V

VAC	vacuum-arc casting
VCSEL	vertical-cavity surface-emitting laser
VDF	vinylidene fluoride
VEC	valence electron concentration
VF	vulcanized fiber
VFT	Vogel, Fulcher, and Tammann
VIP	viewing independent panel
VLS	vapor–liquid–solid

W

WDX	wavelength-dispersive analysis of X-ray

X

XAFS	x-ray absorption spectroscopy
XANES	x-ray absorption near-edge structure
XPS	x-ray photoelectron spectroscopy
XRD	x-ray diffraction
XRF	x-ray fluorescence

Y

YS	yield stress

Part A

Fundame

Part A Fundamentals

1. The Fundamental Constants

Werner Martienssen†

In the quantitative description of physical phenomena and physical relationships, we find constant parameters which appear to be independent of the scale of the phenomena, independent of the place where the phenomena happen, and independent of the time when the phenomena are observed. These parameters are called fundamental constants. In Sect. 1.1, we give a qualitative description of these basic parameters and explain how recommended values for the numerical values of the fundamental constants are found. In Sect. 1.2, we present tables of the most recently determined recommended numerical values for a large number of those fundamental constants which play a role in solid-state physics and chemistry and in materials science.

1.1 What are the Fundamental Constants and Who Takes Care of Them?

The fundamental constants are constant parameters in the laws of nature. They determine the size and strength of the phenomena in the natural and technological worlds. We conclude from observation that the numerical values of the fundamental constants are independent of space and time; at least, we can say that if there is any dependence of the fundamental constants on space and time, then this dependence must be an extremely weak one. Also, we observe that the numerical values are independent of the scale of the phenomena observed; for example, they seem to be the same in astrophysics and in atomic physics. In addition, the numerical values are quite independent of the environmental conditions. So we have confidence in the idea that the numerical values of the fundamental constants form a set of numbers which are the same everywhere in the world, and which have been the same in the past and will be the same in the future. Whereas the properties of all material objects in nature are more or less subject to continuous change, the fundamental constants seem to represent a constituent of the world which is absolutely permanent.

On the basis of this expected invariance of the fundamental constants in space and time, it appears reasonable to relate the units of measurement for physical quantities to fundamental constants as far as possible. This would guarantee that also the units of measurement become independent of space and time and of environmental conditions. Within the frame work of the International System of Units (Système International d'Unités, abbreviated to SI), the International Committee for Weights and Measures (Comité International des Poids et Mesures, CIPM) has succeeded in relating a large number of units of measurement for physical quantities to the numerical values of selected fundamental constants; however, several units for physical quantities are still represented by prototypes. For example, the unit of length 1 m, is defined as the distance light travels in vacuum during a fixed time; so the unit of length is related to the fundamental constant c, i. e., the speed of light, and the unit of time, 1 s. The unit of mass, 1 kg, however, is still represented by a prototype, the mass of a metal cylinder made of a platinum-iridium alloy, which is carefully stored at the International Office

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for Weights and Measures (Bureau International des Poids et Mesures, BIPM), at Sèvres near Paris. In a few years, however, it might become possible also to relate the unit of mass to one or more fundamental constants.

The fundamental constants play an important role in basic physics as well as in applied physics and technology; in fact, they have a key function in the development of a system of reproducible and unchanging units for physical quantities. Nevertheless, there is, at present, no theory which would allow us to calculate the numerical values of the fundamental constants. Therefore, National Institutes for Metrology (NIM), together with research institutes and university laboratories, are making efforts worldwide to determine the fundamental constants experimentally with the greatest possible accuracy and reliability. This, of course, is a continuous process, with hundreds of new publications every year.

The Committee on Data for Science and Technology (CODATA), established in 1966 as an interdisciplinary, international committee of the International Council of the Scientific Unions (ICSU), has taken the responsibility for improving the quality, reliability, processing, management, and accessibility of data of importance to science and technology. The CODATA task group on fundamental constants, established in 1969, has taken on the job of periodically providing the scientific and technological community with a self-consistent set of internationally recommended values of the fundamental constants based on all relevant data available at given points in time.

