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Physical constant

A **physical constant**, sometimes **fundamental physical constant**, is a physical quantity that is generally believed to be both universal in nature and have constant value in time. It is contrasted with a mathematical constant, which has a fixed numerical value, but does not directly involve any physical measurement.

There are many physical constants in science, some of the most widely recognized being the speed of light in vacuum c, the gravitational constant G, Planck's constant h, the electric constant ε_0, and the elementary charge e. Physical constants can take many dimensional forms: the speed of light signifies a maximum speed for any object and is expressed dimensionally as length divided by time; while the fine-structure constant α, which characterizes the strength of the electromagnetic interaction, is dimensionless.

The term *fundamental physical constant* is sometimes used to refer to universal but dimensioned physical constants such as those mentioned above.[1] Increasingly, however, physicists reserve the use of the term *fundamental physical constant* for dimensionless physical constants, such as the fine-structure constant α.

Physical constant in the sense under discussion in this article should not be confused with other quantities called "constants" that are assumed to be constant in a given context without the implication that they are in any way fundamental, such as the "time constant" characteristic of a given system, or material constants, such as the Madelung constant, electrical resistivity, heat capacity, etc., listed for convenience.

Contents

Choice of units

Whereas the physical quantity indicated by a physical constant does not depend on the unit system used to express the quantity, the numerical values of dimensional physical constants do depend on choice of unit system. The term "physical constant" refers to the physical quantity, and not to the numerical value within any given system of units. For example, the speed of light is defined as having the numerical value of 299,792,458 in SI units, and as having the numerical value of 1 in natural units. While its numerical value can be defined at will by the choice of units, the speed of light itself is a single physical constant.

Any ratio between physical constants of the same dimensions results in a dimensionless physical constant, for example, the proton-to-electron mass ratio. Any relation between physical quantities can be expressed as a relation between dimensionless ratios via a process known as nondimensionalisation.

The term of "fundamental physical constant" is reserved for physical quantities which, according to the current state of knowledge, are regarded as immutable and as non-derivable from more fundamental principles. Notable examples are the speed of light c, and the gravitational constant G.[2]

The fine-structure constant α is the best known dimensionless fundamental physical constant. It is the value of the elementary charge squared expressed in Planck units. This value has become a standard example when discussing the derivability or non-derivability of physical constants. Introduced by Arnold Sommerfeld, its value as determined at the time was consistent with 1/137. This motivated Arthur Eddington (1929) to construct an argument why its value might be 1/137 precisely, which related to the Eddington number, his estimate of the number of protons in the Universe.[3] By the 1940s, it became clear that the value of the fine-structure constant deviates significantly from the precise value of 1/137, refuting Eddington's argument.[4]

With the development of quantum chemistry in the 20th century, however, a vast number of previously inexplicable dimensionless physical constants *were* successfully computed from theory. In light of that, some theoretical physicists still hope for continued progress in explaining the values of other dimensionless physical constants.

It is known that the Universe would be very different if these constants took values significantly different from those we observe. For example, a few percent change in the value of the fine structure constant would be enough to eliminate stars like our Sun. This has prompted attempts at anthropic explanations of the values of some of the dimensionless fundamental physical constants.

Natural units

Using dimensional analysis, it is possible to combine dimensional universal physical constants to define a system of units of measurement that has no reference to any human construct. Depending on the choice and arrangement of constants used, the resulting natural units may have useful physical meaning. For example, Planck units, shown in the table below, use c, G, $\hbar$, ε_0 and k_B in such a manner to derive units relevant to unified theories such as quantum gravity.

