François Cardarelli

Encyclopaedia of Scientific Units, Weights and Measures

Their SI Equivalences and Origins

English translation by M.J. Shields, FIInfSc, MITI

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1 Introduction

1.1 Why a Conversion Handbook?

Books on the conversion of scientific units into their SI equivalents are relatively rare in scientific literature. There are several specialized treatises (*see Bibliography*) on the subject as applied to certain areas of science and technology, which contain sections on the subject, supported by conversion tables. However, these tables are anything but exhaustive, and it is often necessary to consult sources in several very different areas in order to obtain the desired information.

This practical manual aims to be the most comprehensive work on the subject of unit conversion. It contains more than 20 000 precise conversion factors, and around 5000 definitions of the units themselves. The units included, and their conversions, are grouped into imperial and US units, conventional metric units, older or out-of-date units, ancient units, and SI units. The subject areas involved are: pure and applied science, technology, medicine, and economics. Some examples of individual sciences covered are mechanical, electrical, chemical, and nuclear engineering, civil and mining engineering, chemistry, physics, biology, medicine, economics, and computer sciences. In other words, this book places unit conversion at the disposal of everyone. It saves working time, and should be available in all research libraries and design offices. It has been kept as small as possible in order to facilitate consultation in all circumstances, whether in the office, on the production line, or on the move.

The aim of this book is to ensure rapid and accurate conversion of scientific units to their SI equivalents. However, the reader should be aware that it does not provide rules and advice for writing the names, nor the recommended symbols for physical quantities used in science and technology. Several specialized works already exist for this purpose.[1]

This book is suitable for researchers, scientists, engineers and technologists, economists, doctors, pharmacists, and patent lawyers, but is equally suitable for teachers and students.

Encyclopaedia of Scientific Units, Weights and Measures is the product of many years spent collecting information spread across scientific and technical literature. Each item of information has been carefully checked and verified. Additionally, certain pieces of information have been extracted from books or standards for the most part published by national and international bodies (e.g. ISO, AFNOR, BSI, DIN, IEC, ANSI, NACE, NIST). Every effort has been made to supply conversion factors as precisely as possible to an accuracy of nine decimal places.

[1] Mills, I., Cvitas, T., Homann, K., Kallay, N. and Kuchitsu, K. (eds.), *Quantities, Units and Symbols in Physical Chemistry, 2nd ed.*, IUPAC, Blackwell Scientific Publications, Oxford, 1993.

1.2 How to Use This Book

Chapter 2 contains a brief history of the metric system, including the organization and a complete description of SI Units (*Système International d'Unités*).

Chapter 3 gives a detailed description of a considerable number of other systems of measurement. This includes several alternative modern systems of measurement, some of which are still in widespread use (e.g. imperial, US, cgs, MTS, FPS). Finally, there is a description of systems used in antiquity (e.g. ancient Chinese, Indian, Egyptian, Persian, Hebrew, Greek, Roman, Arabic), as well as older national or regional systems (e.g. French, Italian, German, Japanese).

Chapter 4, which forms the most important part of the book, consists of an exhaustive set of conversion tables. This chapter covers the units in alphabetical order. Each unit is fully described as follows: name, symbol(s), physical quantity, dimension, conversion factor, notes and definitions. The section covers some 5000 units, each with a precise conversion factor.

Chapter 5 enables a unit to be identified from its area of application. For this purpose, units are classed in groups. It contains thirty five conversion tables ranging from mass to nuclear quantities.

In order to facilitate use of this manual, several supplementary sections have been added to aid the researcher. These include tables of fundamental mathematical and physical constants to allow very precise calculation of conversions. These form the sixth chapter of the book.

Appendices contain a list of many national and international bodies in the area of standardization, rules of nomenclature for large numbers, notation for times and dates, and a brief French-English glossary of names of units and associated physical quantities.

Finally, a detailed bibliography (e.g. national and international standards, textbooks, specialized engineering handbooks) is presented at the end of the book in order to allow the reader to go further in their investigations.

This practical manual provides rapid answers to all questions concerning the conversion of scientific units. Some examples of the sort of questions that can be answered more rapidly thanks to this manual, along with the chapters where their answers can be found, are given below:

- What is the history of SI units? (2)
- What are the base units of the SI? (2)
- What were the ancient systems of measurement? (3)
- How is the imperial system organized? (3)
- What is a kip? (4)
- Which unit has the abbreviation pcu? (4)
- What are the dimensions of the röntgen? (4)
- What is the conversion factor from spats to steradians? (4)
- What is the conversion factor from density in $lb.ft^{-3}$ to $kg.dm^{-3}$? (4)
- What are the different kinds of units of pressure and stress? (4)
- What is the exact value of the velocity of light in vacuum? (5)
- What are the old symbols for imperial units? (6)
- What are the addresses of standards bodies in the US? (6)
- What are the ISO and AFNOR standards for quantities in nuclear physics? (7)

2 The International System of Units

2.1 History

The origin of the metric system, and of its later version, the International System (*Système International*, SI) of units, goes back a long way into French history. Before that, the old French measures had presented two serious problems:

- units with the same name varied from one region to the next and had to be defined accordingly (e.g., pied de Paris)
- subdivisions were not decimal, which increased the complexity of commercial transactions

As early as 1670, the Abbé Gabriel Mouton proposed one thousandth of a minute of arc (or 1/1000) at the meridian as a rational standard of length. This represents a length of about 1.856 m. He gave this unit the name *milliare*, from the Latin for one thousand, and divided it decimally into three multiple units, named respectively *centuria*, *decuria*, and *virga*, and three submultiples *decima*, *centessima*, and *millesima*. Unfortunately, however, the Abbé died before seeing his ideas adopted.

Over the years, the English mathematician and architect Sir Christopher Wren (1667), the French astronomer Abbé Jean Picard (1671), the Dutch scientist Christiaan Huygens (1673), and the French geodesist Charles Marie de la Condamine (1746) proposed the length of the seconds pendulum as a unit of length. Finally, in 1789, there came a general call for the use of the same measures throughout France.