What is the meaning of *recommended values* of the fundamental constants?

Many fundamental constants are not independent of one another; they are related to one another by equations which allow one to calculate a numerical value for one particular constant from the numerical values of other constants. In consequence, the numerical value of a constant can be determined either by measuring it directly or by calculating it from the measured values of other constants related to it. In addition, there are usually several different experimental methods for measuring the value of any particular fundamental constant. This allows one to compute an adjustment on the basis of a least-squares fit to the whole set of experimental data in order to determine a set of best-fitting fundamental constants from the large set of all experimental data. Such an adjustment is done today about every four years by the CODATA task group mentioned above. The resulting set of best-fit values is then called the *CODATA recommended values of the fundamental constants* based on the adjustment of the appropriate year.

The Tables in Sect. 1.2 show the CODATA recommended values of the fundamental constants of science and technology based on the 2014 adjustment. This adjustment takes into account all data that became available before 31 December 2014. A detailed description of the adjustment has been published by *Mohr* et al. of the National Institute of Standards and Technology, Gaithersburg, in [1.1, 2].

1.2 The CODATA Recommended Values of the Fundamental Constants

1.2.1 The Most Frequently Used Fundamental Constants

Tables 1.1–1.9 list the CODATA recommended values of the fundamental constants based on the 2014 adjustment.

Table 1.1 Brief list of the most frequently used fundamental constants

Quantity	Symbol and relation	Numerical value	Units	Relative standard uncertainty
Speed of light in vacuum	c	299 792 458	m/s	Exact
Magnetic constant	$\mu_0 = 4\pi \times 10^{-7}$	$12.566370614\ldots \times 10^{-7}$	$\mathrm{N/A^2}$	Exact
Electric constant	$\varepsilon_0 = 1/(\mu_0 c^2)$	$8.854187817\ldots \times 10^{-12}$	F/m	Exact
Newtonian constant of gravitation	G	$6.67408(31) \times 10^{-11}$	$\mathrm{m^3/(kg\,s^2)}$	4.7×10^{-5}
Planck constant	h	$6.626070040(81) \times 10^{-15}$	J s	1.2×10^{-8}
Reduced Planck constant	$\hbar = h/(2\pi)$	$1.054571800(13) \times 10^{-16}$	J s	1.2×10^{-8}
Elementary charge	e	$1.6021766208(98) \times 10^{-19}$	C	6.1×10^{-9}
Fine-structure constant	$\alpha = (1/(4\pi\varepsilon_0))(e^2/(\hbar c))$	$7.2973525664(17) \times 10^{-3}$		2.3×10^{-10}
Magnetic flux quantum	$\Phi_0 = h/(2e)$	$2.067833831(13) \times 10^{-15}$	Wb	6.1×10^{-9}
Conductance quantum	$G_0 = 2e^2/h$	$7.7480917310(18) \times 10^{-5}$	S	2.3×10^{-10}
Rydberg constant	$R_\infty = \alpha^2 m_e c/(2h)$	10973731.568508(65)	1/m	6.6×10^{-12}
Electron mass	m_e	$9.10938356(11) \times 10^{-31}$	kg	1.2×10^{-8}
Proton mass	m_p	$1.672621898(21) \times 10^{-27}$	kg	1.2×10^{-8}
Proton–electron mass ratio	m_p/m_e	1836.15267389(17)		9.5×10^{-11}
Avogadro number	N_A, L	$6.022140857(74) \times 10^{23}$	1/mol	1.2×10^{-8}
Faraday constant	$F = N_A e$	96485.33289(59)	C/mol	6.2×10^{-9}
Molar gas constant	R	8.3144598(48)	J/(mol K)	5.7×10^{-7}
Boltzmann constant	$k = R/N_A$	$1.38064852(79) \times 10^{-23}$	J/K	1.8×10^{-6}
Stefan–Boltzmann constant	$\sigma = (\pi^2/60)[k^4/(\hbar^3 c^2)]$	$5.670367(13) \times 10^{-8}$	$\mathrm{W/(m^2\,K^4)}$	2.3×10^{-6}

