The Fundamental Physical Constants

The 1998 CODATA least-squares adjustment (the most recent carried out) produced a new set of recommended values of the basic constants and conversion factors of physics and chemistry.

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The Committee on Data for Science and Technology (CODATA) was established in 1966 as an interdisciplinary committee of the International Council of Science (ICSU, formerly the International Council of Scientific Unions). Soon thereafter, in 1969, CODATA established the Task Group on Fundamental Constants to periodically provide the scientific and technological communities with a self-consistent set of internationally recommended values of the basic constants and conversion factors of physics and chemistry. Under the auspices of this task group, we completed a new least-squares adjustment of the values of the constants—termed the 1998 adjustment—that took into account all relevant data available through 31 December 1998.[1] The accompanying tables give the 1998 CODATA recommended values resulting from that adjustment, with the exception of some specialized x-ray-related quantities and various natural and atomic units. The complete 1998 CODATA set of more than 300 recommended values, together with a covariance matrix of some of the more widely used values and a detailed description of the data and their analysis, are given in ref. 1. All of the values and all of their covariances (in the form of correlation coefficients) are available on the Web at http://physics.nist.gov/constants, in a searchable database provided by the Fundamental Constants Data Center of the NIST Physics Laboratory.

The 1998 CODATA set of recommended values replaced its immediate predecessor[2] issued by CODATA in 1986 and is a major step forward. The standard uncertainties (the estimated standard deviations) of many of the 1998 recommended values are about 1/5 to 1/12, and in the case of the Rydberg constant and some associated constants, 1/160 times the standard uncertainties of the corresponding 1986 values. Further, the absolute values of the differences between the 1986 values and the corresponding 1998 values are almost all less than twice the standard uncertainties of the 1986 values. The significant reduction of uncertainties and the relatively small shifts of values are apparent from the accompanying table, which compares the recommended values of a number of constants from the two adjustments.

The Newtonian constant of gravitation G is unique among the 1998 recommended values; its uncertainty is *larger* than that of the 1986 value by nearly a factor of 12. As explained in detail in ref. 1, for a number of reasons, but especially because of the existence of a value of G from a credible experiment that differs significantly from the 1986 value, the CODATA task group decided to retain the 1986 recommended value but to increase its relative uncertainty from $u_r = 1.3 \times 10^{-4}$ to 1.5×10^{-3}.

The Rydberg constant R_∞ with a shift of 2.7 times its 1986 uncertainty has the largest relative change in value of any constant. However, with a 1986 to 1998 uncertainty ratio of nearly 160, R_∞ has undergone the largest reduction in uncertainty of any constant. The large shift in value occurred because the 1986 recommended value of R_∞ is based mainly on a 1981 experimental result that turned out to be in error. The large uncertainty reduction is mainly due to the fact that, beginning in the early 1990s, optical frequency metrology replaced optical wavelength metrology in the measurement of transition frequencies in hydrogenic atoms, thereby significantly reducing the uncertainties of such measurements. Improvements in the theory of the energy levels of hydrogenic atoms also contributed to the uncertainty reduction.

The following experimental and theoretical advances made during the 13-year period between the 1986 and 1998 adjustments contributed to the reduction of the uncertainties for the fine-structure constant α, Planck constant h, and molar gas constant R. These constants are not only important in their own right, but, together with R_∞ and the relative atomic mass of the electron $A_r(e)$, they determine the recommended values of many other constants and conversion factors of prime interest.

- An improved experimental determination of the anomalous magnetic moment of the electron a_e obtained from measurements on a single electron confined in a Penning trap, combined with an improved theoretical expression for a_e calculated from quantum electrodynamics (QED), provides a value of α with $u_r = 3.8 \times 10^{-9}$. The 1998 recommended value of α with $u_r = 3.7 \times 10^{-9}$ is determined mainly by this result.
- The moving-coil watt balance, conceived in 1975 and first brought to a useful operational state in the late 1980s, provides two experimental values of $K_J^2 R_K = 4/h$,

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Comparison of the 1998 and 1986 CODATA recommended values of various constants

Quantity	1998 rel. std. uncert. u_r	1986 rel. std. uncert. u_r	Ratio 1986 u_r to 1998 u_r	D_r
α	3.7×10^{-9}	4.5×10^{-8}	12.2	-1.7
λ_C	7.3×10^{-9}	8.9×10^{-8}	12.2	-1.7
h	7.8×10^{-8}	6.0×10^{-7}	7.7	-1.7
N_A	7.9×10^{-8}	5.9×10^{-7}	7.5	1.5
e	3.9×10^{-8}	3.0×10^{-7}	7.8	-1.8
R	1.7×10^{-6}	8.4×10^{-6}	4.8	-0.5
k	1.7×10^{-6}	8.5×10^{-6}	4.8	-0.6
σ	7.0×10^{-6}	3.4×10^{-5}	4.8	-0.6
G	1.5×10^{-3}	1.3×10^{-4}	0.1	0.0
R_∞	7.6×10^{-12}	1.2×10^{-9}	157.1	2.7
m_e/m_p	2.1×10^{-9}	2.0×10^{-8}	9.5	0.9
A_r(e)	2.1×10^{-9}	2.3×10^{-8}	11.1	0.7

Note: The relative standard uncertainty of a quantity y is defined as $u_r(y) \equiv u(y)/|y|$, if $y \neq 0$, where $u(y)$ is the standard uncertainty of y. D_r is the 1998 value minus the 1986 value divided by the standard uncertainty of the 1986 value. The various constants are defined in subsequent tables.

one with $u_r = 8.7 \times 10^{-8}$ and the other with $u_r = 2.0 \times 10^{-7}$ ($K_J = 2e/h$ is the Josephson constant, characteristic of the Josephson effect, and $R_K = h/e^2$ is the von Klitzing constant, characteristic of the quantum Hall effect). The 1998 recommended value of h with $u_r = 7.8 \times 10^{-8}$ arises primarily from these two results.

▶ A determination of the speed of sound in argon using a spherical acoustic resonator provides an experimental value of R with $u_r = 1.8 \times 10^{-6}$, about 1/5 times the uncertainty of the 1986 recommended value, which is based on a result obtained using a cylindrical acoustic interferometer. The new value is mainly responsible for the 1998 recommended value of R with $u_r = 1.7 \times 10^{-6}$.

Improved measurements and calculations of a number of other quantities also contributed to our better overall knowledge of the constants. Notable are the Penning-trap mass-ratio measurements that furnished more accurate values of the relative atomic masses of the electron, proton, deuteron, helion (nucleus of ^{3}He), and α particle; the crystal diffraction determination of the binding energy of the neutron in the deuteron that led to a more accurate value of the relative atomic mass of the neutron; and the Zeeman transition-frequency determination of the ground-state hyperfine splitting in muonium (μ^+e^- atom) $\Delta\nu_{Mu}$, together with a more accurate theoretical expression for $\Delta\nu_{Mu}$ calculated from QED, that led to a more accurate value of the electron–muon mass ratio m_e/m_μ.

The 1998 adjustment differs from its 1986 predecessor in several important respects. First, we abandoned the 1986 grouping of the input data into the two distinct categories, stochastic input data and auxiliary constants, where the latter were assumed to be exactly known. Instead, we treated all input data on an essentially equal footing, regardless of their uncertainties. This allowed all components of uncertainty and all correlations among the data to be properly taken into account, while at the same time it eliminated an arbitrary division of the data into two categories.

Second, we did not attempt to quantify the "uncertainty" of the uncertainty assigned each input datum as was done in 1986 in order to analyze the data using extended least-squares algorithms. The change was made after reviewing in detail literally hundreds of experimental and theoretical results and concluding that, because of the complexity of the measurements and calculations in the field of fundamental constants, it is difficult enough to evaluate their uncertainties in a meaningful way, let alone the "uncertainties" of those uncertainties. We therefore used the standard least-squares algorithm in our data analysis.