Soon afterwards, on March 9th, 1790, at the instigation of Charles Maurice de Talleyrand, Bishop of Autun and National Assembly Deputy, the *Constituante*[2] initiated a unification project for weights and measures. The project was adopted on May 8th, 1790, and the Academy of Sciences was given the task of studying the matter. A commission of French mathematicians was made responsible for establishing the base unit; its members were Count Louis de Lagrange, Gaspard Monge, Charles de Borda, and Marie Jean Antoine de Condorcet, plus the astronomer the Marquis Pierre Simon de Laplace. On March 19th, 1791, this commission decided on a unit of length equal to one ten millionth of the distance between the equator and the pole. This unit was called the *mètre*, from the Greek word, *metron*, for measure, and it is of course the origin of the name to the system itself.

In 1795, according to the text of the organic law of 18 Germinal year III (in terms of the revolutionary calendar then in force – equivalent to April 7th, 1795), the Système Métrique

[2] Name of the French Revolutionary Assembly from July 9th, 1789 until September 30th, 1791.

Décimal was instituted in France. This decimal metric system established a new set of units, the **are** (Latin *area*) for area, the **litre** (Greek *litra*, a 12-ounce weight) for volume, and for mass the **gram** (Greek *gramma*, the weight of a pea).

In 1795, Jean-Baptiste Delambre and Pierre Méchain, who had spent almost seven years measuring the geodetic distances between Rodez and Barcelona, and Rodez and Dunkerque, respectively, determined the length of the quarter meridian through Paris. The law established the length of the metre at 0.513074 *toises de Paris*, and prototype standards of dense pure platinum for the metre and kilogram, made by Jeannetty from agglomerated platinum sponge, were adopted in June 1799. It is easy to imagine that the substitution of these new metric measures for the old units in use until then was not achieved without a lot of problems and objections.

In 1812, the former units were re-established by the Emperor Napoleon. However, metric units were reinstated by the Law of July 4th, 1837 which declared the Decimal Metric System obligatory in France from January 1840, and instituted penalties for the use of other weights and measures.

After that, the system slowly extended its application beyond the borders of France, and even became legal, though not compulsory, in the United States in 1866. However, the main launching pad for its internationalization was the meeting of the *Commission Internationale du Mètre* (International Metric Commission) in Paris on August 8th–13th, 1872. The treaty known as the *Convention du Mètre* (International Metric Convention) was signed on May 20th, 1875 by an assembly of representatives of 17 countries including the USA. It established the *Conférence Générale des Poids et Mesures* (General Conference on Weights and Measures, CGPM), and the *Bureau International des Poids et Mesures* (International Bureau of Weights and Measures, BIPM). The headquarters of the International Bureau, which is maintained by all the national members, was established at the Pavillon de Breteuil, at Sèvres, near Paris, in consideration of the role of France as the birthplace of the metric system. The first General Conference on Weights and Measures (1st CGPM), held in 1889, organized the distribution of copies of the international standard prototype metre to the 21 member states of the International Metric Convention. The copies of the new standard prototype called *mètre international* were built from platinum-iridium alloy (Pt90-Ir10) which is an outcome of the work of Sainte-Claire Deville et al.[3,4] The secondary standards were a typical bar with X cross-section having a side of 2 cm.

A summary of definitions of the metre is given in ***Table 2-1.***

The *Système International d'Unités* (SI) is the ultimate development of the metric system. Previous versions included the cgs (centimetre-gram-second), the MTS (metre-tonne-second), the MKS (metre-kilogram-force-second), and the MKSA (metre-kilogram-second-ampere) or Giorgi systems.

In 1954, the 10th CGPM adopted a set of base units for the following physical quantities: length, mass, time, electric current, thermodynamic temperature, and luminous intensity. The 11th CGPM, in 1960, by its Resolution 2, adopted the name Système International d'Unités, to be known by its international abbreviation SI. This system established rules for prefixes, for derived units, for supplementary units, as well as an overall control of units of measurement. Since then, the SI has evolved and developed via the various CGPMs.

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[3] Sainte-Claire Deville, H., Broch et Stas, De la règle en forme de X en platine iridié pur à 10 pour cent d'iridium. *Ann. Chim. Phys.*, **22** (1881) 120–144.

[4] Sainte-Claire Deville, H., et Mascart, E., *Ann. École Normale*, **8** (1879) 9.

Table 2-1 Chronology of definitions of the metre since 1795

Standard	Original definition (in French)	Date	Absolute error	Relative error
1/10 000 000 part of the Meridian quarter (measured by Delambre and Méchain)	On appellera mètre la mesure de longueur égale à la dix-millionième partie de l'arc de méridien terrestre compris entre le pôle boréal et l'équateur	April 7th, 1795	0.5–0.1 mm	10^{-4}
First prototype called Mètre des Archives (agglomerated Pt sponge made by Jeannetty)	Le mètre et le kilogramme en platine déposés le 4 Messidor dernier au Corps législatif par l'Institut national des sciences et des arts sont les étalons définitifs des mesures de longueur et de poids dans toute la République	June 22nd 1799	0.05–0.01 mm	10^{-5}
International standard (dense Pt ingot made by Sainte-Claire Deville, Debray, Broch and Stas)	Les 18 Etats signataires de la Convention du mètre . . . sanctionnent à l'unanimité . . . le Prototype du mètre choisi par le Comité international; ce prototype représentera désormais, à la température de la glace fondante, l'unité métrique de longueur.	September 26th, 1889	0.2–0.1 μm	10^{-7}
	L'unité de longueur le mètre, défini par la distance à 0°C, des axes des deux traits médians tracés sur la barre de platine iridié déposée au BIPM, et déclarée Prototype du mètre par la 1ère CGPM, cette règle étant soumise à la pression atmosphérique normale et supportée par deux rouleaux d'au moins un centimètre de diamètre, situés symétriquement dans un même plan horizontal et à la distance de 571 mm l'un de l'autre [7ème CGPM (1927)]	September 30th, 1927	n.a.	n.a.
Hyperfine atomic transition in krypton 86	Le mètre est la longueur égale à 1 650 763.73 longueurs d'onde dans le vide de la radiation correspondante à la transition entre les niveaux $2p^{10}$ et $5d^{5}$ de l'atome de krypton 86 [11ème CGPM (1960)]	October 14th, 1960	0.01–0.005 μm	10^{-8}
Velocity of light *in vacuo*	Le mètre est la longueur du trajet parcouru dans le vide par la lumière pendant une durée de 1/299 792 458 de seconde [17ème CGPM (1983), Résolution 1]	October 20th, 1983	0.1 nm?	10^{-10}

Data from Giacomo, P., Du platine à la lumière, *Bull. Bur. Nat. Metrologie*, **102** (1995) 5–14.