1.2.2 Detailed Lists of the Fundamental Constants in Different Fields of Application

Table 1.2 Universal constants

Quantity	Symbol and relation	Numerical value	Units	Relative standard uncertainty
Speed of light in vacuum	c	299 792 458	m/s	Exact
Magnetic constant	$\mu_0 = 4\pi \times 10^{-7}$	$12.566370614\ldots \times 10^{-7}$	$\mathrm{N/A^2}$	Exact
Electric constant	$\varepsilon_0 = 1/(\mu_0 c^2)$	$8.854187817\ldots \times 10^{-12}$	F/m	Exact
Characteristic impedance of vacuum	$Z_0 = (\mu_0/\varepsilon_0)^{1/2} = \mu_0 c$	376.730313461...	Ω	Exact
Newtonian constant of gravitation	G	$6.67408(31) \times 10^{-11}$	$\mathrm{m^3/(kg\,s^2)}$	4.7×10^{-5}
Reduced Planck constant	$\hbar = h/(2\pi)$	$1.054571800(13) \times 10^{-34}$	J s	1.2×10^{-8}
Planck constant	h	$6.626070040(81) \times 10^{-34}$	J s	1.2×10^{-8}
(Ratio)	$G/(\hbar c)$	$6.70861(31) \times 10^{-39}$	$(\mathrm{GeV}/c^2)^2$	4.7×10^{-5}
(Product)	$\hbar c$	197.3269788(12)	MeV fm	6.1×10^{-9}
(Product)	$c_1 = 2\pi hc^2$	$3.741771790(46) \times 10^{-16}$	$\mathrm{W\,m^2}$	1.2×10^{-8}
(Product)	$(1/\pi)c_1 = 2hc^2$	$1.191042953(15) \times 10^{-16}$	$\mathrm{W\,m^2/sr}$	1.2×10^{-8}
(Product)	$c_2 = h(c/k)$	$1.43877736(83) \times 10^{-2}$	m K	5.7×10^{-7}
Stefan–Boltzmann constant	$\sigma = (\pi^2/60)[k^4/(\hbar^3 c^2)]$	$5.670367(13) \times 10^{-8}$	$\mathrm{W/(m^2\,K^4)}$	2.3×10^{-6}
Wien displacement law constant	$b = \lambda_{max} T = c_2/4.965114231$	$2.8977729(17) \times 10^{-3}$	m K	5.7×10^{-7}
Planck mass	$m_P = (\hbar c/G)^{1/2}$	$2.176470(51) \times 10^{-8}$	kg	2.3×10^{-5}
Planck temperature	$T_P = (1/k)(\hbar c^5/G)^{1/2}$	$1.416808(33) \times 10^{32}$	K	2.3×10^{-5}
Planck length	$l_P = \hbar/(m_P c) = (\hbar G/c^3)^{1/2}$	$1.616229(38) \times 10^{-35}$	m	2.3×10^{-5}
Planck time	$t_P = l_P/c = (\hbar G/c^5)^{1/2}$	$5.39116(13) \times 10^{-44}$	s	2.3×10^{-5}