Third, in order to properly take into account the uncertainties of various theoretical expressions—for example, those for the energy levels of hydrogen (H) and deuterium (D) required to obtain R_∞ from measurements of transition frequencies in these atoms—we introduced in the 1998 adjustment an additive correction δ_i for each such expression. The δ's are included among the variables of the least-squares adjustment, and their estimated values are taken as input data. The best *a priori* estimate of each δ_i is assumed to be zero but with a standard uncertainty equal to the standard uncertainty of the theoretical expression. This approach enabled us to account for the uncertainties in the theory in a rigorous way, although it increased the number of variables that we had to deal with and the size of the matrices that we had to invert. Fortunately, modern computers have little difficulty with such inversions.

Fourth, we analyzed the data using the method of least squares for correlated input data. This means that the covariance matrix of the input data was not diagonal. Although the need to consider correlations among the input data in the evaluation of the fundamental constants was first emphasized half a century ago, the 1998 adjustment was the first time it was actually done.

Our analysis of the input data proceeded in multiple stages. First, we compared the various measured values of each quantity. Next, we compared measured values of different quantities by comparing values of a common inferred constant. Prominent among those inferred constants are R_∞, α, and h. Finally, we carried out a multivariate analysis of the data using the method of least squares as discussed above. Because the input data related to R_∞ are not strongly tied to the rest of the input data, various stages of the analysis were done independently on those two groups of data before the data were combined for final analysis. The focus of all of these investigations was the compatibility of the data and the extent to which a particular datum would contribute to the determination of the 1998 recommended values of the constants.

The final least-squares adjustment on which the 1998 recommended values are based used 93 of the 107 input data that were initially considered and 57 variables or adjusted constants. The 93 input data included values of 9 silicon lattice-spacing differences and 27 H and D transition frequencies and frequency differences. The 57 adjusted constants included 28 δ's, 8 {220} silicon lattice spacings, R_∞, α, h, R, A_r(e), and the relative atomic masses of five other particles. Although a number of the 1998 recommended values are adjusted constants and hence were directly determined in the adjustment, most recommended values were subsequently calculated from the adjusted constants. For example, the elementary charge follows from the expression $e = (2\alpha h/\mu_0 c)^{1/2}$, the mass of

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CODATA Recommended Values of the Fundamental Physical Constants – 1998

Quantity	Symbol	Value	Unit	Relative standard uncertainty u_r
UNIVERSAL				
speed of light in vacuum	c, c_0	299 792 458	m s^{-1}	(exact)
magnetic constant	μ_0	$4\pi\times10^{-7}$	N A^{-2}	
		$=12.566\,370\,614\ldots\times10^{-7}$	N A^{-2}	(exact)
electric constant $1/\mu_0c^2$	ϵ_0	$8.854\,187\,817\ldots\times10^{-12}$	F m^{-1}	(exact)
characteristic impedance of vacuum $\sqrt{\mu_0/\epsilon_0}=\mu_0c$	Z_0	376.730 313 461. . .	Ω	(exact)
Newtonian constant of gravitation	G	$6.673(10)\times10^{-11}$	m^3 kg^{-1} s^{-2}	1.5×10^{-3}
	$G/\hbar c$	$6.707(10)\times10^{-39}$	(GeV/c^2)$^{-2}$	1.5×10^{-3}
Planck constant	h	$6.626\,068\,76(52)\times10^{-34}$	J s	7.8×10^{-8}
in eV s		$4.135\,667\,27(16)\times10^{-15}$	eV s	3.9×10^{-8}
$h/2\pi$	$\hbar$	$1.054\,571\,596(82)\times10^{-34}$	J s	7.8×10^{-8}
in eV s		$6.582\,118\,89(26)\times10^{-16}$	eV s	3.9×10^{-8}
Planck mass $(\hbar c/G)^{1/2}$	m_P	$2.1767(16)\times10^{-8}$	kg	7.5×10^{-4}
Planck length $\hbar/m_Pc=(\hbar G/c^3)^{1/2}$	l_P	$1.6160(12)\times10^{-35}$	m	7.5×10^{-4}
Planck time $l_P/c=(\hbar G/c^5)^{1/2}$	t_P	$5.3906(40)\times10^{-44}$	s	7.5×10^{-4}
ELECTROMAGNETIC				
elementary charge	e	$1.602\,176\,462(63)\times10^{-19}$	C	3.9×10^{-8}
	e/h	$2.417\,989\,491(95)\times10^{14}$	A J^{-1}	3.9×10^{-8}
magnetic flux quantum $h/2e$	Φ_0	$2.067\,833\,636(81)\times10^{-15}$	Wb	3.9×10^{-8}
conductance quantum $2e^2/h$	G_0	$7.748\,091\,696(28)\times10^{-5}$	S	3.7×10^{-9}
inverse of conductance quantum	G_0^{-1}	12 906.403 786(47)	Ω	3.7×10^{-9}
Josephson constant[a] $2e/h$	K_J	$483\,597.898(19)\times10^9$	Hz V^{-1}	3.9×10^{-8}
von Klitzing constant[b] $h/e^2=\mu_0c/2\alpha$	R_K	25 812.807 572(95)	Ω	3.7×10^{-9}
Bohr magneton $e\hbar/2m_e$	μ_B	$927.400\,899(37)\times10^{-26}$	J T^{-1}	4.0×10^{-8}
in eV T^{-1}		$5.788\,381\,749(43)\times10^{-5}$	eV T^{-1}	7.3×10^{-9}
	μ_B/h	$13.996\,246\,24(56)\times10^9$	Hz T^{-1}	4.0×10^{-8}
	μ_B/hc	46.686 4521(19)	m^{-1} T^{-1}	4.0×10^{-8}
	μ_B/k	0.671 7131(12)	K T^{-1}	1.7×10^{-6}
nuclear magneton $e\hbar/2m_p$	μ_N	$5.050\,783\,17(20)\times10^{-27}$	J T^{-1}	4.0×10^{-8}
in eV T^{-1}		$3.152\,451\,238(24)\times10^{-8}$	eV T^{-1}	7.6×10^{-9}
	μ_N/h	7.622 593 96(31)	MHz T^{-1}	4.0×10^{-8}
	μ_N/hc	$2.542\,623\,66(10)\times10^{-2}$	m^{-1} T^{-1}	4.0×10^{-8}
	μ_N/k	$3.658\,2638(64)\times10^{-4}$	K T^{-1}	1.7×10^{-6}
ATOMIC AND NUCLEAR				
General				
fine-structure constant $e^2/4\pi\epsilon_0\hbar c$	α	$7.297\,352\,533(27)\times10^{-3}$		3.7×10^{-9}
inverse fine-structure constant	α^{-1}	137.035 999 76(50)		3.7×10^{-9}
Rydberg constant $\alpha^2m_ec/2h$	R_∞	10 973 731.568 549(83)	m^{-1}	7.6×10^{-12}
	$R_\infty c$	$3.289\,841\,960\,368(25)\times10^{15}$	Hz	7.6×10^{-12}
	$R_\infty hc$	$2.179\,871\,90(17)\times10^{-18}$	J	7.8×10^{-8}
$R_\infty hc$ in eV		13.605 691 72(53)	eV	3.9×10^{-8}
Bohr radius $\alpha/4\pi\,R_\infty=4\pi\epsilon_0\hbar^2/m_ee^2$	a_0	$0.529\,177\,2083(19)\times10^{-10}$	m	3.7×10^{-9}
Hartree energy $e^2/4\pi\epsilon_0a_0=2R_\infty hc=\alpha^2m_ec^2$	E_h	$4.359\,743\,81(34)\times10^{-18}$	J	7.8×10^{-8}
in eV		27.211 3834(11)	eV	3.9×10^{-8}
quantum of circulation	$h/2m_e$	$3.636\,947\,516(27)\times10^{-4}$	m^2 s^{-1}	7.3×10^{-9}
	h/m_e	$7.273\,895\,032(53)\times10^{-4}$	m^2 s^{-1}	7.3×10^{-9}
Electroweak				
Fermi coupling constant[c]	$G_F/(\hbar c)^3$	$1.166\,39(1)\times10^{-5}$	GeV^{-2}	8.6×10^{-6}
weak mixing angle[d] θ_W (on-shell scheme)				
$\sin^2\theta_W=s^2_W\equiv1-(m_W/m_Z)^2$	$\sin^2\theta_W$	0.2224(19)		8.7×10^{-3}
Electron, e^-				
electron mass	m_e	$9.109\,381\,88(72)\times10^{-31}$	kg	7.9×10^{-8}
in u, $m_e=A_r$(e) u (electron rel. atomic mass times u)		$5.485\,799\,110(12)\times10^{-4}$	u	2.1×10^{-9}
energy equivalent	m_ec^2	$8.187\,104\,14(64))\times10^{-14}$	J	7.9×10^{-8}
in MeV		0.510 998 902(21)	MeV	4.0×10^{-8}
electron–muon mass ratio	m_e/m_μ	$4.836\,332\,10(15)\times10^{-3}$		3.0×10^{-8}
electron–tau mass ratio	m_e/m_τ	$2.875\,55(47)\times10^{-4}$		1.6×10^{-4}
electron–proton mass ratio	m_e/m_p	$5.446\,170\,232(12)\times10^{-4}$		2.1×10^{-9}
electron–neutron mass ratio	m_e/m_n	$5.438\,673\,462(12)\times10^{-4}$		2.2×10^{-9}
electron–deuteron mass ratio	m_e/m_d	$2.724\,437\,1170(58)\times10^{-4}$		2.1×10^{-9}
electron to alpha particle mass ratio	m_e/m_α	$1.370\,933\,5611(29)\times10^{-4}$		2.1×10^{-9}
electron charge to mass quotient	$-e/m_e$	$-1.758\,820\,174(71)\times10^{11}$	C kg^{-1}	4.0×10^{-8}
electron molar mass N_Am_e	M(e), M_e	$5.485\,799\,110(12)\times10^{-7}$	kg mol^{-1}	2.1×10^{-9}