In France, the SI became mandatory in 1961[5]. The 14th CGPM, in 1972, defined a new unit, the **mole**, for amount of substance, to be adopted as the seventh SI base unit. Figure 2-1 charts the advance of metric usage throughout the world. Table 2-2 gives the dates of adoption and compulsory implementation for individual countries.

The SI possesses several advantages. First, it is both metric and decimal. Second, fractions have been eliminated, multiples and submultiples being indicated by a system of standard prefixes, thus greatly simplifying calculations. Each physical quantity is expressed by one unique unit, and derived SI units are defined by simple equations relating two or more base units. Some derived units have been given individual names. In the interests of clarity, SI provides a direct relationship between mechanical, electrical, nuclear, chemical, thermodynamic, and optical units, thus forming a coherent system. There is no duplication of units for the same physical quantity, and all derived units are obtained by direct one-to-one relationships between base or other derived units. The same system of units can be used by researchers, engineers, or technologists.

2.2 The General Conference on Weights and Measures

The General Conference on Weights and Measures (CGPM) is an international organization made up of the delegates of all member states. In October 1985, the number of member states was 47. The remit of this organization is to take all necessary measures to ensure the propagation and the development of the SI, and to adopt various international scientific resolutions relative to new and fundamental developments in metrology.

Under the authority of the CGPM, the International Committee for Weights and Measures (CIPM) is responsible for the establishment and control of units of measurement. A permanent organization, the International Bureau of Weights and Measures (BIPM) created by the Metric Convention and signed by the 17 nations in Paris in 1875, operates under the supervision of the CIPM. The BIPM, which is located at the Pavillon of Breteuil[6], in the Saint-Cloud Park at Sèvres, has the remit of ensuring unification of measurements throughout the world, specifically:

- to establish fundamental standards and scales of the main physical quantities, and to preserve international prototypes
- to carry out comparisons of national and international standards
- to ensure co-ordination of appropriate measurement techniques
- to carry out and co-ordinate determination of physical constants involved in the above activities

A timetable of the major decisions of the CGPM is given in Table 2-3.

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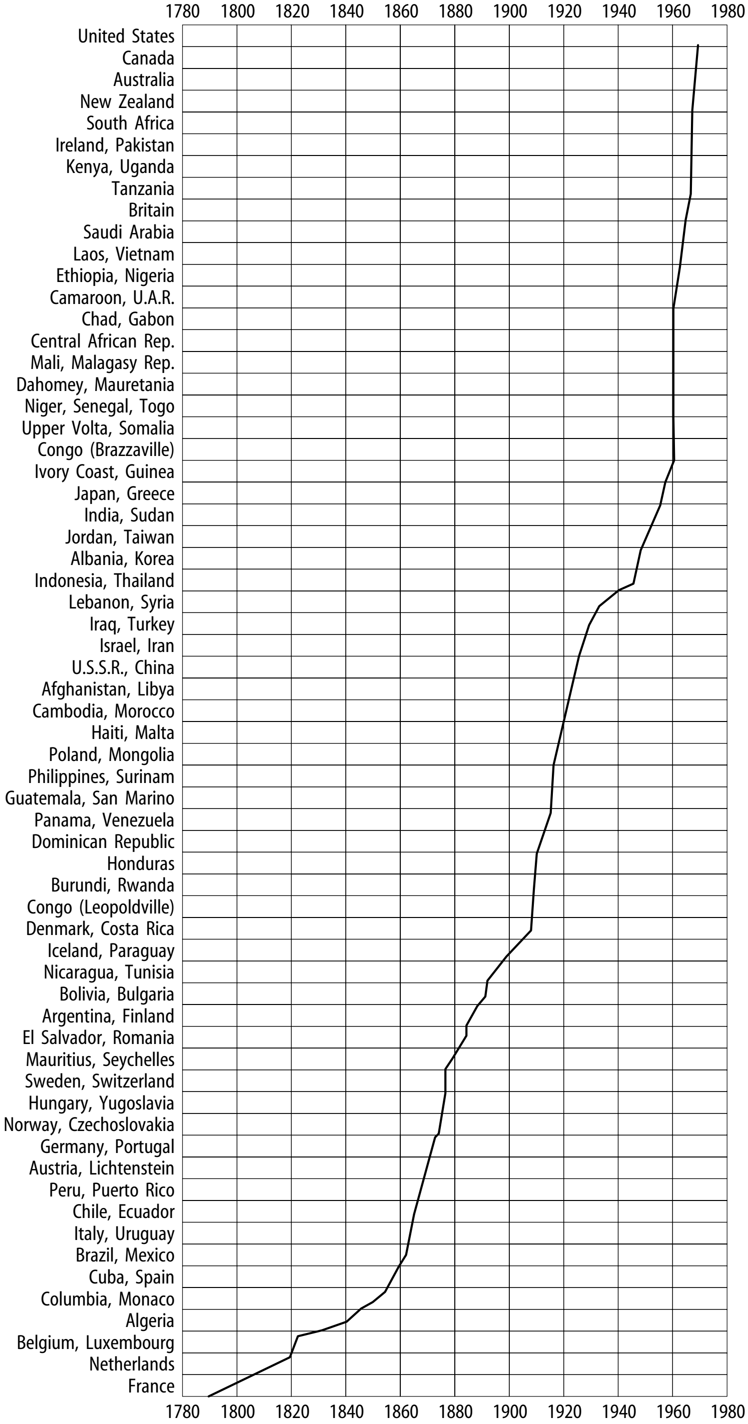
[5] Subsequent to the statutory order no. 61-501 of May 3rd, 1961, which appeared in the *Journal Officiel de la République Française* of May 20th, 1961 (Lois et Décrets, Ministère de l'Industrie, pp 4584–4593).
[6] Le Pavillon de Breteuil at Sèvres is an enclave which has international status.