Name	Quantity	Expression	Value (SI units)
Planck length	Length (L)	$l_\text{P} = \sqrt{\frac{\hbar G}{c^3}}$	1.616 229(38) × 10^{-35} m[5]
Planck mass	Mass (M)	$m_\text{P} = \sqrt{\frac{\hbar c}{G}}$	2.176 470(51) × 10^{-8} kg[6]
Planck time	Time (T)	$t_\text{P} = \frac{l_\text{P}}{c} = \frac{\hbar}{m_\text{P} c^2} = \sqrt{\frac{\hbar G}{c^5}}$	5.391 16(13) × 10^{-44} s[7]
Planck charge	Electric charge (Q)	$q_\text{P} = \sqrt{4\pi\varepsilon_0 \hbar c}$	1.875 545 956(41) × 10^{-18} C[8][9][10]
Planck temperature	Temperature (Θ)	$T_\text{P} = \frac{m_\text{P} c^2}{k_\text{B}} = \sqrt{\frac{\hbar c^5}{G k_\text{B}^2}}$	1.416 808(33) × 10^{32} K[11]

Number of fundamental constants

The number of fundamental physical constants depends on the physical theory accepted as "fundamental". Currently, this is the theory of general relativity for gravitation and the Standard Model for electromagnetic, weak and strong nuclear interactions and the matter fields. Between them, these theories account for a total of 19 independent fundamental constants. There is, however, no single "correct" way of enumerating them, as it is a matter of arbitrary choice which quantities are considered "fundamental" and which as "derived". Uzan (2011) lists 22 "unknown constants" in the fundamental theories, which give rise to 19 "unknown dimensionless parameters", as follows:

- the gravitational constant G,
- the speed of light c,
- the Planck constant h,
- the 9 Yukawa couplings for the quarks and leptons (equivalent to specifying the rest mass of these elementary particles),
- 2 parameters of the Higgs field potential,
- 4 parameters for the quark mixing matrix,
- 3 coupling constants for the gauge groups SU(3) × SU(2) × U(1) (or equivalently, two coupling constants and the Weinberg angle),
- a phase for the QCD vacuum.

The number of 19 independent fundamental physical constants is subject to change under possible extensions of the Standard Model, notably by the introduction of neutrino mass (equivalent to seven additional constants, i.e. 3 Yukawa couplings and 4 lepton mixing parameters).[12]

The discovery of variability in any of these constants would be equivalent to the discovery of "new physics".[13]

The question as to which constants are "fundamental" is neither straightforward nor meaningless, but a question of interpretation of the physical theory regarded as fundamental; as pointed out by Lévy-Leblond (1979), not all physical constants are of the same importance, with some having a deeper role than others. Lévy-Leblond (1979) proposed a classification schemes of three types of fundamental constant:

- A: characteristic of a particular system
- B: characteristic of a class of physical phenomena
- C: universal constants

The same physical constant may move from one category to another as the understanding of its role deepens; this has notably happened to the speed of light, which was a class A constant (characteristic of light) when it was first measured, but became a class B constant (characteristic of electromagnetic phenomena) with the development of classical electromagnetism, and finally a class C constant with the discovery of special relativity.[14]

Tests on time-independence

By definition, fundamental physical constants are subject to measurement, so that their being constant (independent on both the time and position of the performance of the measurement) is necessarily an experimental result and subject to verification.

Paul Dirac in 1937 speculated that physical constants such as the gravitational constant or the fine-structure constant might be subject to change over time in proportion of the age of the universe. Experiments can in principle only put an upper bound on the relative change per year. For the fine-structure constant, this upper bound is comparatively low, at roughly 10^{-17} per year (as of 2008).[15]

The gravitational constant is much more difficult to measure with precision, and conflicting measurements in the 2000s have inspired the controversial suggestions of a periodic variation of its value in a 2015 paper.[16] However, while its value is not known to great precision, the possibility of observing type Ia supernovae which happened in the universe's remote past, paired with the assumption that the physics involved in these events is universal, allows for an upper bound of less than 10^{-10} per year for the gravitational constant over the last nine billion years.[17]

Similarly, an upper bound of the change in the proton-to-electron mass ratio has been placed at 10^{-7} over a period of 7 billion years (or 10^{-16} per year) in a 2012 study based on the observation of methanol in a distant galaxy.[18][19]

It is problematic to discuss the proposed rate of change (or lack thereof) of a single *dimensional* physical constant in isolation. The reason for this is that the choice of a system of units may arbitrarily select as its basis, making the question of which constant is undergoing change an artefact of the choice of units.[20][21]

For example, in SI units, the speed of light has been given a *defined* value in 1983. Thus, it was meaningful to experimentally measure the speed of light in SI units prior to 1983, but it is not so now. The proposed redefinition of SI base units, scheduled for 2018, seeks to express all SI base units in terms of fundamental physical constants.