CODATA Recommended Values of the Fundamental Physical Constants – 1998

Quantity	Symbol	Value	Unit	Relative standard uncertainty u_r
Compton wavelength $h/m_e c$	λ_C	2.426 310 215(18)×10^{-12}	m	7.3×10^{-9}
$\lambda_C/2\pi = \alpha a_0 = \alpha^2/4\pi R_\infty$	$\lambda\!\!\!^{-}_C$	386.159 2642(28)×10^{-15}	m	7.3×10^{-9}
classical electron radius $\alpha^2 a_0$	r_e	2.817 940 285(31)×10^{-15}	m	1.1×10^{-8}
Thomson cross section $(8\pi/3)r_e^2$	σ_e	0.665 245 854(15)×10^{-28}	m^2	2.2×10^{-8}
electron magnetic moment	μ_e	−928.476 362(37)×10^{-26}	J T^{-1}	4.0×10^{-8}
to Bohr magneton ratio	μ_e/μ_B	−1.001 159 652 1869(41)		4.1×10^{-12}
to nuclear magneton ratio	μ_e/μ_N	−1 838.281 9660(39)		2.1×10^{-9}
electron magnetic moment anomaly $\lvert\mu_e\rvert/\mu_B - 1$	a_e	1.159 652 1869(41)×10^{-3}		3.5×10^{-9}
electron g-factor $-2(1+a_e)$	g_e	−2.002 319 304 3737(82)		4.1×10^{-12}
electron–muon magnetic moment ratio	μ_e/μ_μ	206.766 9720(63)		3.0×10^{-8}
electron–proton magnetic moment ratio	μ_e/μ_p	−658.210 6875(66)		1.0×10^{-8}
electron to shielded proton magnetic moment ratio (H_2O, sphere, 25 °C)	μ_e/μ_p'	−658.227 5954(71)		1.1×10^{-8}
electron–neutron magnetic moment ratio	μ_e/μ_n	960.920 50(23)		2.4×10^{-7}
electron–deuteron magnetic moment ratio	μ_e/μ_d	−2 143.923 498(23)		1.1×10^{-8}
electron to shielded helion[e] magnetic moment ratio (gas, sphere, 25 °C)	μ_e/μ_h'	864.058 255(10)		1.2×10^{-8}
electron gyromagnetic ratio $2\lvert\mu_e\rvert/\hbar$	γ_e	1.760 859 794(71)×10^{11}	s^{-1} T^{-1}	4.0×10^{-8}
	$\gamma_e/2\pi$	28 024.9540(11)	MHz T^{-1}	4.0×10^{-8}
Muon, μ^-				
muon mass	m_μ	1.883 531 09(16)×10^{-28}	kg	8.4×10^{-8}
in u, $m_\mu = A_r(\mu)$ u (muon rel. atomic mass times u)		0.113 428 9168(34)	u	3.0×10^{-8}
energy equivalent	$m_\mu c^2$	1.692 833 32(14)×10^{-11}	J	8.4×10^{-8}
in MeV		105.658 3568(52)	MeV	4.9×10^{-8}
muon–electron mass ratio	m_μ/m_e	206.768 2657(63)		3.0×10^{-8}
muon–tau mass ratio	m_μ/m_τ	5.945 72(97)×10^{-2}		1.6×10^{-4}
muon–proton mass ratio	m_μ/m_p	0.112 609 5173(34)		3.0×10^{-8}
muon–neutron mass ratio	m_μ/m_n	0.112 454 5079(34)		3.0×10^{-8}
muon molar mass $N_A m_\mu$	$M(\mu)$, M_μ	0.113 428 9168(34)×10^{-3}	kg mol^{-1}	3.0×10^{-8}
muon Compton wavelength $h/m_\mu c$	$\lambda_{C,\mu}$	11.734 441 97(35)×10^{-15}	m	2.9×10^{-8}
$\lambda_{C,\mu}/2\pi$	$\lambda\!\!\!^{-}_{C,\mu}$	1.867 594 444(55)×10^{-15}	m	2.9×10^{-8}
muon magnetic moment	μ_μ	−4.490 448 13(22)×10^{-26}	J T^{-1}	4.9×10^{-8}
to Bohr magneton ratio	μ_μ/μ_B	−4.841 970 85(15)×10^{-3}		3.0×10^{-8}
to nuclear magneton ratio	μ_μ/μ_N	−8.890 597 70(27)		3.0×10^{-8}
muon magnetic moment anomaly $\lvert\mu_\mu\rvert/(e\hbar/2m_\mu) - 1$	a_μ	1.165 916 02(64)×10^{-3}		5.5×10^{-7}
muon g-factor $-2(1+a_\mu)$	g_μ	−2.002 331 8320(13)		6.4×10^{-10}
muon–proton magnetic moment ratio	μ_μ/μ_p	−3.183 345 39(10)		3.2×10^{-8}
Tau, τ^-				
tau mass[f]	m_τ	3.167 88(52)×10^{-27}	kg	1.6×10^{-4}
in u, $m_\tau = A_r(\tau)$ u (tau rel. atomic mass times u)		1.907 74(31)	u	1.6×10^{-4}
energy equivalent	$m_\tau c^2$	2.847 15(46)×10^{-10}	J	1.6×10^{-4}
in MeV		1 777.05(29)	MeV	1.6×10^{-4}
tau–electron mass ratio	m_τ/m_e	3 477.60(57)		1.6×10^{-4}
tau–muon mass ratio	m_τ/m_μ	16.8188(27)		1.6×10^{-4}
tau–proton mass ratio	m_τ/m_p	1.893 96(31)		1.6×10^{-4}
tau–neutron mass ratio	m_τ/m_n	1.891 35(31)		1.6×10^{-4}
tau molar mass $N_A m_\tau$	$M(\tau)$, M_τ	1.907 74(31)×10^{-3}	kg mol^{-1}	1.6×10^{-4}
tau Compton wavelength $h/m_\tau c$	$\lambda_{C,\tau}$	0.697 70(11)×10^{-15}	m	1.6×10^{-4}
$\lambda_{C,\tau}/2\pi$	$\lambda\!\!\!^{-}_{C,\tau}$	0.111 042(18)×10^{-15}	m	1.6×10^{-4}
Proton, p				
proton mass	m_p	1.672 621 58(13)×10^{-27}	kg	7.9×10^{-8}
in u, $m_p = A_r(p)$ u (proton rel. atomic mass times u)		1.007 276 466 88(13)	u	1.3×10^{-10}
energy equivalent	$m_p c^2$	1.503 277 31(12)×10^{-10}	J	7.9×10^{-8}
in MeV		938.271 998(38)	MeV	4.0×10^{-8}
proton–electron mass ratio	m_p/m_e	1 836.152 6675(39)		2.1×10^{-9}
proton–muon mass ratio	m_p/m_μ	8.880 244 08(27)		3.0×10^{-8}
proton–tau mass ratio	m_p/m_τ	0.527 994(86)		1.6×10^{-4}
proton–neutron mass ratio	m_p/m_n	0.998 623 478 55(58)		5.8×10^{-10}
proton charge to mass quotient	e/m_p	9.578 834 08(38)×10^7	C kg^{-1}	4.0×10^{-8}
proton molar mass $N_A m_p$	$M(p)$, M_p	1.007 276 466 88(13)×10^{-3}	kg mol^{-1}	1.3×10^{-10}
proton Compton wavelength $h/m_p c$	$\lambda_{C,p}$	1.321 409 847(10)×10^{-15}	m	7.6×10^{-9}
$\lambda_{C,p}/2\pi$	$\lambda\!\!\!^{-}_{C,p}$	0.210 308 9089(16)×10^{-15}	m	7.6×10^{-9}