Table 2-2 Adoption and compulsory implementation dates for the metric system

Acores	1852
Afghanistan	1926
Albany	1951
Algeria	1843
Angola	1905 (1910)
Argentina	1863 (1887)
Australia	1961 ; 1970
Austria	1871 (1876)
Bahrein	(1969)
Barbados	1973
Belgium	1816 (1820)
Benin	1884–91
Bermuda	1971
Bolivia	1868 (1871)
Botswana	1969–70 (1973)
Brazil	1862 (1874)
Brunei	(1986–91)
Bulgaria	1888 (1892)
Burkina	1884–1907
Cambodia	1914
Cameroun	1894
Canada	1871 (1976)
Cap-Vert	1891
Central African (Rep.)	1884–1907
Chile	1848 (1865)
China	1929 (1930)
Colombia	1853 (1854)
Comores	1914
Congo	1884–1907 (1910)
Costa Rica	1881 (1912)
Cuba	1882 (1960)
Cyprus	1972–74
Czech Republic	1871 (1876)
Denmark	1907 (1912)
Djibouti	1898
Dominican (Rep.)	1849 (1942–55)
Dutch Antilles	1875 (1876)
Ecuador	1865–71
Egypt	1939 (1951–61)
El Salvador	1910 (1912)
Ethiopia	1963
Fiji	1972
Finland	1886 (1892)
France	1795 (1840) (Guadalupe 1844) (French Guyana 1840) (Martinique 1844) Réunion 1839) (New Caledonia 1862) (Polynesia 1847) (St-Pierre-et-Miquelon 1824–39)
Gabon	1884–1907
Gambia	1979
Germany	1871 (1872)
Ghana	1972 (1975)
Gibraltar	1970
Greece	1836 (1959)
Guatemala	1910 (1912)
Guinea	1901–06
Guinea-Bissau	1905 (1910)
Guyana	1971
Haiti	1920 (1922)
Honduras	1910 (1912)
Hungary	1874 (1876)
Iceland	1907
India	1920 (1956)
Indonesia	1923 (1938)
Iran	1933 (1935–49)
Iraq	1931; 1960
Ireland	1897 (1968–69)
Israel	1947 (1954)
Italy	1861 (1863)
Ivory Coast	1884–90
Jamaica	1973
Japan	1893; 1951 (1959–66)
Jordan	1953 (1954)
Kenya	1951; 1967–68
Korea (South)	1949
Korea (Dem Rep of)	1947
Kuwait	1961 (1964)
Lebanon	1935
Lesotho	1970
Libya	1927
Liechtenstein	1875 (1876)
Luxemburg	1816 (1820)
Macao	1957
Madagascar	1897
Madeira	1852
Malawi	1979
Malaysia	1971–72
Mali	1884–1907
Malta	1910 (1921)
Mauritania	1884–1907
Mauritius	1876 (1878)
Mexico	1857 (1896)
Monaco	1854
Morocco	1923
Mozambique	1905 (1910)
Namibia	1967
Nauru	1973–80
Nepal	1963 (1966–71)
New Zealand	1925 (1969)
Nicaragua	1910 (1912)
Niger	1884–1907
Nigeria	1971–73
Norway	1875 (1882)
Pakistan	1967–72
Panama	1916
Papua-New Guinea	1970
Paraguay	1899
Netherlands	1816 (1832)
Peru	1862 (1869)
Philippines	1906 (1973–75)
Poland	1919
Portugal	1852 (1872)
Puerto Rico	1849
Romania	1864 (1884)
Russia	1899; 1918 (1927)
San-Marino	1907
Saudi Arabia	1962 (1964)
Salvador	1910 (1912)
Senegal	1840
Seychelles	1880
Singapore	1968–70
Slovakia	1871 (1876)
Solomon (British Islands)	1970
Somalia	1950 (1972)
South Africa	1922; 1967 (1974)
Spain	1849 (1871)
Sri Lanka	1970 (1974)
Sudan	1955
Surinam	1871 (1916)
Swaziland	1969 (1973)
Sweden	1878 (1889)
Switzerland	1868 (1877)
Syria	1935
Taiwan	1954
Tanzania	1967–69
Tchad	1884–1907
Thailand	1923 (1936)
Timor	1957
Togo	1924
Tonga Islands	1975
Trinidad and Tobago	1970–71
Tunisia	1895
Turkey	1869; 1931 (1933)
Uganda	1950 (1967–69)
United Kingdom	1897 (1995)
United States of America	1866
Uruguay	1862 (1894)
Venezuela	1857 (1912–14)
Vietnam	1911 (1950)
Yugoslavia	1873 (1883)
Zambia	1937 (1970)
Zimbabwe	1969

Important note: In 2002, the remaining non-metric countries are the USA, Myanmar (ex-Burma), and Sierra Leone.

Figure 2.1 Advance of metric usage throughout the world. (© U.S. Metric Association, Inc.)



Note: To the best of our knowledge the dates shown are accurate. Information in the graph is based upon certain indicators which gauge metric usage or upon official government policy regarding usage.