Tests on the immutability of physical constants look at *dimensionless* quantities, i.e. ratios between quantities of like dimensions, in order to escape this problem. Changes in physical constants are not meaningful if they result in an *observationally indistinguishable* universe. For example, a "change" in the speed of light c would be meaningless if accompanied by a corresponding change in the elementary charge e so that the ratio $e^2/(4\pi\varepsilon_0\hbar c)$ (the fine-structure constant) remained unchanged.[22]

Fine-tuned Universe

Some physicists have explored the notion that if the dimensionless physical constants had sufficiently different values, our Universe would be so radically different that intelligent life would probably not have emerged, and that our Universe therefore seems to be fine-tuned for intelligent life. The anthropic principle states a logical truism: the fact of our existence as intelligent beings who can measure physical constants requires those constants to be such that beings like us can exist. There are a variety of interpretations of the constants' values, including that of a divine creator (the apparent fine-tuning is actual and intentional), or that ours is one universe of many in a multiverse (e.g. the Many-worlds interpretation of quantum mechanics), or even that, if information is an innate property of the universe and logically inseparable from consciousness, a universe without the capacity for conscious beings cannot exist.

Table of physical constants

Universal constants

Quantity	Symbol	Value[23][24]	Relative standard uncertainty
speed of light in vacuum	c	299 792 458 m·s^{-1}	defined
Newtonian constant of gravitation	G	6.674 08(31) × 10^{-11} m^3·kg^{-1}·s^{-2}	4.7 × 10^{-5}
Planck constant	h	6.626 070 040(81) × 10^{-34} J·s	1.2 × 10^{-8}
reduced Planck constant	$\hbar = h/2\pi$	1.054 571 800(13) × 10^{-34} J·s	1.2 × 10^{-8}

Electromagnetic constants

Quantity	Symbol	Value[23][24] (SI units)	Relative standard uncertainty
magnetic constant (vacuum permeability)	μ_0	4π × 10^{-7} N·A^{-2} = 1.256 637 061... × 10^{-6} N·A^{-2}	defined
electric constant (vacuum permittivity)	$\varepsilon_0 = 1/\mu_0 c^2$	8.854 187 817... × 10^{-12} F·m^{-1}	defined
characteristic impedance of vacuum	$Z_0 = \mu_0 c$	376.730 313 461... Ω	defined
Coulomb's constant	$k_\mathrm{e} = 1/4\pi\varepsilon_0$	8.987 551 787 368 176 4 × 10^{9} kg·m^{3}·s^{-4}·A^{-2}	defined
elementary charge	e	1.602 176 6208(98) × 10^{-19} C	6.1 × 10^{-9}
Bohr magneton	$\mu_\mathrm{B} = e\hbar/2m_\mathrm{e}$	9.274 009 994(57) × 10^{-24} J·T^{-1}	6.2 × 10^{-9}
conductance quantum	$G_0 = 2e^2/h$	7.748 091 7310(18) × 10^{-5} S	2.3 × 10^{-10}
inverse conductance quantum	$G_0^{-1} = h/2e^2$	12 906.403 7278(29) Ω	2.3 × 10^{-10}
Josephson constant	$K_\mathrm{J} = 2e/h$	4.835 978 525(30) × 10^{14} Hz·V^{-1}	6.1 × 10^{-9}
magnetic flux quantum	$\phi_0 = h/2e$	2.067 833 831(13) × 10^{-15} Wb	6.1 × 10^{-9}
nuclear magneton	$\mu_\mathrm{N} = e\hbar/2m_\mathrm{p}$	5.050 783 699(31) × 10^{-27} J·T^{-1}	6.2 × 10^{-9}
von Klitzing constant	$R_\mathrm{K} = h/e^2$	25 812.807 4555(59) Ω	2.3 × 10^{-10}