Table 1.3 Electromagnetic constants

Quantity	Symbol and relation	Numerical value	Units	Relative standard uncertainty
Elementary charge	e	$1.6021766208(98) \times 10^{-19}$	C	6.1×10^{-9}
(Ratio)	e/h	$2.417989262(15) \times 10^{14}$	A/J	6.1×10^{-9}
Fine-structure constant	$\alpha = (1/(4\pi\varepsilon_0))(e^2/(\hbar c))$	$7.2973525664(17) \times 10^{-3}$		2.3×10^{-10}
Inverse fine-structure constant	$1/\alpha$	$137.035999139(31)$		2.3×10^{-10}
Magnetic flux quantum	$\Phi_0 = h/(2e)$	$2.067833831(13) \times 10^{-15}$	Wb	6.1×10^{-9}
Conductance quantum	$G_0 = 2e^2/h$	$7.7480917310(18) \times 10^{-5}$	S	2.3×10^{-10}
Inverse of conductance quantum	$1/G_0$	$12906.4037278(29)$	Ω	2.3×10^{-10}
Josephson constant [a]	$K_J = 2e/h$	$483597.8525(30) \times 10^9$	Hz/V	6.1×10^{-9}
Von Klitzing constant [b]	$R_K = h/e^2 = \mu_0 c/(2\alpha)$	$25812.8074555(59)$	Ω	2.3×10^{-10}
Bohr magneton	$\mu_B = e\hbar/(2m_e)$	$927.4009994(57) \times 10^{-26}$ $5.7883818012(26) \times 10^{-5}$	J/T eV/T	6.2×10^{-9} 4.5×10^{-10}
(Ratio)	μ_B/h	$13.996245042(86) \times 10^9$	Hz/T	6.2×10^{-9}
(Ratio)	$\mu_B/(hc)$	$46.68644814(29)$	1/(m T)	6.2×10^{-9}
(Ratio)	μ_B/k	$0.67171405(39)$	K/T	5.7×10^{-7}
Nuclear magneton	$\mu_N = e\hbar/(2m_p)$	$5.050783699(31) \times 10^{-27}$ $3.1524512550(15) \times 10^{-8}$	J/T eV/T	6.2×10^{-9} 4.6×10^{-10}
(Ratio)	μ_N/h	$7.622593285(47)$	MHz/T	6.2×10^{-9}
(Ratio)	$\mu_N/(hc)$	$2.542623432(16) \times 10^{-2}$	1/(m T)	6.2×10^{-9}
(Ratio)	μ_N/k	$3.6582690(21) \times 10^{-4}$	K/T	5.7×10^{-7}

[a] See Table 2.16 for the conventional value adopted internationally for realizing representations of the volt using the Josephson effect.
[b] See Table 2.16 for the conventional value adopted internationally for realizing representations of the ohm using the quantum Hall effect.

Table 1.4 Thermodynamic constants

Quantity	Symbol and relation	Numerical value	Units	Relative standard uncertainty
Avogadro constant	N_A, L	$6.022140857(74) \times 10^{23}$	1/mol	1.2×10^{-8}
Atomic mass constant	$m_u = (1/12)m(^{12}C)$ $= (1/N_A) \times 10^{-3}$ kg	$1.660539040(20) \times 10^{-27}$	kg	1.2×10^{-8}
Energy equivalent of atomic mass constant	$m_u c^2$	$1.492418062(18) \times 10^{-10}$ $931.4940954(57)$	J MeV	1.2×10^{-8} 6.2×10^{-9}
Faraday constant	$F = N_A e$	$96485.33289(59)$	C/mol	6.2×10^{-9}
Molar Planck constant	$N_A h$	$3.9903127110(18) \times 10^{-10}$	J s/mol	4.5×10^{-10}
(Product)	$N_A hc$	$0.119626565582(54)$	J m/mol	4.5×10^{-10}
Molar gas constant	R	$8.3144598(48)$	J/(K mol)	5.7×10^{-7}
Boltzmann constant	$k = R/N_A$	$1.38064852(79) \times 10^{-23}$ $8.6173303(50) \times 10^{-5}$	J/K eV/K	5.7×10^{-7} 5.7×10^{-7}
(Ratio)	k/h	$2.0836612(12) \times 10^{10}$	Hz/K	5.7×10^{-7}
(Ratio)	k/hc	$69.503457(40)$	1/(m K)	5.7×10^{-7}
Molar volume of ideal gas at STP	$V_m = RT/p$ at $T = 273.15$ K and $p = 100$ kPa	$22.710947(13) \times 10^{-3}$	m_3/mol	5.7×10^{-7}
Loschmidt constant	$n_0 = N_A/V_m$	$2.6516467(15) \times 10^{25}$	1/m^3	5.7×10^{-7}
Stefan–Boltzmann constant	$\sigma = (\pi^2/60)[k^4/(\hbar^3 c^2)]$	$5.670367(13) \times 10^{-8}$	W/(m^2 K^4)	2.3×10^{-6}
Wien displacement law constant	$b = \lambda_{max} T = c_2/4.965114231$	$2.8977729(17) \times 10^{-3}$	m K	5.7×10^{-7}