Table 2-3 Timetable of the major decisions of the CGPM

CGPM	Date	Decisions
1st CGPM	1889	Sanction of the international prototypes of the *metre* and the *kilogram*
3rd CGPM	1901	Declaration concerning the definition of the *litre* as the volume occupied by 1 kg of pure water at the temperature of its maximum density (abroged in 1964). Declaration of the *kilogram* as the unit of mass. The weight was defined as a quantity with the dimension of a force. Adoption of the con ventional value of *standard acceleration due to gravity*, i.e., $g_n = 980.665$ cm.s^{-2} (E)
7th CGPM	1927	Definition of the metre by the international Prototype. Definitions of photometric units: the *new candle*, and *new lumen*. Definitions of mechanical units which enter the definitions of electrical units: *joule*, *watt*. Definitions of electric units: *ampere*, *volt*, *ohm*, *coulomb*, *farad*, *henry*, and *weber* (CIPM, 1946).
9th CGPM	1948	Replacement of the melting point of ice by the triple point of water for thermometric reference. Thermodynamic scale with a single fixed point. Adoption of the *joule* as unit of quantity of heat. Adoption of degree Celsius to denote the degree of temperature.
10th CGPM	1954	Definition of the thermodynamic temperature scale by choosing the triple point of water as the fundamental fixed point. Definition of the standard atmosphere: 101 325 N/m^2. Adoption of six base units of the future SI: *metre*, *kilogram*, *second*, *ampere*, *kelvin,* and *candela*. Definition of the unit of time (CIPM, 1956).
11th CGPM	1960	New definitions of the *metre*, and of the second. Adoption of the *Système International d'unités* with the acronym SI. The *litre* is exactly defined as one cubic decimetre (CIPM, 1961).
12th CGPM	1964	Atomic standard of frequency. Standardization of the *curie* to exactly 3.7×10^{10} s^{-1}. Introduction of new SI prefixes *femto* and *atto*.
13th CGPM	1967-68	New definition for the *second*, the *kelvin*, and the *candela*. Abrogation of obsolete units: *micron*, and *new candle*. Multiples and submultiples of the unit of mass (CIPM, 1967). Rules of application of the SI (CIPM, 1969).
14th CGPM	1971	Definition of the SI unit of the amount of a substance: *mole*, and adoption of two new SI derived units: the *pascal* and the *siemens*, International atomic time (TAI).
15th CGPM	1975	Recommended values for the velocity of light in vacuum, and new names and units for ionizing radiation quantities: *becquerel*; *gray*, and two new SI prefixes *peta* and *exa*. Universal coordinated time (UTC).
16th CGPM	1979	New definition of the *candela*. Special name for the SI derived unit of the dose equivalent: *sievert*. The symbol L for *litre* in addition to the lower case letter l. Introduction of two supplementary units: *radian* and *steradian* (CIPM, 1980).
17th CGPM	1983	New definition of the metre as unit of length based on the velocity of light in vacuum. New SI prefixes: *zetta*, *zepto*, *yotta*, and *yocto* (CIPM, 1990).
20th CGPM	1995	Abrogation of the two supplementary units. Hence radian and steradian are now considered as SI derived units with special names.
21st CGPM	1999	Adoption of a new SI derived unit of enzymatic activity: the katal.

2.3 Organization of the SI

The International System of Units (*Système International d'Unités*, SI) consists of three classes of units:

- seven base units
- two supplementary units
- a number of derived units

In total, they form a coherent system of units officially known as **SI units**. Those units which do not form part of this system are known as **out-of-system units**.

It is recommended that only SI units should be used in scientific and technological applications, with SI prefixes where appropriate. The use of some out-of-system units (e.g. nautical mile, hectare, litre, hour, ampere-hour, bar) remains legal and they are temporarily retained because of their importance or their usefulness in certain specialized fields. Nevertheless, they should always be defined in terms of SI units, and SI units should be used wherever possible in order to maintain coherence in calculations.

2.3.1 SI Base Units

The seven SI base units are listed in ***Table 2-4*** below:

Table 2-4 The seven SI base units

Physical quantity	**Dimension**	**Name**	**Symbol**
Mass	M	kilogram	kg
Length	L	metre	m
Time	T	second	s
Temperature	Θ	kelvin	K
Amount of substance	N	mole	mol
Electric current intensity	I	ampere	A
Luminous intensity	J	candela	cd

These seven SI base units are officially and bilingually (French-English) defined as follows:

mètre Le mètre est la longueur du trajet parcouru dans le vide par la lumière pendant une durée de 1/299 792 458 s. [17ème CGPM (1983), Résolution 1].
The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 s. [17th CGPM (1983), Resolution 1].

kilogramme Le kilogramme est l'unité de masse; il est égal à la masse du prototype international du kilogramme [1ère CGPM (1889), 3ème CGPM (1901)].
The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram [1st CGPM (1889), 3rd CGPM (1901)].

seconde

La seconde est la durée de 9 192 631 770 périodes de la radiation correspondant à la transition entre les deux niveaux hyperfins ($F = 4$, $m_F = 0$ à $F = 3$, $m_F = 0$) de l'état fondamental de l'atome de césium 133 [13ème CGPM (1967)].
The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels ($F = 4$, $m_F = 0$ to $F = 3$, $m_F = 0$) of the ground state of the cesium 133 atom [13th CGPM (1967)].

ampère

L'ampère est l'intensité d'un courant électrique constant qui maintenu dans deux conducteurs parallèles, rectilignes, de longueur infinie, de section circulaire négligeable et placés à une distance de 1 mètre l'un de l'autre dans le vide, produit entre ces conducteurs une force égale à 2×10^{-7} newton par mètre de longueur [9ème CGPM (1948), Résolution 2 et 7].
The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per metre of length [9th CGPM (1948), Resolution 2 and 7].

kelvin

Le kelvin, unité de température thermodynamique, est la fraction 1/273,16 de la température thermodynamique du point triple de l'eau [13ème CGPM (1967), Résolution 4].
The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water [13th CGPM (1967), Resolution 4].

mole

(i) La mole représente la quantité de matière totale d'un système qui contient autant d'entités élémentaires que 0,012 kg de carbone 12.
(ii) Lorsque l'on emploie la mole, les entités élémentaires doivent être spécifiées et pêuvent être des atomes, des ions, des électrons, d'autres particules ou des groupements spécifiés de telles particules [14ème CGPM (1971), Résolution 3]. Dans cette définition, il est sous-entendu que les atomes de carbone 12 sont libres, au repos et dans leur état fondamental.
(i) The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kg of carbon 12.
(ii) When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particules, or specified groups of such particles [14th CGPM (1971), Resolution 3]. In this definition, it is understood that the carbon 12 atoms are unbound, at rest and in their ground state.

candela	La candela est l'intensité lumineuse, dans une direction donnée, d'une source qui émet un rayonnement monochromatique de fréquence 540×10^{12} Hz et dont l'intensité énergétique dans cette direction est de 1/683 watt par stéradian. [16$^{\text{ème}}$ CGPM (1979), Résolution 3]. The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} Hz and that has a radiant intensity in that direction of 1/683 watt per steradian [16th CGPM (1979), Resolution 3].

2.3.2 SI Supplementary Units

In addition to the seven base units, the SI has two supplementary units, the **radian** for plane angle and the **steradian** for solid angle (see ***Table 2-5***). These two units are dimensionless (i.e. in a dimension equation they have the value unity). However, for clarity, they are sometimes included in dimensional equations using an arbitrary dimensional symbol, for example the Greek letter α or a Roman capital 'A' for plane angle, and the Greek capital Ω for solid angle. Equally, because of the non-official nature of this notation, it is possible to omit these symbols from a dimensional equation in cases where this does not cause ambiguity.

