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Units of Measurement

Contents of Brochure

The ordinance of units is available in German, French and Italian. The German version may be found at www.admin.ch/ch/d/sr/c941_202.

A unit conversion utility for current units may be found at www.metas.ch/conversion.

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Units of Measurement

Units of measurement are needed to determine the value of physical quantities. The quantity being measured is compared to the unit or to a reference measurement which is a multiple or fraction of the unit. Two measurement results can only be compared if they both refer to the same unit.

A system of units is a set of rules which regulates unambiguously the units of measurement in science and technology. It must meet the very variant requirements of science, technology, trade and society. The system of units must also keep in step with scientific-technological advances.

People have been measuring for thousands of years, since measuring helps them to orientate themselves within the multitude of elements and events of their environment. Right from the beginning of trade it was necessary to be able to determine accurately and reliably quantities of trade goods. The use and control of weights and measures was originally undertaken only at the local level, or at most regional. As a result, for centuries there existed the greatest variety of units of measurement and systems of units alongside each other. Units of measurement would change from place to place, and units of measurement with the same name could even represent different quantities in different areas.

With the expansion of commercial exchanges in the 18th century and advances in science and technology, it became gradually more evident how costly in time and money the confusion over units was. In addition, the multifarious units of the Middle Ages and the early Modern Era, such as ounce, talent, ell and pound, could not satisfy the modern demands for consistency and uniformity. In order to reduce the effects of having an excessive number of different units of measurement alongside each other, in 1875 seventeen states, one of which was

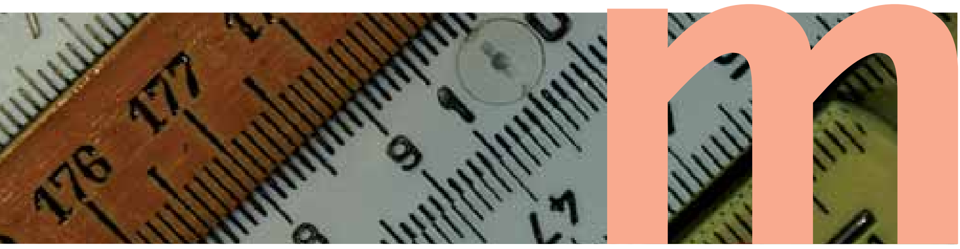
Switzerland, signed an international scientific-technological agreement called the *Metre Convention*. As a result the multitude of units of measurement was replaced by the metric system, which later was to become the *International System of Units*. And what is more, a metrological infrastructure was created (see pages 14/15).

The *International System of Units* – also known as SI after the French name *Système international d'unités* – used today worldwide is the result of a long history of development. The SI was introduced in 1960 by the 11th General Conference on Weights and Measures (CGPM), which was followed up by the release of a series of different systems of units, which are mainly used in scientific contexts. These made complicated conversion calculations redundant.

Switzerland adopted the SI on 1st January 1978. The legal prescriptions for its introduction are contained in the federal law on metrology and in the units of measurement ordinance. In the SI, base units are differentiated from derived units. The base units are: the metre, the kilogram, the second, the ampere, the kelvin, the mole and the candela.

The derived units are formed from the base units, maintaining the same algebraic relationships which hold for the natural laws governing the respective physical quantities. An important point concerning base units is their coherence: that is the property that derived units are formed by the multiplication or division of base units without introducing numerical factors.

An important requirement of base units is their independence of space and time. Base units must be reproducible at any time in any laboratory. Fulfilling this requirement has led to a number of changes in their definitions. Today, with the exception of the kilogram, they are no longer based on physical artefacts, but rather on constant properties of nature, which make them usable experimentally at any time or place.



Metre

The metre (m) is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second.