CODATA Recommended Values of the Fundamental Physical Constants – 1998

Quantity	Symbol	Value	Unit	Relative standard uncertainty u_r
proton magnetic moment	μ_p	$1.410\,606\,633(58)\times10^{-26}$	J T^{-1}	4.1×10^{-8}
to Bohr magneton ratio	μ_p/μ_B	$1.521\,032\,203(15)\times10^{-3}$		1.0×10^{-8}
to nuclear magneton ratio	μ_p/μ_N	2.792 847 337(29)		1.0×10^{-8}
proton g-factor $2\mu_p/\mu_N$	g_p	5.585 694 675(57)		1.0×10^{-8}
proton–neutron magnetic moment ratio	μ_p/μ_n	−1.459 898 05(34)		2.4×10^{-7}
shielded proton magnetic moment (H_2O, sphere, 25 °C)	μ'_p	$1.410\,570\,399(59)\times10^{-26}$	J T^{-1}	4.2×10^{-8}
to Bohr magneton ratio	μ'_p/μ_B	$1.520\,993\,132(16)\times10^{-3}$		1.1×10^{-8}
to nuclear magneton ratio	μ'_p/μ_N	2.792 775 597(31)		1.1×10^{-8}
proton magnetic shielding correction $1-\mu'_p/\mu_p$ (H_2O, sphere, 25 °C)	σ'_p	$25.687(15)\times10^{-6}$		5.7×10^{-4}
proton gyromagnetic ratio $2\mu_p/\hbar$	γ_p	$2.675\,222\,12(11)\times10^{8}$	s^{-1} T^{-1}	4.1×10^{-8}
	$\gamma_p/2\pi$	42.577 4825(18)	MHz T^{-1}	4.1×10^{-8}
shielded proton gyromagnetic ratio $2\mu'_p/\hbar$ (H_2O, sphere, 25 °C)	γ'_p	$2.675\,153\,41(11)\times10^{8}$	s^{-1} T^{-1}	4.2×10^{-8}
	$\gamma'_p/2\pi$	42.576 3888(18)	MHz T^{-1}	4.2×10^{-8}
Neutron, n				
neutron mass	m_n	$1.674\,927\,16(13)\times10^{-27}$	kg	7.9×10^{-8}
in u, $m_n=A_r(n)$ u (neutron rel. atomic mass times u)		1.008 664 915 78(55)	u	5.4×10^{-10}
energy equivalent	m_nc^2	$1.505\,349\,46(12)\times10^{-10}$	J	7.9×10^{-8}
in MeV		939.565 330(38)	MeV	4.0×10^{-8}
neutron–electron mass ratio	m_n/m_e	1 838.683 6550(40)		2.2×10^{-9}
neutron–muon mass ratio	m_n/m_μ	8.892 484 78(27)		3.0×10^{-8}
neutron–tau mass ratio	m_n/m_τ	0.528 722(86)		1.6×10^{-4}
neutron–proton mass ratio	m_n/m_p	1.001 378 418 87(58)		5.8×10^{-10}
neutron molar mass N_Am_n	$M(n), M_n$	$1.008\,664\,915\,78(55)\times10^{-3}$	kg mol^{-1}	5.4×10^{-10}
neutron Compton wavelengths h/m_nc	$\lambda_{C,n}$	$1.319\,590\,898(10)\times10^{-15}$	m	7.6×10^{-9}
$\lambda_{C,n}/2\pi$	$\lambda\!\!\!^{-}_{C,n}$	$0.210\,019\,4142(16)\times10^{-15}$	m	7.6×10^{-9}
neutron magnetic moment	μ_n	$-0.966\,236\,40(23)\times10^{-26}$	J T^{-1}	2.4×10^{-7}
to Bohr magneton ratio	μ_n/μ_B	$-1.041\,875\,63(25)\times10^{-3}$		2.4×10^{-7}
to nuclear magneton ratio	μ_n/μ_N	−1.913 042 72(45)		2.4×10^{-7}
neutron g-factor $2\mu_n/\mu_N$	g_n	−3.826 085 45(90)		2.4×10^{-7}
neutron–electron magnetic moment ratio	μ_n/μ_e	$1.040\,668\,82(25)\times10^{-3}$		2.4×10^{-7}
neutron–proton magnetic moment ratio	μ_n/μ_p	−0.684 979 34(16)		2.4×10^{-7}
neutron to shielded proton magnetic moment ratio (H_2O, sphere, 25 °C)	μ_n/μ'_p	−0.684 996 94(16)		2.4×10^{-7}
neutron gyromagnetic ratio $2\lvert\mu_n\rvert/\hbar$	γ_n	$1.832\,471\,88(44)\times10^{8}$	s^{-1} T^{-1}	2.4×10^{-7}
	$\gamma_n/2\pi$	29.164 6958(70)	MHz T^{-1}	2.4×10^{-7}
Deuteron, d				
deuteron mass	m_d	$3.343\,583\,09(26)\times10^{-27}$	kg	7.9×10^{-8}
in u, $m_d=A_r(d)$ u (deuteron rel. atomic mass times u)		2.013 553 212 71(35)	u	1.7×10^{-10}
energy equivalent	m_dc^2	$3.005\,062\,62(24)\times10^{-10}$	J	7.9×10^{-8}
in MeV		1 875.612 762(75)	MeV	4.0×10^{-8}
deuteron–electron mass ratio	m_d/m_e	3 670.482 9550(78)		2.1×10^{-9}
deuteron–proton mass ratio	m_d/m_p	1.999 007 500 83(41)		2.0×10^{-10}
deuteron molar mass N_Am_d	$M(d), M_d$	$2.013\,553\,212\,71(35)\times10^{-3}$	kg mol^{-1}	1.7×10^{-10}
deuteron magnetic moment	μ_d	$0.433\,073\,457(18)\times10^{-26}$	J T^{-1}	4.2×10^{-8}
to Bohr magneton ratio	μ_d/μ_B	$0.466\,975\,4556(50)\times10^{-3}$		1.1×10^{-8}
to nuclear magneton ratio	μ_d/μ_N	0.857 438 2284(94)		1.1×10^{-8}
deuteron–electron magnetic moment ratio	μ_d/μ_e	$-4.664\,345\,537(50)\times10^{-4}$		1.1×10^{-8}
deuteron–proton magnetic moment ratio	μ_d/μ_p	0.307 012 2083(45)		1.5×10^{-8}
deuteron–neutron magnetic moment ratio	μ_d/μ_n	−0.448 206 52(11)		2.4×10^{-7}
Helion, h				
helion mass[e]	m_h	$5.006\,411\,74(39)\times10^{-27}$	kg	7.9×10^{-8}
in u, $m_h=A_r(h)$ u (helion rel. atomic mass times u)		3.014 932 234 69(86)	u	2.8×10^{-10}
energy equivalent	m_hc^2	$4.499\,538\,48(35)\times10^{-10}$	J	7.9×10^{-8}
in MeV		2 808.391 32(11)	MeV	4.0×10^{-8}
helion–electron mass ratio	m_h/m_e	5 495.885 238(12)		2.1×10^{-9}
helion–proton mass ratio	m_h/m_p	2.993 152 658 50(93)		3.1×10^{-10}
helion molar mass N_Am_h	$M(h), M_h$	$3.014\,932\,234\,69(86)\times10^{-3}$	kg mol^{-1}	2.8×10^{-10}
shielded helion magnetic moment (gas, sphere, 25 °C)	μ'_h	$-1.074\,552\,967(45)\times10^{-26}$	J T^{-1}	4.2×10^{-8}
to Bohr magneton ratio	μ'_h/μ_B	$-1.158\,671\,474(14)\times10^{-3}$		1.2×10^{-8}

