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1.1 Units

1.1.1 The international system of units (SI)

History

In the second half of the nineteenth century the centimetre, gram and second were in fairly general use as base units for scientific work even in such countries as the UK and the USA where the foot and the pound were employed for commerce and engineering. As a result, the units required by the rapidly emerging science of electricity were based on the centimetre, gram and second, with which they formed a coherent system known as the CGS electromagnetic system. A system of units is said to be coherent when derived units are formed from the base units without the insertion of factors of proportionality other than unity. There was also the CGS electrostatic system, but the only quantities frequently expressed in electrostatic units were electric charge, electric potential, and capacitance.

The young but fast-growing electrical industry soon found that many CGS electromagnetic units were of an extremely inconvenient size for its needs. Accordingly, in 1881, international agreement was reached to fix the practical unit of potential, to be called the volt, at 10^8 CGS units (which is approximately equal to the e.m.f. of a primary cell), and the unit of resistance, the ohm, at 10^9 CGS units (which is approximately the resistance of a column of mercury 1 m long and 1 mm^2 in cross-section). The unit of electric current, the ampere, was made a tenth of the CGS unit. A coherent system of practical electric units was thus secured which, however, was not coherent with the mechanical units based on the centimetre and gram. The practical electric units suited the needs of telegraphy, which was then the main electrical industry, and they also happen to be convenient for heavy electrical engineering and for electronics.

The magnetic units, however, were left at their CGS values, presumably because the CGS unit of magnetic flux density, subsequently called 'gauss', is of the order of the flux density of the Earth's field, and, as it was suitable for geomagnetism, there seemed no point in changing it for a unit 10^4 times larger. Coherence was thereby lost to electromagnetism as it had already been lost to the system embracing the mechanical units and the practical electric units.

Whereas the electric units, by the agreement of 1881, were chosen to be of suitable magnitude for everyday use, and whereas the centimetre and the second have acceptable sizes, the gram is too small for the practical needs of man, which are better served by a unit nearer the size of the pound or the kilogram. Moreover, the CGS unit of force, the dyne, and the unit of energy, the erg, are much too small. On the other hand, the unit of energy provided by the practical electric units, the volt-ampere-second, called the joule—which equals 10^7 ergs—is of a satisfactory size.

These considerations—the advantages of coherence and the fortuitous circumstance that a mechanical system based on the metre and the kilogram has precisely the same unit of energy as is provided by the practical electric units—led G. Giorgi in 1902 to propose a system based on the **metre**, the **kilogram**, the **second**, and one of the practical electric units. He pointed out that if magnetic field strength were expressed as amperes per metre instead of 4π times amperes per metre, which is the definition corresponding to that of the CGS unit, the number π would disappear from most electric and magnetic formulae involving rectilinear geometry, but would appear, as is to be expected, in those involving cylinders or spheres.

The International Electrotechnical Commission eventually chose the **ampere** as the fourth base unit of the MKSA or 'Giorgi' system, and in 1948 the 9th General Conference of Weights and Measures[†] recommended it for science and technology, as well as for commerce and industry. This system admirably covers mechanics and electromagnetism, but it does not provide for other branches of science such as heat. In 1960, in the hope of securing world-wide uniformity in the units employed in natural science, the 11th CGPM added to the units metre, kilogram, second and ampere, the **kelvin** for thermodynamic temperature, the **candela** for luminous intensity, and the radian and steradian for plane and solid angle. The first two joined the original four in being called 'base' units, and the last two were called 'supplementary' units. Any unit formed from two or more base units is called 'derived'. The radian and steradian are regarded as derived units. The MKSA system thus broadened is called the International System of Units, often abbreviated to SI, and is the most satisfactory system of units we have had so far, in that it caters for the commercial and industrial activities of man as well as for the needs of science. In 1971, the 14th CGPM added the **mole,** the unit of amount of substance used in chemistry, to the list of base units, thus making them seven in all.

[†] The General Conference of Weights and Measures (CGPM) is the authority set up by the Metre Convention of 1875 to promote and improve the metric system, and to secure international uniformity in metric units and standards of measurement. It consists of delegations from the member nations (of which there were 46, including the UK, in 1982), which meet every few years, the 15th, 16th and 17th Conferences having been held in 1975, 1979, and 1983. The International Bureau of Weights and Measures (BIPM), Sèvres (near Paris) is the central office and laboratory of the organization, and is managed, under the authority of the General Conference, by the International Committee for Weights and Measures (CIPM) consisting of 18 members, each from a different nation. The International Committee meets yearly and is responsible for recommending proposals for approval by the General Conference. Eight specialist advisory committees assist the International Committee in planning co-operative programmes of research, and in the preparation of recommendations on units of measurement, on length (definition of the metre), mass, time (definition of the second), temperature, electricity, photometry and radiometry, and ionizing radiations.