Expressed as a mathematical equation, this definition becomes $1\ \mathrm{m} = c \cdot t$, with $t = 1/299\,792\,458$ s. From this can be derived $c = 299\,792\,458$ m/s. The symbols c, t and s mean speed of light in vacuum, time and second, respectively. The metre definition assigns a fixed value to the speed of light c. This fundamental constant can therefore no longer be measured; it has been fixed by definition. From this can be concluded that the unit of length is dependent on the unit of time, the second.
The physical realisation of the unit of length is usually done with a laser of known and highly stable frequency. From the frequency ν and the speed of light c, the wavelength λ of the stabilised laser can be calculated from the known relationship $\lambda = c/\nu$. This wavelength then serves directly as a reference in interferometric length measurements. The primary standard is usually a helium-neon laser, whose optical frequency is stabilised to an atomic transition – in this case an absorption line of iodine gas. The metre at METAS is based on a group of three iodine-stabilised helium-neon lasers. They are compared on a regular basis one to each other and against similarly stabilised lasers of foreign metrological institutes. The optical frequency of these lasers is directly linked to the METAS atomic clocks (realisation of the second) by means of a fibre optic frequency comb.

Kilogram

The kilogram (kg) is equal to the mass of the international prototype of the kilogram.

At present, the unit of mass cannot yet be traced back to fundamental constants with sufficient accuracy. Thus, the reference standard for mass measurement is still the international prototype of the kilogram. It was manufactured in 1889 from an alloy of 90 % platinum and 10 % iridium. It is kept at the International Bureau of Weights and Measures (BIPM) at Sèvres near Paris.
To distribute the mass unit, copies of the international prototype kilogram – so-called national prototypes – have been provided to the majority of the member states of the Metre Convention. These are used in national metrology institutes to check the working standards against which the weights and scales used in practice can be calibrated.
The comparison of the working standards to the national prototype kilogram is carried out in Switzerland with the help of an automatic mass comparator, housed inside an air-sealed steel casing. With this comparator it is possible to compare up to six mass standards in an atmosphere which is almost perfectly shielded from pressure and temperature variations, with a reproducibility of 0.25 µg.
To bring the mass unit into line with other base units, the world-wide attempt to find a means of referencing the mass unit to natural constants continues; e. g. via electrical quantum standards or the manufacture of high-purity silicon monocrystals with a known number of atoms. METAS is working actively on such a project, called the *Watt Balance*. The aim of this experiment is to link the mass unit to fundamental constants by an extremely precise comparison between electrical and mechanical power.

Second

The second (s) 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.

Time divisions in the lives of humans are based on the rotation of the earth on its own axis (day) and the orbit of the earth around the sun (year). Ever more precise measurements have shown, however, that these planetary movements are not sufficiently stable for the current demands on accuracy. As a result, the unit of time is nowadays defined by an atomic process.

The starting point for this is Planck's Law $E = h \cdot \nu$, where the difference E between two energy levels of well selected atomic electrons corresponds to electromagnetic radiation at frequency ν. Two levels of the caesium nuclide of atomic mass number 133 have proven to be particularly suitable, the energy difference of which corresponds to a frequency in the microwave range. After comparison of the astronomically defined second with a caesium atomic clock, the duration of the second was redefined in 1967 as 9 192 631 770 periods of the Cs radiative transition. With a caesium clock built on this principle, today an accuracy of better than 0.1 ns per day can be achieved, whereas the rotation of the earth fluctuates by up to a few ms per day. In co-operation with 50 other time laboratories around the world, METAS contributes with its commercial atomic clocks to the so-called Universal Time Coordinated (UTC) which is calculated at the International Bureau of Weights and Measures (BIPM) in Sèvres near Paris. The Official Swiss Time is derived from UTC and disseminated by the HBG Time Signal Transmitter.

Moreover, METAS operates a primary frequency standard in a laboratory insulated from environmental influences: the second is realised by using a continuous beam of cesium atoms cooled down to -273 °C by means of laser radiation.

Ampere

The ampere (A) is the 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 $2 \cdot 10^{-7}$ newton per metre of length.