CODATA Recommended Values of the Fundamental Physical Constants – 1998

Quantity	Symbol	Value	Unit	Relative standard uncertainty u_r
to nuclear magneton ratio	μ'_h/μ_N	−2.127 497 718(25)		1.2×10^{-8}
shielded helion to proton magnetic moment ratio (gas, sphere, 25 °C)	μ'_h/μ_p	−0.761 766 563(12)		1.5×10^{-8}
shielded helion to shielded proton magnetic moment ratio (gas/H_2O, spheres, 25 °C)	μ'_h/μ'_p	−0.761 786 1313(33)		4.3×10^{-9}
shielded helion gyromagnetic ratio $2\lvert\mu'_h\rvert/\hbar$ (gas, sphere, 25 °C)	γ'_h	$2.037\,894\,764(85)\times10^{8}$	$s^{-1}\,T^{-1}$	4.2×10^{-8}
	$\gamma'_h/2\pi$	32.434 1025(14)	MHz T^{-1}	4.2×10^{-8}
Alpha particle, α				
alpha particle mass	m_α	$6.644\,655\,98(52)\times10^{-27}$	kg	7.9×10^{-8}
in u, $m_\alpha = A_r(\alpha)$ u (alpha particle rel. atomic mass times u)		4.001 506 1747(10)	u	2.5×10^{-10}
energy equivalent	$m_\alpha c^2$	$5.971\,918\,97(47)\times10^{-10}$	J	7.9×10^{-8}
in MeV		3 727.379 04(15)	MeV	4.0×10^{-8}
alpha particle to electron mass ratio	m_α/m_e	7 294.299 508(16)		2.1×10^{-9}
alpha particle to proton mass ratio	m_α/m_p	3.972 599 6846(11)		2.8×10^{-10}
alpha particle molar mass $N_A m_\alpha$	$M(\alpha), M_\alpha$	$4.001\,506\,1747(10)\times10^{-3}$	kg mol^{-1}	2.5×10^{-10}
PHYSICOCHEMICAL				
Avogadro constant	N_A, L	$6.022\,141\,99(47)\times10^{23}$	mol^{-1}	7.9×10^{-8}
atomic mass constant $m_u = \frac{1}{12}m(^{12}C) = 1\ u = 10^{-3}\ kg\ mol^{-1}/N_A$	m_u	$1.660\,538\,73(13)\times10^{-27}$	kg	7.9×10^{-8}
energy equivalent	$m_u c^2$	$1.492\,417\,78(12)\times10^{-10}$	J	7.9×10^{-8}
in MeV		931.494 013(37)	MeV	4.0×10^{-8}
Faraday constant[g] $N_A e$	F	96 485.3415(39)	C mol^{-1}	4.0×10^{-8}
molar Planck constant	$N_A h$	$3.990\,312\,689(30)\times10^{-10}$	J s mol^{-1}	7.6×10^{-9}
	$N_A hc$	0.119 626 564 92(91)	J m mol^{-1}	7.6×10^{-9}
molar gas constant	R	8.314 472(15)	J $mol^{-1}\,K^{-1}$	1.7×10^{-6}
Boltzmann constant R/N_A	k	$1.380\,6503(24)\times10^{-23}$	J K^{-1}	1.7×10^{-6}
in eV K^{-1}		$8.617\,342(15)\times10^{-5}$	eV K^{-1}	1.7×10^{-6}
	k/h	$2.083\,6644(36)\times10^{10}$	Hz K^{-1}	1.7×10^{-6}
	k/hc	69.503 56(12)	$m^{-1}\,K^{-1}$	1.7×10^{-6}
molar volume of ideal gas RT/p				
T = 273.15 K, p = 101.325 kPa	V_m	$22.413\,996(39)\times10^{-3}$	$m^3\,mol^{-1}$	1.7×10^{-6}
Loschmidt constant N_A/V_m	n_0	$2.686\,7775(47)\times10^{25}$	m^{-3}	1.7×10^{-6}
T = 273.15 K, p = 100 kPa	V_m	$22.710\,981(40)\times10^{-3}$	$m^3\,mol^{-1}$	1.7×10^{-6}
Sackur–Tetrode constant (absolute entropy constant)[h] $\frac{5}{2}+\ln[(2\pi m_u kT_1/h^2)^{3/2}kT_1/p_0]$				
T_1 = 1 K, p_0 = 100 kPa	S_0/R	−1.151 7048(44)		3.8×10^{-6}
T_1 = 1 K, p_0 = 101.325 kPa		−1.164 8678(44)		3.7×10^{-6}
Stefan–Boltzmann constant $(\pi^2/60)k^4/\hbar^3c^2$	σ	$5.670\,400(40)\times10^{-8}$	W $m^{-2}\,K^{-4}$	7.0×10^{-6}
first radiation constant $2\pi hc^2$	c_1	$3.741\,771\,07(29)\times10^{-16}$	W m^2	7.8×10^{-8}
first radiation constant for spectral radiance $2hc^2$	c_{1L}	$1.191\,042\,722(93)\times10^{-16}$	W $m^2\,sr^{-1}$	7.8×10^{-8}
second radiation constant hc/k	c_2	$1.438\,7752(25)\times10^{-2}$	m K	1.7×10^{-6}
Wien displacement law constant $b = \lambda_{max}T = c_2/4.965\,114\,231\ldots$	b	$2.897\,7686(51)\times10^{-3}$	m K	1.7×10^{-6}