Definitions of some SI units

The seven base quantities, each with its unit and unit symbol, are listed below.

SI base quantities and units

Quantity	*Name of unit*	*Unit symbol*
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

The SI base units are defined as follows:

The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second.
The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.
The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom.
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.
The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.
The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.
The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of (1/683) watt per steradian.

The SI supplementary units are defined thus:

The radian is the plane angle between two radii of a circle which cut off on the circumference an arc equal in length to the radius.
The steradian is the solid angle which, having its vertex in the centre of a sphere, cuts off an area of the surface of the sphere equal to that of a square with sides of length equal to the radius of the sphere.

Derived units. The table below lists some of the more common SI derived quantities, each with its unit and unit symbol. The composite symbols in the last column are to some extent indicative of the definition of the quantity.

Quantity	*Unit*	*Symbol*	
Supplementary			
Plane angle	radian	rad	
Solid angle	steradian	sr	
Derived			
Area	square metre		m^2
Volume	cubic metre		m^3
Frequency	hertz	Hz	s^{-1}
Density	kilogram per cubic metre		$kg\ m^{-3}$
Concentration	mole per cubic metre		$mol\ m^{-3}$
Velocity	metre per second		$m\ s^{-1}$
Angular velocity	radian per second		$rad\ s^{-1}$
Acceleration	metre per second squared		$m\ s^{-2}$
Angular acceleration	radian per second squared		$rad\ s^{-2}$
Force	newton	N	$m\ kg\ s^{-2}$
Pressure, stress	pascal	Pa	$N\ m^{-2}$
Viscosity (dynamic)	pascal second		Pa s
Viscosity (kinematic)	metre squared per second		$m^2\ s^{-1}$
Energy, work, quantity of heat	joule	J	N m
Power, radiant flux	watt	W	$J\ s^{-1}$
Quantity of electricity	coulomb	C	A s
Potential difference, electromotive force	volt	V	$W\ A^{-1}$
Electric field strength	volt per metre		$V\ m^{-1}$
Electric resistance	ohm	Ω	$V\ A^{-1}$
Electric conductance	siemens	S	W^{-1}
Capacitance	farad	F	CV^{-1}
Magnetic flux	weber	Wb	Vs
Magnetic flux density	tesla	T	$Wb\ m^{-2}$

Inductance	henry	H	W s
Magnetic field strength	ampere per metre		A m^{-1}
Magnetomotive force	ampere	A	
Wave number*	1 per radian		m^{-1}
Activity (of a radionuclide)	becquerel	Bq	s^{-1}
Absorbed dose	gray	Gy	J kg^{-1}
Dose equivalent	sievert	Sv	J kg^{-1}
Luminous flux	lumen	lm	cd sr
Luminance	candela per square metre		cd m^{-2}
Illuminance	lux	lx	lm m^{-2}
Heat flux density, irradiance	watt per square metre		W m^{-2}
Heat capacity, entropy	joule per kelvin		J K^{-1}
Specific heat capacity, specific entropy	joule per kilogram kelvin		J kg^{-1} K^{-1}
Thermal conductivity	watt per metre kelvin		W m^{-1} K^{-1}
Molar energy	joule per mole		J mol^{-1}
Molar entropy, molar heat capacity	joule per mole kelvin		J mol^{-1} K^{-1}

*Wave numbers in the infra-red are still often expressed in cm^{-1}

Prefixes. Prefixes may be used, instead of powers of 10, to express certain decimal multiples of the units. Their names and symbols are listed below.

Factor	*Name*	*Symbol*	*Factor*	*Name*	*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	μ
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	deca	da	10^{-24}	yocto	y

An exponent attached to a symbol containing a prefix indicates that the multiple of the unit is raised to the power expressed by the exponent.

Example: 1 $cm^3 = 10^{-6}\ m^3$; 1 $cm^{-1} = 10^2\ m^{-1}$.

Compound prefixes should not be used, e.g. use p not μμ. Names of multiples of the unit of mass are formed by attaching prefixes to the word 'gram'.

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