Atomic and nuclear constants

Quantity	Symbol	Value[23][24] (SI units)	Relative standard uncertainty
Bohr radius	$a_0 = \hbar/\alpha m_e c$	5.291 772 1067(12) × 10^{-11} m	2.3 × 10^{-9}
classical electron radius	$r_\mathrm{e} = e^2/4\pi\varepsilon_0 m_\mathrm{e} c^2$	2.817 940 3227(19) × 10^{-15} m	6.8 × 10^{-10}
electron mass	m_e	9.109 383 56(11) × 10^{-31} kg	1.2 × 10^{-8}
Fermi coupling constant	$G_\mathrm{F}/(\hbar c)^3$	1.166 3787(6) × 10^{-5} GeV^{-2}	5.1 × 10^{-7}
fine-structure constant	$\alpha = \mu_0 e^2 c/2h = e^2/4\pi\varepsilon_0 \hbar c$	7.297 352 5664(17) × 10^{-3}	2.3 × 10^{-10}
Hartree energy	$E_\mathrm{h} = 2R_\infty hc$	4.359 744 650(54) × 10^{-18} J	1.2 × 10^{-8}
proton mass	m_p	1.672 621 898(21) × 10^{-27} kg	1.2 × 10^{-8}
quantum of circulation	$h/2m_\mathrm{e}$	3.636 947 5486(17) × 10^{-4} $\mathrm{m}^2\ \mathrm{s}^{-1}$	4.5 × 10^{-10}
Rydberg constant	$R_\infty = \alpha^2 m_\mathrm{e} c/2h$	10 973 731.568 508(65) m^{-1}	5.9 × 10^{-12}
Thomson cross section	$(8\pi/3)r_\mathrm{e}^2$	6.652 458 7158(91) × 10^{-29} m^2	1.4 × 10^{-9}
weak mixing angle	$\sin^2\theta_\mathrm{W} = 1 - (m_\mathrm{W}/m_\mathrm{Z})^2$	0.2223(21)	9.5 × 10^{-3}
Efimov factor		22.7	

Physico-chemical constants

Quantity		Symbol	Value[23][24] (SI units)	Relative standard uncertainty
Atomic mass constant		$m_{\mathrm{u}} = 1\,\mathrm{u}$	1.660 539 040(20) × 10^{-27} kg	1.2 × 10^{-8}
Avogadro constant		N_{A}, L	6.022 140 857(74) × 10^{23} $\mathrm{mol^{-1}}$	1.2 × 10^{-8}
Boltzmann constant		$k = k_{\mathrm{B}} = R/N_{\mathrm{A}}$	1.380 648 52(79) × 10^{-23} $\mathrm{J \cdot K^{-1}}$	5.7 × 10^{-7}
Faraday constant		$F = N_{\mathrm{A}} e$	96 485.332 89(59) $\mathrm{C \cdot mol^{-1}}$	6.2 × 10^{-9}
first radiation constant		$c_1 = 2\pi hc^2$	3.741 771 790(46) × 10^{-16} $\mathrm{W \cdot m^2}$	1.2 × 10^{-8}
	for spectral radiance	$c_{1\mathrm{L}} = c_1/\pi$	1.191 042 953(15) × 10^{-16} $\mathrm{W \cdot m^2 \cdot sr^{-1}}$	1.2 × 10^{-8}
Loschmidt constant	at T = 273.15 K and p = 101.325 kPa	$n_0 = N_{\mathrm{A}}/V_{\mathrm{m}}$	2.686 7811(15) × 10^{25} $\mathrm{m^{-3}}$	5.7 × 10^{-7}
gas constant		R	8.314 4598(48) $\mathrm{J \cdot mol^{-1} \cdot K^{-1}}$	5.7 × 10^{-7}
molar Planck constant		$N_{\mathrm{A}} h$	3.990 312 7110(18) × 10^{-10} $\mathrm{J \cdot s \cdot mol^{-1}}$	4.5 × 10^{-10}
molar volume of an ideal gas	at T = 273.15 K and p = 100 kPa	$V_{\mathrm{m}} = RT/p$	2.271 0947(13) × 10^{-2} $\mathrm{m^3 \cdot mol^{-1}}$	5.7 × 10^{-7}
	at T = 273.15 K and p = 101.325 kPa		2.241 3962(13) × 10^{-2} $\mathrm{m^3 \cdot mol^{-1}}$	5.7 × 10^{-7}
Sackur–Tetrode constant	at T = 1 K and p = 100 kPa	$S_0/R = \frac{5}{2} + \ln\left[(2\pi m_{\mathrm{u}} kT/h^2)^{3/2} kT/p\right]$	−1.151 7084(14)	1.2 × 10^{-6}
	at T = 1 K and p = 101.325 kPa		−1.164 8714(14)	1.2 × 10^{-6}
second radiation constant		$c_2 = hc/k$	1.438 777 36(83) × 10^{-2} m·K	5.7 × 10^{-7}
Stefan–Boltzmann constant		$\sigma = \pi^2 k^4/60\hbar^3 c^2$	5.670 367(13) × 10^{-8} $\mathrm{W \cdot m^{-2} \cdot K^{-4}}$	2.3 × 10^{-6}
Wien displacement law constant		$b_{\mathrm{energy}} = hck^{-1}/$ 4.965 114 231...	2.897 7729(17) × 10^{-3} m·K	5.7 × 10^{-7}
Wien-Bonal entropy displacement law constant[25]		$b_{\mathrm{entropy}} = hck^{-1}/$ 4.791 267 357...	3.002 9152(05) × 10^{-3} m·K	5.7 × 10^{-7}