1.2.3 Constants from Atomic Physics and Particle Physics

Table 1.5 Constants from atomic physics

Quantity	Symbol and relation	Numerical value	Units	Relative standard uncertainty
Rydberg constant	$R_\infty = \alpha^2 m_e c/2h$	10973731.568508(65)	1/m	5.9×10^{-12}
(Product)	$R_\infty c$	$3.289841960355(19) \times 10^{15}$	Hz	5.9×10^{-12}
(Product)	$R_\infty hc$	$2.179872325(27) \times 10^{-18}$ 13.605693009(84)	J eV	1.2×10^{-8} 6.1×10^{-9}
Bohr radius	$a_0 = \alpha/(4\pi R_\infty)$ $= 4\pi\varepsilon_0\hbar^2/(m_e e^2)$	$0.52917721067(12) \times 10^{-10}$	m	2.3×10^{-10}
Hartree energy	$E_H = e^2/(4\pi\varepsilon_0 a_0)$ $= 2R_\infty hc = \alpha^2 m_e c^2$	$4.359744650(54) \times 10^{-18}$ 27.21138602(17)	J eV	1.2×10^{-8} 6.1×10^{-9}
Quantum of circulation	$h/(2m_e)$	$3.6369475486(17) \times 10^{-4}$	m^2/s	4.5×10^{-10}
(Product)	h/m_e	$7.2738950972(33) \times 10^{-4}$	m^2/s	4.5×10^{-10}

Table 1.6 Properties of the electron

Quantity	Symbol and relation	Numerical value	Units	Relative standard uncertainty
Electron mass	m_e	$9.10938356(11) \times 10^{-31}$ $5.48579909070(16) \times 10^{-4}$	kg u	1.2×10^{-8} 2.9×10^{-11}
Energy equivalent of electron mass	$m_e c^2$	$8.18710565(10) \times 10^{-14}$ 0.5109989461(31)	J MeV	1.2×10^{-8} 6.2×10^{-9}
Electron–proton mass ratio	m_e/m_p	$5.44617021352(52) \times 10^{-4}$		9.5×10^{-11}
Electron–neutron mass ratio	m_e/m_n	$5.4386734428(27) \times 10^{-4}$		4.9×10^{-10}
Electron–muon mass ratio	m_e/m_μ	$4.83633170(11) \times 10^{-3}$		2.2×10^{-8}
Electron molar mass	$M(e) = N_A m_e$	$5.48579909070(16) \times 10^{-7}$	kg/mol	2.9×10^{-11}
Charge-to-mass ratio	$-e/m_e$	$-1.758820024(11) \times 10^{11}$	C/kg	6.2×10^{-9}
Compton wavelength	$\lambda_C = h/(m_e c)$	$2.4263102367(11) \times 10^{-12}$	m	4.5×10^{-10}
(Ratio)	$\lambda_C/(2\pi) = \alpha a_0 = \alpha^2/(4\pi R_\infty)$	$386.15926764(18) \times 10^{-15}$	m	4.5×10^{-10}
Classical electron radius	$r_e = \alpha^2 a_0$	$2.8179403227(19) \times 10^{-15}$	m	6.8×10^{-10}
Thomson cross section	$\sigma_e = (8\pi/3) r_e^2$	$0.66524587158(91) \times 10^{-28}$	m^2	1.4×10^{-9}
Magnetic moment	μ_e	$-928.4764620(57) \times 10^{-26}$	J/T	6.2×10^{-9}
Ratio of magnetic moment to Bohr magneton	μ_e/μ_B	−1.00115965218091(26)		2.6×10^{-13}
Ratio of magnetic moment to nuclear magneton	μ_e/μ_N	−1838.28197234(17)		9.5×10^{-11}
Ratio of magnetic moment to proton magnetic moment	μ_e/μ_p	−658.2106866(20)		3.0×10^{-9}
Ratio of magnetic moment to neutron magnetic moment	μ_e/μ_n	960.92050(23)		2.4×10^{-7}
Electron magnetic moment anomaly	$a_e = \lvert\mu_e\rvert/(\mu_B - 1)$	$1.15965218091(26) \times 10^{-3}$		2.3×10^{-10}
g-factor	$g_e = -2(1 + a_e)$	−2.00231930436182(52)		2.6×10^{-13}
Gyromagnetic ratio	$\gamma_e = 2\lvert\mu_e\rvert/\hbar$	$1.760859644(11) \times 10^{11}$	1/(s T)	6.2×10^{-9}
(Ratio)	$\gamma_e/(2\pi)$	28024.95164(17)	MHz/T	6.2×10^{-9}