[a] See the "Internationally Adopted Values" table for the conventional value for realizing representations of the volt using the Josephson effect.
[b] See the "Internationally Adopted Values" table for the conventional value for realizing representations of the ohm using the quantum Hall effect.
[c] Value recommended by the Particle Data Group [C. Caso *et al.*, Eur. Phys. J. C **3**, 1 (1998)].
[d] Based on the ratio of the masses of the W and Z bosons m_W/m_Z recommended by the Particle Data Group [C. Caso *et al.*, Eur. Phys. J. C **3**, 1 (1998)]. The value for $\sin^2\theta_W$ they recommend, which is based on a particular variant of the modified minimal subtraction ($\overline{MS}$) scheme, is $\sin^2\hat{\theta}_W(M_Z) = 0.231\,24(24)$.
[e] The helion, symbol h, is the nucleus of the ^{3}He atom.
[f] This and all other values involving m_τ are based on the value of $m_\tau c^2$ in MeV recommended by the Particle Data Group [C. Caso *et al.*, Eur. Phys. J. C **3**, 1 (1998)], but with a standard uncertainty of 0.29 MeV rather than the quoted uncertainty of −0.26 MeV, +0.29 MeV.
[g] The numerical value of F to be used in coulometric chemical measurements is 96 485.3432(76) [7.9×10^{-8}] when the relevant current is measured in terms of representations of the volt and ohm based on the Josephson and quantum Hall effects and the conventional values of the Josephson and von Klitzing constants K_{J-90} and R_{K-90} given in the "Internationally Adopted Values" table.
[h] The entropy of an ideal monoatomic gas of relative atomic mass A_r is given by $S = S_0 + \frac{3}{2}R\ln A_r - R\ln(p/p_0) + \frac{5}{2}R\ln(T/K)$.

Internationally Adopted Values of Various Quantities

Quantity	Symbol	Value	Unit	Relative standard uncertainty u_r
molar mass of ^{12}C	$M(^{12}C)$	12×10^{-3}	kg mol^{-1}	(exact)
molar mass constant[a] $M(^{12}C)/12$	M_u	1×10^{-3}	kg mol^{-1}	(exact)
conventional value of Josephson constant[b]	K_{J-90}	483 597.9	GHz V^{-1}	(exact)
conventional value of von Klitzing constant[c]	R_{K-90}	25 812.807	Ω	(exact)
standard atmosphere		101 325	Pa	(exact)
standard acceleration of gravity	g_n	9.806 65	m s^{-2}	(exact)

[a]The relative atomic mass $A_r(X)$ of particle X with mass $m(X)$ is defined by $A_r(X) = m(X)/m_u$, where $m_u = m(^{12}C)/12 = M_u/N_A = 1$ u is the atomic mass constant, N_A is the Avogadro constant, and u is the (unified) atomic mass unit. Thus the mass of particle X is $m(X) = A_r(X)$ u and the molar mass of X is $M(X) = A_r(X)M_u$.
[b]This is the value adopted internationally for realizing representations of the volt using the Josephson effect.
[c]This is the value adopted internationally for realizing representations of the ohm using the quantum Hall effect.

CODATA Recommended Values of Energy Equivalents – 1998

	Relevant unit			
	J	kg	m^{-1}	Hz
1 J	$(1\text{ J}) =$ 1 J	$(1\text{ J})/c^2 =$ $1.112\,650\,056\times10^{-17}$ kg	$(1\text{ J})/hc =$ $5.034\,117\,62(39)\times10^{24}$ m^{-1}	$(1\text{ J})/h =$ $1.509\,190\,50(12)\times10^{33}$ Hz
1 kg	$(1\text{ kg})c^2 =$ $8.987\,551\,787\times10^{16}$ J	$(1\text{ kg}) =$ 1 kg	$(1\text{ kg})c/h =$ $4.524\,439\,29(35)\times10^{41}$ m^{-1}	$(1\text{ kg})c^2/h =$ $1.356\,392\,77(11)\times10^{50}$ Hz
1 m^{-1}	$(1\text{ m}^{-1})hc =$ $1.986\,445\,44(16)\times10^{-25}$ J	$(1\text{ m}^{-1})h/c =$ $2.210\,218\,63(17)\times10^{-42}$ kg	$(1\text{ m}^{-1}) =$ 1 m^{-1}	$(1\text{ m}^{-1})c =$ 299 792 458 Hz
1 Hz	$(1\text{ Hz})h =$ $6.626\,068\,76(52)\times10^{-34}$ J	$(1\text{ Hz})h/c^2 =$ $7.372\,495\,78(58)\times10^{-51}$ kg	$(1\text{ Hz})/c =$ $3.335\,640\,952\times10^{-9}$ m^{-1}	$(1\text{ Hz}) =$ 1 Hz
1 K	$(1\text{ K})k =$ $1.380\,6503(24)\times10^{-23}$ J	$(1\text{ K})k/c^2 =$ $1.536\,1807(27)\times10^{-40}$ kg	$(1\text{ K})k/hc =$ 69.503 56(12) m^{-1}	$(1\text{ K})k/h =$ $2.083\,6644(36)\times10^{10}$ Hz
1 eV	$(1\text{ eV}) =$ $1.602\,176\,462(63)\times10^{-19}$ J	$(1\text{ eV})/c^2 =$ $1.782\,661\,731(70)\times10^{-36}$ kg	$(1\text{ eV})/hc =$ $8.065\,544\,77(32)\times10^{5}$ m^{-1}	$(1\text{ eV})/h =$ $2.417\,989\,491(95)\times10^{14}$ Hz
1 u	$(1\text{ u})c^2 =$ $1.492\,417\,78(12)\times10^{-10}$ J	$(1\text{ u}) =$ $1.660\,538\,73(13)\times10^{-27}$ kg	$(1\text{ u})c/h =$ $7.513\,006\,658(57)\times10^{14}$ m^{-1}	$(1\text{ u})c^2/h =$ $2.252\,342\,733(17)\times10^{23}$ Hz
1 E_h	$(1\ E_h) =$ $4.359\,743\,81(34)\times10^{-18}$ J	$(1\ E_h)/c^2 =$ $4.850\,869\,19(38)\times10^{-35}$ kg	$(1\ E_h)/hc =$ $2.194\,746\,313\,710(17)\times10^{7}$ m^{-1}	$(1\ E_h)/h =$ $6.579\,683\,920\,735(50)\times10^{15}$ Hz