As an example, the expression for angular velocity could be equally well be written as either $[\alpha.T^{-1}]$ or $[T^{-1}]$.

However, for physical quantities in specialist areas such as particle transfer in stastistical physics or luminous transfer in photometry, it is usual to include solid angle in dimensional equations in order to avoid confusion.

Example: depending on whether the area of photometric work involves measurement of energy, visible light, or particle emissions, luminous intensity can be defined in three ways (see ***Table 2-6***). It is clear that confusion can be avoided by introduction of a symbol for the steradian in the dimensional equation.

Note: since Resolution 8 from the 20th CGPM (Oct. 1995) the radian and the steradian are defined as common dimensionless SI derived units.

Table 2-5 The two supplementary SI units

Physical quantity	Dimension	Name	Symbol
Plane angle	α	radian	rad
Solid angle	Ω	steradian	sr

Table 2-6 Comparison of dimension equation for several quantities in photometry with and without symbol of solid angle

Photometry	Quantity	Dimensions		SI unit
		without symbol	with symbol	
Energy	Radiant intensity	$[E.T^{-1}]$	$[E.T^{-1}.\Omega^{-1}]$	$W.sr^{-1}$
Visible	Luminous intensity	[J]	[J]	cd
Particle	Photon intensity	$[T^{-1}]$	$[T^{-1}.\Omega^{-1}]$	$s^{-1}.sr^{-1}$

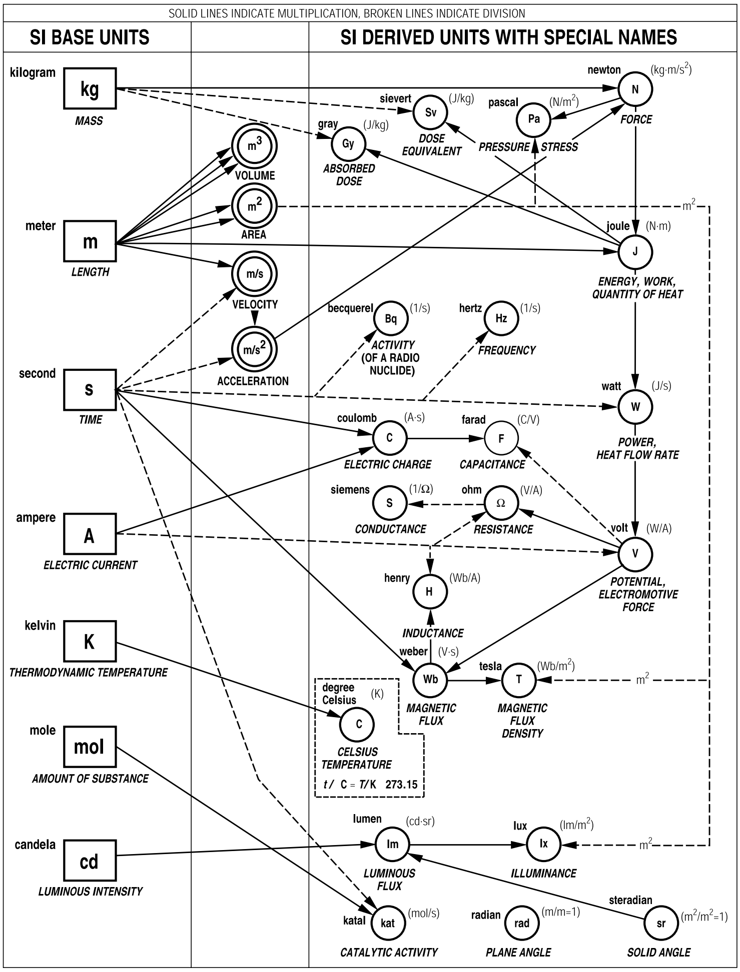
2.3.3 SI Derived Units

The SI derived units are defined by simple equations relating two or more base units. The names and symbols of some derived units may be substituted by special names and symbols. The twenty (since the adoption of the katal) derived units with special names and symbols are listed in ***Table 2-7***. These derived units may themselves by used in combination to form further derived units.

Table 2-7 SI derived units with special names and symbols

Name	Symbol	Physical quantity	Dimension	Equivalent in SI base units
becquerel	Bq	radioactivity	T^{-1}	1 Bq = 1 s^{-1}
coulomb	C	quantity of electricity, electric charge	IT	1 C = 1 A.s
farad	F	electric capacitance	$M^{-1}L^{-2}T^4I^2$	1 F = 1 $kg^{-1}.m^{-2}.s^4.A^2$
gray	Gy	absorbed dose of radiation, kerma, specific energy imparted	L^2T^{-2}	1 Gy = 1 $m^2.s^{-2}$
henry	H	electric inductance	$ML^2T^{-2}I^{-2}$	1 H = 1 $kg.m^2.s^{-2}.A^{-2}$
hertz	Hz	frequency	T^{-1}	1 Hz = 1 s^{-1}
joule	J	energy, work, heat	ML^2T^{-2}	1 J = 1 $kg.m^2.s^{-2}$
katal	kt	enzymatic activity	NT^{-1}	1 kt = 1 $mol.s^{-1}$
lumen	lm	luminous flux	JΩ	1 lm = 1 cd.sr
lux	lx	illuminance	$J\Omega L^{-2}$	1 lx = 1 $cd.sr.m^{-2}$
newton	N	force, weight	MLT^{-2}	1 N = 1 $kg.m.s^{-2}$
ohm	Ω	electric resistance	$ML^2T^{-3}I^{-2}$	1 Ω = 1 $kg.m^2.s^{-3}.A^{-2}$
pascal	Pa	pressure, stress	$ML^{-1}T^{-2}$	1 Pa = 1 $kg.m^{-1}.s^{-2}$
poiseuille (pascal-second)	Po	absolute viscosity, dynamic viscosity	$ML^{-1}T^{-1}$	1 Po = 1 $kg.m^{-1}.s^{-1}$
siemens	S	electric conductance	$M^{-1}L^{-2}T^3I^2$	1 S = 1 $kg^{-1}.m^{-2}.s^3.A^2$
sievert	Sv	dose equivalent, dose equivalent index	L^2T^{-2}	1 Sv = 1 $m^2.s^{-2}$
tesla	T	induction field, magnetic flux density	$MT^{-2}I^{-1}$	1 T = 1 $kg.A^{-1}.s^{-2}$
volt	V	electric potential, electromotive force, potential difference	$ML^2T^{-3}I^{-1}$	1 V = 1 $kg.m^2.s^{-3}.A^{-1}$
watt	W	power, radiant flux	ML^2T^{-3}	1 W = 1 $kg.m^2.s^{-3}$
weber	Wb	induction magnetic flux	$ML^2T^{-2}I^{-1}$	1 Wb = 1 $kg.m^2.s^{-2}.A^{-1}$