Table 1.7 Properties of the proton

Quantity	Symbol and relation	Numerical value	Units	Relative standard uncertainty
Proton mass	m_p	$1.672621898(21) \times 10^{-27}$ $1.007276466879(91)$	kg u	1.2×10^{-8} 9.0×10^{-11}
Energy equivalent of proton mass	$m_p c^2$	$1.503277593(18) \times 10^{-10}$ $938.2720813(58)$	J MeV	1.2×10^{-8} 6.2×10^{-9}
Proton–electron mass ratio	m_p/m_e	$1836.15267389(17)$		9.5×10^{-11}
Proton–neutron mass ratio	m_p/m_n	$0.99862347844(51)$		5.1×10^{-10}
Proton molar mass	$M(p) = N_A m_p$	$1.007276466879(91) \times 10^{-3}$	kg/mol	9.0×10^{-11}
Charge-to-mass ratio	e/m_p	$9.578833226(59) \times 10^{7}$	C/kg	6.2×10^{-9}
Compton wavelength	$\lambda_{C,p} = h/(m_p c)$	$1.32140985396(61) \times 10^{-15}$	m	4.6×10^{-10}
(Ratio)	$(1/(2\pi))\lambda_{C,p}$	$0.210308910109(97) \times 10^{-15}$	m	4.6×10^{-10}
rms charge radius	R_p	$0.8751(61) \times 10^{-15}$	m	7.0×10^{-3}
Magnetic moment	μ_p	$1.4106067873(97) \times 10^{-26}$	J/T	6.9×10^{-9}
Ratio of magnetic moment to Bohr magneton	μ_p/μ_B	$1.5210322053(46) \times 10^{-3}$		3.0×10^{-9}
Ratio of magnetic moment to nuclear magneton	μ_p/μ_N	$2.7928473508(85)$		3.0×10^{-9}
Ratio of magnetic moment to neutron magnetic moment	μ_p/μ_n	$-1.45989805(34)$		2.4×10^{-7}
g-factor	$g_p = 2\mu_p/\mu_N$	$5.585694702(17)$		3.0×10^{-9}
Gyromagnetic ratio	$\gamma_p = 2\mu_p/\hbar$	$2.67522205(23) \times 10^{8}$	1/(s T)	6.9×10^{-9}
(Ratio)	$(1/(2\pi))\gamma_p$	$42.57747892(29)$	MHz/T	6.9×10^{-9}