CODATA Recommended Values of Energy Equivalents – 1998

	Relevant unit			
	K	eV	u	E_h
1 J	$(1\text{ J})/k =$ $7.242\,964(13)\times10^{22}$ K	$(1\text{ J}) =$ $6.241\,509\,74(24)\times10^{18}$ eV	$(1\text{ J})/c^2 =$ $6.700\,536\,62(53)\times10^{9}$ u	$(1\text{ J}) =$ $2.293\,712\,76(18)\times10^{17}\ E_h$
1 kg	$(1\text{ kg})c^2/k =$ $6.509\,651(11)\times10^{39}$ K	$(1\text{ kg})c^2 =$ $5.609\,589\,21(22)\times10^{35}$ eV	$(1\text{ kg}) =$ $6.022\,141\,99(47)\times10^{26}$ u	$(1\text{ kg})c^2 =$ $2.061\,486\,22(16)\times10^{34}\ E_h$
1 m^{-1}	$(1\text{ m}^{-1})hc/k =$ $1.438\,7752(25)\times10^{-2}$ K	$(1\text{ m}^{-1})hc =$ $1.239\,841\,857(49)\times10^{-6}$ eV	$(1\text{ m}^{-1})h/c =$ $1.331\,025\,042(10)\times10^{-15}$ u	$(1\text{ m}^{-1})hc =$ $4.556\,335\,252\,750(35)\times10^{-8}\ E_h$
1 Hz	$(1\text{ Hz})h/k =$ $4.799\,2374(84)\times10^{-11}$ K	$(1\text{ Hz})h =$ $4.135\,667\,27(16)\times10^{-15}$ eV	$(1\text{ Hz})h/c^2 =$ $4.439\,821\,637(34)\times10^{-24}$ u	$(1\text{ Hz})h =$ $1.519\,829\,846\,003(12)\times10^{-16}\ E_h$
1 K	$(1\text{ K}) =$ 1 K	$(1\text{ K})k =$ $8.617\,342(15)\times10^{-5}$ eV	$(1\text{ K})k/c^2 =$ $9.251\,098(16)\times10^{-14}$ u	$(1\text{ K})k =$ $3.166\,8153(55)\times10^{-6}\ E_h$
1 eV	$(1\text{ eV})/k =$ $1.160\,4506(20)\times10^{4}$ K	$(1\text{ eV}) =$ 1 eV	$(1\text{ eV})/c^2 =$ $1.073\,544\,206(43)\times10^{-9}$ u	$(1\text{ eV}) =$ $3.674\,932\,60(14)\times10^{-2}\ E_h$
1 u	$(1\text{ u})c^2/k =$ $1.080\,9528(19)\times10^{13}$ K	$(1\text{ u})c^2 =$ $931.494\,013(37)\times10^{6}$ eV	$(1\text{ u}) =$ 1 u	$(1\text{ u})c^2 =$ $3.423\,177\,709(26)\times10^{7}\ E_h$
1 E_h	$(1\ E_h)/k =$ $3.157\,7465(55)\times10^{5}$ K	$(1\ E_h) =$ 27.211 3834(11) eV	$(1\ E_h)/c^2 =$ $2.921\,262\,304(22)\times10^{-8}$ u	$(1\ E_h) =$ 1 E_h

(continued from page 7)

the electron from $m_e = 2R_\infty h/c\alpha^2$, and the Avogadro constant from $N_A = c\alpha^2 A_r(e) M_u / 2R_\infty h$, where $\mu_0 = 4\pi \times 10^{-7}$ N A^{-2}, $c = 299\,792\,458$ m s^{-1}, and $M_u = 10^{-3}$ kg/mol, are the exactly known magnetic constant, speed of light in vacuum, and molar mass constant, respectively. The uncertainties of such derived values are obtained from the uncertainties and covariances of the adjusted constants.

The improvement in our knowledge of the values of the constants represented by the 1998 CODATA set of recommended values is truly impressive. Still, it is not as well founded as one might like. Specifically, there is little redundancy among some of the key input data of the 1998 adjustment. As indicated above, α, h, and R play an especially critical role in the determination of many constants, yet the recommended value of each is to a large extent determined by a single input datum or, at best, two input data with rather different standard uncertainties u and hence rather different weights $1/u^2$. In the case of α, the input data are merely the single experimental value of a_e and the single calculated value of the mass-independent eighth-order coefficient $A_1^{(8)}$ in the QED-based theoretical expression for a_e. In the case of h, the input data are the two watt-balance values of $K_J^2 R_K$, with uncertainties that differ by a factor of about 2.3. And in the case of the molar gas constant, the input data are the two values of R based on speed-of-sound measurements in argon using a resonator and an interferometer with uncertainties that differ by about a factor of 4.7. The experimental and theoretical work required to solidify and continue the progress of the last 13 years is thus clear: We must obtain new input data related to α, h, and R with uncertainties no larger than their current uncertainties, and eventually with significantly smaller uncertainties.

The existence of the Web has dramatically changed the availability of information—we can expect to have the latest data available electronically only a mouse-click away. In fact, the new 1998 CODATA set of recommended values was available at the NIST Web site mentioned above seven months before the appearance of the first printed version. Because of the Web and the new modes of work and thought it has engendered, and because new experimental and theoretical data that influence our knowledge of the values of the constants appear nearly continuously, the CODATA task group has concluded that 13 years between adjustments is no longer acceptable. (The first set of CODATA recommended values of the constants was issued in 1973,[3] 13 years before the second set in 1986 and 26 years before the 1998 set.) Thus, in the future, by taking advantage of the high degree of automation we have incorporated in the 1998 adjustment, CODATA plans to issue a new set of recommended values every four years, or more frequently if new data become available that have a significant impact on the values of the constants. You can thus expect a much shorter wait to see the next revision of this article in the PHYSICS TODAY *Buyers' Guide*.

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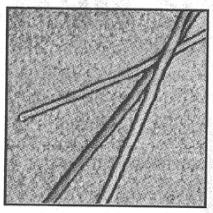
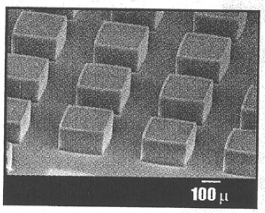


300nm AFM phase contrast image of SWNT ropes imaged with SWNT probe



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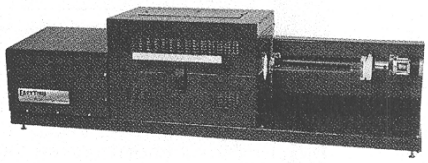

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Internationally recognized conventions have been established for standard usage of SI units.

Robert A. Nelson

The modernized metric system is known as the *Système International d'Unités* (International System of Units), with the international abbreviation SI. It is founded on seven base units, listed in table 1, that by convention are regarded as dimensionally independent. All other units are derived units, formed coherently by multiplying and dividing units within the system without numerical factors. Examples of derived units, including some with special names, are listed in table 2. The expression of multiples and submultiples of SI units is facilitated through the use of the prefixes listed in table 3.

SI obtains its international authority from the Meter Convention, signed in Paris by the delegates of 17 countries, including the United States, on 20 May 1875, and amended in 1921. Today 51 countries are members. The treaty established the *Conférence Générale des Poids et Mesures* (General Conference on Weights and Measures) as the formal diplomatic body responsible for ratification of new proposals related to metric units. The scientific decisions are made by the *Comité International des Poids et Mesures* (International Committee for Weights and Measures). It is assisted by the advice of ten Consultative Committees specializing in particular areas of metrology. The activities of the national standards laboratories are coordinated by the *Bureau International des Poids et Mesures* (International Bureau of Weights and Measures), which has its headquarters in Sèvres, France, and operates under the supervision of the CIPM. The SI was established by the 11th CGPM in 1960, when the metric unit definitions, symbols, and terminology were extensively revised and simplified.[1]

The BIPM, with the guidance of the Consultative Committee for Units and approval of the CIPM, periodically publishes a document[2] that summarizes the historical decisions of the CGPM and the CIPM and gives some conventions for metric practice. In addition, Technical Committee 12 of the International Organization for Standardization has prepared recommendations concerning the practical use of the SI.[3] Some other recommendations have been given by the Commission for Symbols, Units, Nomenclature, Atomic Masses and Fundamental Constants of the International Union of Pure and Applied Physics.[4] The National Institute of Standards and Technology (NIST) has published a practical guide for the use of the SI.[5] The Institute of Electrical and Electronics Engineers (IEEE) and the American Society for Testing and Materials (ASTM) have jointly prepared a metric practice manual[6] that has been recognized by the American National Standards Institute (ANSI). The Secretary of Commerce, through NIST, has also issued recommendations for US metric practice,[7] as provided under the Metric Conversion Act of 1975 and the Omnibus Trade and Competitiveness Act of 1988. Additional information is available on the Internet at the BIPM[8] and NIST[9] Web sites.