The definition of the ampere in use today was proposed in 1946 by the International Committee for Weights and Measures (CIPM), and – along with the other electrical units, then called «absolute units» – adopted internationally in 1948. They were denominated «absolute» since, following purely theoretical considerations, only the magnitude of the electrical units was specified, but not their practical realisation. As a result, the definition of the ampere is not suitable for the practical realisation of the unit of current; it fixes only the value of the magnetic field constant μ_0. If indeed the force between the two parallel conductors placed one metre apart is calculated according to Ampere's law, and the values given in the definition are introduced into the equation, it follows

$$\frac{F}{l} = \mu_0 \cdot \frac{I^2}{2\pi d} \rightarrow \mu_0 = 4\pi \cdot 10^{-7} \frac{N}{A^2}$$

F/l: force per metre of conductor length; I: current strength; d: separation of the conductors

The definition of the ampere serves, as does the definition of the metre, only for the determination of a fundamental constant. Through the definition of μ_0 and the speed of light c (definition of the metre) the electrical field constant ε_0 is also defined. With knowledge of these values and the known laws of physics, many possibilities are open for the realisation of electrical units for calibration purposes. In many national metrology institutes this is done with the help of quantum effects.

Kelvin

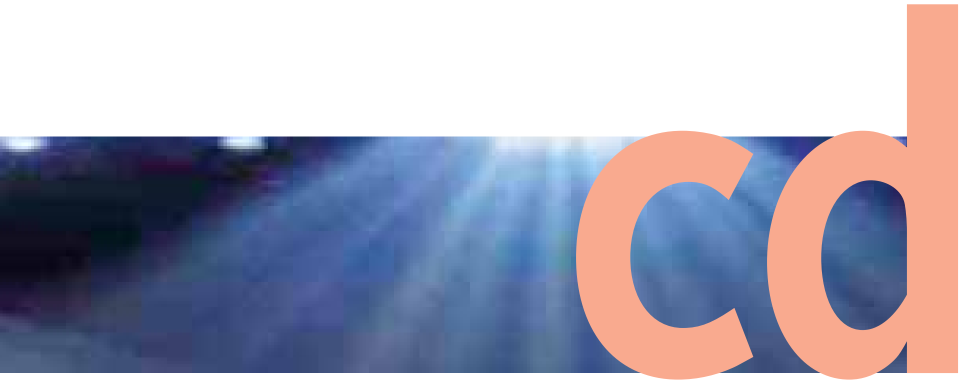
The kelvin (K) is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.

The triple point of water is the only thermodynamic state in which the three phases of water vapour, water and ice can co-exist in equilibrium. Provided all three phases are present, temperature and pressure remain constant and are independent of the respective amounts of substances in each of the individual phases. The triple point of water and absolute zero point given by nature define the thermodynamic temperature scale.
The practical realisation of the temperature scale is usually done by means of a number of highly stable temperature fixed points whose thermodynamic temperature values are determined by means of primary thermometers – e. g. gas thermometers. The values of these fixed points as well as specified methods of interpolating between them have been chosen by international agreement and constitute the International Temperature Scale 1990 (ITS-90).
The thermometric basis at METAS consists of about 30 fixed-point cells allowing for redundant coverage of the temparature range from -189 °C to 961 °C. With the help of these cells, quartz glass-coated standard resistance thermometers, containing a wire spiral of high purity platinum (Standard Platinum Resistance Thermometer, SPRT), are calibrated. According to ITS-90, the SPRTs can then be used as interpolating instruments for calibrations between the fixed points.

Mole

The mole (mol) 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. It is understood that unbound atoms of carbon 12, at rest and in their ground state, are referred to in the definition.

The amount of a substance can be specified in principle by simply counting its constituents (atoms, molecules, etc.) one by one. For that, no new unit is necessary at all. The problem is that atoms and molecules are so tiny and their number in macroscopic amounts is so large, that normal counting is not possible.
However, when the ratios of atomic or molecular masses are known, the amount of a substance can be determined by weighing. The reference measure for weighing is the mole. In a mole of a pure substance there are as many entities as there are atoms in 0.012 kilogram of carbon 12. This number is called Avogadro constant – formerly also known as Loschmidt‘s number – and its value amounts to (6.022 141 79 (30) $\cdot 10^{23}$ mol^{-1}. The mole was adopted as the seventh base unit of the SI by the 14th General Conference on Weights and Measures in 1971.



Candela

The candela (cd) is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of a frequency $540 \cdot 10^{12}$ hertz and has a radiant intensity in that direction of 1/683 watt per steradian.