Figure 2.2 Relationships of the SI derived units with special names and the SI base units (© NIST)



2.3.4 Non-SI and SI Units Used in Combination

For consistency and clarity, it is a general rule of SI that the use of non-SI units should be discontinued. However, there are some important instances where this is either impracticable or inadvisable. The SI therefore recognizes four categories of out-of-system units which may be used in combination with SI.

2.3.4.1 Commonly Used Legal Non-SI Units

The CIPM (1969) recognized that users of SI would wish to employ certain units that are important and widely used, but which do not properly fall within the SI. The special names and symbols for these units, and their definitions in terms of SI units, are listed in ***Table 2-8.***

2.3.4.2 Non-SI Units Defined by Experiment

This class incorporates units accepted for use, the values of which are obtained by experiment; they are listed in ***Table 2-9*** opposite. These are important units widely used for special problems, and were accepted by the CIPM (1969) for continuing use in parallel with SI units.

Table 2-8 Commonly used non-SI units

Name	Symbol	Physical quantity	Dimension	Equivalent in SI base units
ampere-hour	Ah	electric charge	IT	1 Ah = 3600 C
day	d	time, duration, period	T	1 d = 86 400 s
degree	°	plane angle	α	$1° = \pi/180$ rad
dioptre	d	refractive power	L^{-1}	1 d = 1 m^{-1}
hour	h	time, duration, period	T	1 h = 3600 s
kilowatt-hour	kWh	energy, work, heat	ML^2T^{-2}	1 kWh = 3.6×10^6 J
litre	l, L	capacity, volume	L^3	1 L = 10^{-3} m^3
minute	min	time, duration, period	T	1 min = 60 s
minute of angle	′	plane angle	α	$1' = \pi/10\,800$ rad
second of angle	″	plane angle	α	$1'' = \pi/648\,000$ rad
tex	tex	linear mass density	ML^{-1}	1 tex = 10^{-6} kg.m^{-1}
tonne (metric)	t	mass	M	1 t = 10^3 kg

Table 2-9 Commonly used legal non-SI units defined by experiment

Name	Symbol	Physical quantity	Dimension	Equivalent in SI base units
electronvolt	eV	energy, work	ML^2T^{-2}	$1\ \text{eV} = \frac{e}{C}\ \text{J}$
faraday	F	molar electric charge	ITN^{-1}	$1\ \text{F} = eN_A\ \text{C.mol}^{-1}$
unified atomic mass unit	u, u.m.a.	mass	M	$1\ \text{u} = \frac{m_{^{12}C}}{12}\ \text{kg}$

2.3.4.3 Non-SI Units Temporarily Maintained

In view of existing practice, the CIPM (1978) considered it acceptable to retain for the time being a third class of non-SI units for use with those of SI. These temporarily-maintained units are listed in ***Table 2-10***. The use of any and all of these units may be abandoned at some time in the future. They should not therefore be introduced where they are not already in current use.

2.3.4.4 Non-SI Units Which Must Be Discontinued

These units, listed in ***Table 2-11***, are to be avoided in favour of an appropriate SI unit or decimal multiples using the common SI prefixes listed in ***Table 2-11.***

2.4 SI Prefixes

The SI is a decimal system of units. Fractions have been eliminated, multiples and sub-multiples being formed using a series of prefixes ranging from yotta (10^{24}) to yocto (10^{-24}). The twenty SI prefixes that are to be used for multiples and sub-multiples of an SI unit are shown in ***Table 2-12***. Each prefix beyond $10^{\pm 3}$ represents a change in magnitude of 10^3 (power of 10 notation). Non-SI discontinued prefixes are shown in Table 2-13 (p. 17).

Table 2-10 Temporarily-maintained non-SI units

Name	Symbol	Physical quantity	Dimension	SI base units
ångström	Å	length	L	1 Å = 10^{-10} m
are	a	surface, area	L^2	1 a = 10^2 m^2
bar	bar	pressure	$ML^{-1}T^{-2}$	1 bar = 10^5 Pa
barn	b	surface, area	L^2	1 b = 10^{-28} m^2
curie	Ci	radioactivity	T^{-1}	1 Ci = 3.7 × 10^{10} Bq
gal	Gal	acceleration	LT^{-2}	1 Gal = 10^{-2} $m.s^{-2}$
hectare	ha	surface, area	L^2	1 ha = 10^4 m^2
hogshead (tonneau de jauge)	–	capacity, volume	L^3	1 tonneau = 2.83 m^3
nautical mile	naut. mi	length	L	1 naut. mi = 1852 m
noeud, knot	kn	linear velocity	LT^{-1}	1 knot = 1852/3600 = 5.14444 × 10^{-1} $m.s^{-1}$
rad	rad	absorbed dose of radiation, kerma	L^2T^{-2}	1 rad = 10^{-2} Gy
rem	rem	dose equivalent, dose equivalent index	L^2T^{-2}	1 rem = 10^{-2} Sv
röntgen	R	exposure	$M^{-1}TI$	1 R = 2.58 × 10^{-4} $C.kg^{-1}$