Adopted values

Quantity		Symbol	Value (SI units)	Relative standard uncertainty
conventional value of Josephson constant[26]		$K_{\mathrm{J-90}}$	$4.835\ 979 \times 10^{14}$ Hz·V^{-1}	defined
conventional value of von Klitzing constant[27]		$R_{\mathrm{K-90}}$	25 812.807 Ω	defined
molar mass	constant	$M_{\mathrm{u}} = M(^{12}\mathrm{C})/12$	1×10^{-3} kg·mol^{-1}	defined
	of carbon-12	$M(^{12}\mathrm{C}) = N_{\mathrm{A}}m(^{12}\mathrm{C})$	1.2×10^{-2} kg·mol^{-1}	defined
standard acceleration of gravity (gee, free-fall on Earth)		g_{n}	9.806 65 m·s^{-2}	defined
standard atmosphere		atm	101 325 Pa	defined

See also

- Variables commonly used in physics

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22. Barrow, John D. (2002), *The Constants of Nature; From Alpha to Omega - The Numbers that Encode the Deepest Secrets of the Universe*, Pantheon Books, ISBN 0-375-42221-8 "[An] important lesson we learn from the way that pure numbers like α define the World is what it really means for worlds to be different. The pure number we call the fine structure constant and denote by α is a combination of the electron charge, *e*, the speed of light, *c*, and Planck's constant, *h*. At first we might be tempted to think that a world in which the speed of light was slower would be a different world. But this would be a mistake. If *c*, *h*, and *e* were all changed so that the values they have in metric (or any other) units were different when we looked them up in our tables of physical constants, but the value of α remained the same, this new world would be *observationally indistinguishable* from our World. The only thing that counts in the definition of worlds are the values of the dimensionless constants of Nature. If all masses were doubled in value you cannot tell, because all the pure numbers defined by the ratios of any pair of masses are unchanged."

23. The values are given in the so-called *concise form*; the number in parentheses after the mantissa is the ***standard uncertainty***, which is the value multiplied by the ***relative standard uncertainty***, and indicates the amount by which the least significant digits of the value are uncertain. For example, 75 is the standard uncertainty in "8.314 4621(75)", and means that the value is between 8.314 4546 and 8.314 4696.
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External links

- Sixty Symbols (http://www.sixtysymbols.com/#), University of Nottingham
- IUPAC - Gold Book (http://goldbook.iupac.org/list_goldbook_phys_constants_defs.html)

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