Table 1.8 Properties of the neutron

Quantity	Symbol and relation	Numerical value	Units	Relative standard uncertainty
Neutron mass	m_n	$1.674927471(21) \times 10^{-27}$ $1.00866491588(49)$	kg u	1.2×10^{-8} 4.9×10^{-10}
Energy equivalent	$m_n c^2$	$939.5654133(58)$	MeV	6.2×10^{-9}
Neutron–electron mass ratio	m_n/m_e	$1838.68366158(90)$		4.9×10^{-10}
Neutron–proton mass ratio	m_n/m_p	$1.00137841898(51)$		5.1×10^{-10}
Molar mass	$M(n) = N_A m_n$	$1.00866491588(49) \times 10^{-3}$	kg/mol	5.5×10^{-10}
Compton wavelength	$\lambda_{C,n} = h/(m_n c)$	$1.31959090481(88) \times 10^{-15}$	m	6.7×10^{-10}
(Ratio)	$(1/(2\pi))\lambda_{C,n}$	$0.21001941536(14) \times 10^{-15}$	m	6.7×10^{-10}
Magnetic moment	μ_n	$-0.96623650(23) \times 10^{-26}$	J/T	2.4×10^{-7}
Ratio of magnetic moment to Bohr magneton	μ_n/μ_B	$-1.04187563(25) \times 10^{-3}$		2.4×10^{-7}
Ratio of magnetic moment to nuclear magneton	μ_n/μ_N	$-1.91304273(45)$		2.4×10^{-7}
Ratio of magnetic moment to electron magnetic moment	μ_n/μ_e	$1.04066882(25) \times 10^{-3}$		2.4×10^{-7}
Ratio of magnetic moment to proton magnetic moment	μ_n/μ_p	$-0.68497934(16)$		2.4×10^{-7}
g-factor	$g_n = 2\mu_n/\mu_N$	$-3.82608545(90)$		2.4×10^{-7}
Gyromagnetic ratio	$\gamma_n = 2\lvert\mu_n\rvert/\hbar$	$1.83247172(43) \times 10^{8}$	1/(s T)	2.4×10^{-7}
(Ratio)	$(1/(2\pi))\gamma_n$	$29.1646933(69)$	MHz/T	2.4×10^{-7}

Table 1.9 Properties of the alpha particle

Quantity	Symbol and relation	Numerical value	Units	Relative standard uncertainty
Alpha particle mass[a]	m_α	$6.644657230(82) \times 10^{-27}$ $4.001506179127(63)$	kg u	1.2×10^{-8} 1.6×10^{-11}
Energy equivalent of alpha particle mass	$m_\alpha c^2$	$5.971920097(73) \times 10^{-10}$ $3727.379378(23)$	J MeV	1.2×10^{-8} 6.2×10^{-9}
Ratio of alpha particle mass to electron mass	m_α / m_e	$7294.29954136(24)$		3.3×10^{-11}
Ratio of alpha particle mass to proton mass	m_α / m_p	$3.97259968907(36)$		9.2×10^{-11}
Alpha particle molar mass	$M(\alpha) = N_A m_\alpha$	$4.001506179127(63) \times 10^{-3}$	kg/mol	1.6×10^{-11}

[a] The mass of the alpha particle in units of the atomic mass unit u is given by $m_\alpha = A_r(\alpha)\,u$; in words, the alpha particle mass is given by the relative atomic mass $A_r(\alpha)$ of the alpha particle, multiplied by the atomic mass unit u

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2. The International System of Units (SI), Physical Quantities, and Their Dimensions

Werner Martienssen[†]

In this chapter, we introduce the International System of Units (SI) on the basis of the SI brochure *Le Système International d'unités* (SI) [2.1], supplemented by [2.2]. We give a short review of how the SI was worked out and who is responsible for the further development of the system. Following the above-mentioned publications, we explain the concepts of base physical quantities and derived physical quantities on which the SI is founded, and present a detailed description of the SI base units and of a large selection of SI derived units. The base units comprise the meter, the kilogram, the second, the ampere, the kelvin, the mole, and the candela. For derived units, we describe how they are defined by equations in terms of the base physical quantities as products or ratios of the units for the base quantities. We also discuss a number of non-SI units which still are in use, especially in some specialized fields. A table (Table 2.17) presenting the values of various energy equivalents closes the chapter.

2.1 The International System of Units (SI)

All data in this handbook are given in the International System of Units (Système International d'Unités), abbreviated internationally to SI, which is the modern metric system of measurement and is acknowledged worldwide. The system of SI units was introduced by the General Conference of Weights and Measures (Conférence Générale des Poids et Measures), abbreviated internationally to CGPM, in 1960. The system not only is used in science, but also is dominant in technology, industrial production, and international commerce and trade.