Table 2-11 Non-SI units to be discontinued

Name	Symbol	Physical quantity	Dimension	SI base units
calorie (15°C)	$cal_{15°C}$	energy, heat	ML^2T^{-2}	1 $cal_{15°C}$ = 4.1855 J
calorie (IT)	cal_{IT}	energy, heat	ML^2T^{-2}	1 cal_{IT} = 4.1868 J
calorie (therm.)	cal_{th}	energy, heat	ML^2T^{-2}	1 cal_{th} = 4.1840 J
carat (metric)	ct	mass	M	1 ct = 2 × 10^{-4} kg
fermi	F	length	L	1 F = 10^{-15} m
gamma (induction)	γ	magnetic induction	$MT^{-2}I^{-1}$	1 γ = 10^{-9} T
gamma (mass)	γ	mass	M	1 γ = 10^{-9} kg
grade (gon)	gr, ^{g}	plane angle	α	1 gon = π/200 rad
kilogram-force	kgf	force	MLT^{-2}	1 kgf = 9.80665 N
lambda	λ	capacity, volume	L^3	1 λ = 10^{-9} m^3
micron	μ	length	L	1 μ = 10^{-6} m
revolution	rev	plane angle	α	1 rev = 2π rad
revolutions per minute	rpm	angular velocity	αT^{-1}	1 rpm = π/30 $rad.s^{-1}$
standard atmosphere	atm	pressure	$ML^{-1}T^{-2}$	1 atm = 101 325 Pa
stère	st	capacity, volume	L^3	1 st = 1 m^3
torr	torr	pressure	$ML^{-1}T^{-2}$	1 torr = (101 325/760) Pa
X-unit	XU	length	L	1 XU = 1.0023 × 10^{-13} m

Important Note: in Computer Science, the prefixes kilo, mega, and giga are commonly used, although in that context they are only approximations to powers of 10. These multiples of the byte are not equal to the SI prefixes because they are equal to the power of two according to the binary digit numeration. In order to avoid confusion, it is therefore recommended that in this context they are expressed with an initial capital as shown in ***Table 2-13.***

Table 2-12 The twenty SI prefixes

SI prefixes: multiples and submultiples					
Multiple			**Submultiple**		
Prefix (Etymology)	Symbol	Multiply by	Prefix (Etymology)	Symbol	Multiply by
yotta	Y	10^{24}	deci (Latin *decimus* tenth)	d	10^{-1}
zetta	Z	10^{21}	centi (Latin *centum* hundredth)	c	10^{-2}
exa	E	10^{18}	milli (Latin *milli* thousandth	m	10^{-3}
peta	P	10^{15}	micro (Greek *μικρος* small)	μ	10^{-6}
tera (Greek *τεραζ* monster)	T	10^{12}	nano (Greek *νανος* dwarf)	n	10^{-9}
giga (Greek *γιγαζ* giant)	G	10^{9}	pico (Italian *piccolo* small)	p	10^{-12}
mega (Greek *μεγαζ* big)	M	10^{6}	femto (Danish *femten* fifteen)	f	10^{-15}
kilo (Greek *κιλιοι* thousand)	k	10^{3}	atto (Danish *atten* eighteen)	a	10^{-18}
hecto (Greek *εκατον* hundred)	h	10^{2}	zepto	z	10^{-21}
deca (Greek *δεκα* ten)	da	10	yocto	y	10^{-24}

Table 2.13 Non-SI discontinued metric prefixes

Prefix	**Symbol**	**Value**
hebdo	H	10^{7}
lacta	L	10^{5}
myria	my	10^{4}
dimi	dm	10^{-4}
micri	mc	10^{-14}

Binary Prefixes: In computing, a custom arose of using the metric prefixes to specify powers of 2. For example, a kilobit is usually equal to $2^{10} = 1024$ bits instead of 1000 bits. This practice led, and still leads, to considerable confusion. In 1998, the *International Electrotechnical Commission* (IEC) approved new prefixes especially dedicated to the powers of 2. These binary prefixes are shown in Table 2-15. Therefore, the metric prefixes should be used in computing just as they are used in other fields. Thus, 5 gigabytes (denoted GB) should mean exactly 5×10^{9} bytes, while 5 gibibytes (denoted GiB) should mean exactly 5 368 709 120 bytes.

Table 2-14 Prefixes for computer science units

Name of unit (English, French)	Symbol	Conversion factor
Kilobyte, Kilooctet	KB, Ko	1 KB $= 2^{10} =$ 1024 bytes
Megabyte, Mégaoctet	MB, Mo	1 MB $= 2^{20} =$ 1 048 576 bytes
Gigabyte, Gigaoctet	GB, Go	1 GB $= 2^{30} =$ 1 073 741 824 bytes

Table 2-15 New binary prefixes for power of two (IEC, 1998)

Name	Symbol	Equivalent
kibi-	Ki	$2^{10} = 1\,024$
mebi-	Mi	$2^{20} = 1\,048\,576$
gibi-	Gi	$2^{30} = 1\,073\,741\,824$
tebi-	Ti	$2^{40} = 1\,099\,511\,627\,776$
pebi-	Pi	$2^{50} = 1\,125\,899\,906\,842\,624$
exbi-	Ei	$2^{60} = 1\,152\,921\,504\,606\,846\,976$

Prefixes and symbols should be printed in roman (upright) type with no space between the prefix and the unit symbol.

Example: 1 millimetre = 1 mm = 10^{-3} m (not m/m or m m)

When a prefix symbol is used with a unit symbol, the combination should be considered as a single new symbol that can be raised to a positive or negative power of 10 without using brackets.

Example: 1 cm^3 = $(10^{-2}$ m$)^3$ = 10^{-6} m^3 (not μ(m^3) or 10^{-2} m^3)

Prefixes are not to be combined into compound prefixes.

Example:
1 nm = 10^{-9} m (not mμm)
1 GW = 10^9 W (not MkW)
1 pF = 10^{-12} F (not μμF)

A prefix should never be used alone.

Example: 1 μm = 10^{-6} m (not μ)

Prefixes used with the kilogram (which already has the prefix kilo) are constructed by adding the appropriate prefix to the word gram and the symbol g.

Example: 1 Mg = 10^6 g (not kkg)

The prefixes apply to all standard and associated SI units with the exception of the following: h (hour), d (day), min (minute), rev (revolution), ° (degree), ′ (plane angle minute), and ″ (plane angle second).

If the name of the unit begins with a vowel, the prefix may be fused with it:

Example: 1 MΩ = one me**go**hm rather than megaohm