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Table 1. SI base units

Quantity	Unit	
	Name	Symbol
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

Table 2. Examples of SI derived units

Quantity	Unit		
	Special name	Symbol	Equivalent
plane angle	radian	rad	m/m=1
solid angle	steradian	sr	$m^2/m^2=1$
speed, velocity			m/s
acceleration			m/s^2
angular velocity			rad/s
angular acceleration			rad/s_2
frequency	hertz	Hz	s^{-1}
force	newton	N	$kg·m/s^2$
pressure, stress	pascal	Pa	N/m^2
work, energy, heat	joule	J	$N·m, kg·m^2/s^2$
impulse, momentum			N·s, kg·m/s
power	watt	W	J/s
electric charge	coulomb	C	A·s
electric potential, emf	volt	V	J/C, W/A
resistance	ohm	W	V/A
conductance	siemens	S	$A/V, W^{-1}$
magnetic flux	weber	Wb	V·s
inductance	henry	H	Wb/A
capacitance	farad	F	C/V
electric field strength			V/m, N/C
magnetic flux density	tesla	T	Wb/m^2, N/(A·m)
electric displacement			C/m^2
magnetic field strength			A/m
Celsius temperature	degree Celsius	°C	K
luminous flux	lumen	lm	cd·sr
illuminance	lux	lx	lm/m^2
radioactivity	becquerel	Bq	s^{-1}
catalytic activity	katal	kat	mol/s

Style conventions

Letter symbols include quantity symbols and unit symbols. Symbols for physical quantities are set in italic (sloping) type, while symbols for units are set in roman (upright) type (for example, F = 15 N).

A unit symbol is a universal mathematical entity. It is not an abbreviation and is not followed by a period (for example, the symbol for second is s, not sec or s.). Symbols for units with proper names have the first letter capitalized—otherwise unit symbols are lower case—but the unit names themselves are not capitalized (for example, tesla, T; meter, m). In contrast to unit symbols, the spelling and grammar for unit names are specific to a given language and are not part of the SI (for example, the spellings kilogram and ampere are used in English, while kilogramme and ampère are used in French, but kg and A are the universal SI symbols). Plurals of unit names are formed according to the usual rules of grammar (for example, kilopascals, henries) with the exceptions lux, hertz, and siemens, which are irregular.[5] Unit symbols are not plu-

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Table 3. SI prefixes

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{24}	yotta	Y	10^{-1}	deci	d
10^{21}	zetta	Z	10^{-2}	centi	c
10^{18}	exa	E	10^{-3}	milli	m
10^{15}	peta	P	10^{-6}	micro	m
10^{12}	tera	T	10^{-9}	nano	n
10^{9}	giga	G	10^{-12}	pico	p
10^{6}	mega	M	10^{-15}	femto	f
10^{3}	kilo	k	10^{-18}	atto	a
10^{2}	hecto	h	10^{-21}	zepto	z
10^{1}	deka	da	10^{-24}	yocto	y

Table 4. Units accepted for use with the SI

Quantity	Name	Unit Symbol	Definition
time	minute	min	1 min=60 s
	hour	h	1 h=60 min=3600 s
	day	d	1 d=24 h=86 400 s
plane angle	degree	°	$1°=(\pi/180)$ rad
	minute	′	$1′=(1/60)°=(\pi/10\,800)$ rad
	second	″	$1″=(1/60)′=(\pi/648\,000)$ rad
volume	liter	L	$1\ L=1\ dm^3=10^{-3}\ m^3$
mass	metric ton	t	1 t=1000 kg
attenuation, level	neper	Np	1 Np=1
	bel	B	1 B=½ ln 10 Np

ralized (for example, 3 kg, not 3 kgs).

The word "degree" and its symbol, °, are omitted from the unit of thermodynamic temperature T (that is, one uses kelvin or K, not degree Kelvin or °K). However, they are retained in the unit of Celsius temperature t, defined as $t \equiv T–T_0$, where $T_0 = 273.15$ K exactly (that is, degree Celsius, °C).

Symbols for prefixes representing 10^6 or greater are capitalized; all others are lower case. There is no space between the prefix and the unit. Compound prefixes are to be avoided (for example, pF, not $\mu\mu$F). An exponent applies to the whole unit including its prefix (for example, $cm^3 = 10^{-6}\ m^3$). When a unit multiple or submultiple is written out in full, the prefix should be written in full, beginning with a lower-case letter (for example, megahertz, not Megahertz or Mhertz). The kilogram is the only base unit whose name, for historical reasons, contains a prefix; names of multiples and submultiples of the kilogram and their symbols are formed by attaching prefixes to the word "gram" and the symbol "g."

Multiplication of units is indicated by inserting a raised dot or by leaving a space between the units (for example, N·m or N m). Division may be indicated by the use of the solidus, a horizontal fraction bar or a negative exponent (for example, m/s, or $m{\cdot}s^{-1}$), but repeated use of the solidus is not permitted (for example, m/s^2, not m/s/s). To avoid possible misinterpretation when more than one unit appears in the denominator, the preferred practice is to use parentheses or negative exponents (for example, $W/(m^2{\cdot}K^4)$ or $W{\cdot}m^{-2}{\cdot}K^{-4}$). The unit expression may include a prefixed unit in the numerator or denominator (for example, mN/m, W/cm^2).

Unit names should not be mixed with symbols for mathematical operations. (For example, one should write "meter per second" but not "meter/second" or "meter second^{-1}.") When spelling out the product of two units, a space is recommended (although a hyphen is permissible), but one should never use a centered dot. (Write, for example, "newton meter" or "newton-meter," but not "newton·meter.")

Three-digit groups in numbers with more than four digits are separated by thin spaces instead of commas (for example, 299 792 458, not 299,792,458) to avoid confusion with the decimal marker in European literature. This

Table 5. Non-SI units accepted for use with the SI whose values in SI units are obtained experimentally

Quantity	Name	Unit Symbol	Value
energy	electron volt*	eV	$1.602\ 176\ 462(63)\times10^{-19}$ J
mass	unified atomic mass unit*	u	$1.660\ 538\ 73(13)\times10^{-27}$ kg
distance	astronomical unit**	ua	$1.495\ 978\ 706\ 91(6)\times10^{11}$ m m

* P. J. Mohr, B. N. Taylor, *J. Phys. Chem. Ref. Data* **28**, 1713 (1999). *Rev. Mod. Phys.* **72**, 351 (2000).

** D. D. McCarthy, ed., *IERS Conventions (2000)*, to be published; http://www.iers.org.

spacing convention is also used to the right of the decimal marker. The numerical value and unit symbol must be separated by a space, even when used as an adjective (for example, 35 mm, not 35mm or 35-mm). A zero should be placed in front of the decimal marker in decimal fractions (for example, 0.3 J, not .3 J).

Non-SI units

An important function of the SI is to discourage the proliferation of unnecessary units. However, there are three categories of units outside the SI that are recognized. "Units accepted for use with the SI" are listed in Table 4. As exceptions to the rules, the symbols °, ′ and ″ for plane angle are not preceded by a space, and the symbol for liter, L, is capitalized to avoid confusion with the number 1. "Non-SI units accepted for use with the SI whose values in SI units are obtained experimentally" are given in Table 5. The third category, "other non-SI units currently accepted for use with the SI," consists of the nautical mile, knot, are, hectare, bar, angstrom, and barn.

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