Who takes care of this system of SI units?

The Bureau International des Poids et Mesures (BIPM), which has its headquarters in Sèvres near Paris, has taken on a commitment to ensure worldwide unification of physical measurements. Its function is thus to:

- Establish fundamental standards and scales for the measurement of the principal physical quantities and maintain the international prototypes
- Carry out comparison of national and international standards
- Ensure the coordination of the corresponding measuring techniques
- Carry out and coordinate measurements of the fundamental physical constants relevant to those activities.

The BIPM operates under the exclusive supervision of the Comité International des Poids et Mesures (CIPM), which itself comes under the authority of the Conférence Générale des Poids et Mesures and reports to it on the work accomplished by the BIPM. The BIPM itself was set up by the convention du Mètre signed in

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Paris in 1875 by 17 states during the final session of the Conference on the Meter. The convention was amended in 1921.

Delegates from all member states of the Convention du Mètre attend the Conférence Générale, which, at present, meets every four years. The function of these meetings is to:

- Discuss and initiate the arrangements required to ensure the propagation and improvement of the International System of Units.
- Confirm the results of new fundamental metrological determinations and confirm various scientific resolutions with international scope.
- Take all major decisions concerning the finance, organization, and development of the BIPM.

The CIPM has 18 members, each from a different state; at present, it meets every year. The officers of this committee present an annual report on the administrative and financial position of the BIPM to the governments of the member states of the Convention du Mètre. The principal task of the CIPM is to ensure worldwide uniformity in units of measurement. It does this by direct action or by submitting proposals to the CGPM.

The BIPM publishes monographs on special metrological subjects and the brochure *Le Système international d'unités (SI)* [2.1, 2], which is periodically updated and in which all decisions and recommendations concerning units are collected together.

The scientific work of the BIPM is published in the open scientific literature, and an annual list of publications appears in the *Procès-Verbaux* of the CIPM.

Since 1965, *Metrologica*, an international journal published under the auspices of the CIPM, has printed articles dealing with scientific metrology, improvements in methods of measurements, and work on standards and units, as well as reports concerning the activities, decisions, and recommendations of the various bodies created under the Convention du Mètre.

2.2 Physical Quantities

Physical quantities are tools which allow us to specify and quantify the properties of physical objects and to model the events, phenomena, and patterns of behavior of objects in nature and in technology. The system of physical quantities used with the SI units is dealt by Technical Committee 12 of the International organization for standardization (ISO/TC 12). Since 1955, ISO/TC 12 has published a series of international standards on quantities and their units, in which the use of SI units is strongly recommended.

2.2.1 How Are Physical Quantities Defined?

It turns out that it is possible to divide the system of all known physical quantities into two groups:

- A small number of *base quantities*
- A much larger number of other quantities, which are called *derived quantities*.x

The derived quantities are introduced into physics unambiguously by a defining equation in terms of the base quantities; the relationships between the derived quantities and the base quantities are expressed in a series of equations, which contain a good deal of our knowledge of physics but are used in this system as the defining equations for new physical quantities. One might say that, in this system, physics is described in the rather low-dimensional space of a small number of base quantities.

Base quantities, on the other hand, cannot be introduced by a defining equation; they cannot be traced back to other quantities; this is what we mean by calling them *base*. How can base quantities then be introduced unambiguously into physics at all?

Base physical quantities are introduced into physics in three steps:

- We borrow the qualitative meaning of the word for a base quantity from the meaning of the corresponding word in everyday language.
- We specify this meaning by indicating an appropriate method for measuring the quantity. For example, length is measured by a measuring rule, and time is measured by a clock.
- We fix a unit for this quantity, which allows us to communicate the result of a measurement. Length, for example, is measured in meters; time is measured in seconds.

On the basis of these three steps, it is expected that everyone will understand what is meant when the name of a base quantity is mentioned.

In fact, the number of base quantities chosen and the selection of the quantities which are considered as base quantities are a matter of expediency; in different fields and applications of physics, it might well be expedient to use different numbers of base quantities and different selections of base quantities. It should be kept