The measurement of light *per se* needs no special units since light is nothing more than electromagnetic radiation and consequently can be expressed in terms of units already known. However, given that the human sense of sight carries such a great importance, there is nevertheless general agreement that the subjective effect of electromagnetic radiation on the human visual organ should have its own units, and, for historical reasons, its own base unit. Photometric units measure light not only for its physical nature, but also in terms of the sensitivity of the human visual organ.
The sensitivity to brightness of the human eye depends on the wavelength, or colour, of the light, and demonstrates in this slight differences from individual to individual. If we want to measure light with physical instruments, as is common today in photometry, we require a measure of the subjective perception of brightness of the individual colour components. This measurement scale gives rise to the so-called spectral luminous efficiency function $V(\lambda)$, whose values for the wavelengths from 360 nm to 830 nm have been determined on an international basis from measurements on a large number of test persons.
At METAS, the candela is represented by a group of calibrated illuminance meters. These instruments consist of silicon detectors with 100 % quantum efficiency and a colour filter for adaptation to $V(\lambda)$. They are linked to the primary realisation of the optical power scale (cryogenic radiometre).

Alphabetic List of Symbols

Symbol	Unit	Quantity
A	ampere	electric current
a	are	area
a	atto	prefix for 10^{-18}
acre	acre	area
Å	ångström	length
asb	apostilb	illuminance
at	technical atmosphere	pressure
atm	standard atmosphere	pressure
b	barn	cross sectional area
bar	bar	pressure
bbl	barrel	volume
Bq	becquerel	activity
Btu	British thermal unit	energy
C	coulomb	electric charge
c	centi	prefix for 10^{-2}
cal	calorie	energy
cd	candela	luminous intensity
Ci	curie	activity
ct	carat	mass
cu (in, ft, yd)	cubic ...	volume
cwt	hundredweight (UK)	mass
d	deci	prefix for 10^{-1}
d	day	time
da	deca	prefix for 10^{1}
dB	decibel	sound pressure level, sound power level
dpt	dioptre	refraction power of optical systems
den	denier	mass per length
dr	dram	mass
dry (pt, qt)	dry ...	volume
E	exa	prefix for 10^{18}
erg	erg	energy
eV	electron volt	energy
F	farad	capacitance
f	femto	prefix for 10^{-15}

red = SI base unit
bold = SI derived unit, SI prefixes
regular = non SI unit, but legally regulated unit
italic = legally non regulated unit or non metric unit (US or UK unit)

Symbol	Unit	Quantity
fl (dr, oz)	fluid …	volume
fL	foot lambert	illuminance
fc	foot candle	illuminance
ft	foot	length
G	gauss	magnetic induction
G	giga	prefix for 10^9
g	gram	mass
Gal	gal	acceleration
gal	gallon	volume
gi	US gill	volume
gill	UK gill	volume
gon	gon	plane angle
gr	grain	mass
Gy	gray	absorbed dose
H	henry	inductance
h	hecto	prefix for 10^2
h	hour	time
ha	hectare	area
hp	horsepower	power
Hz	hertz	frequency
in	inch	length
J	joule	energy, work, quantity of heat
K	kelvin	temperature
k	kilo	prefix for 10^3
kat	katal	catalytic activity
kg	kilogram	mass
km	kilometre	length
kn	knot	velocity
kp	kilopond	force
l, L	litre	volume
lb	pound	mass
lbf	pound-force	force
liq (pt, qt)	liquid …	volume
lm	lumen	luminous flux
lx	lux	illuminance
M	mega	prefix for 10^6
M (nmi)	nautic mile	length

Symbol	Unit	Quantity
m	metre	length
m	milli	prefix for 10^{-3}
m^2	square metre	area
m^3	cubic metre	volume
µ	micro	prefix for 10^{-6}
mi	mile (statute)	length
min	minute	time
mm Hg	mm mercury	pressure
mol	mol	amount of substance
Mx	maxwell	magnetic flux
N	newton	force
n	nano	prefix for 10^{-9}
nmi (M)	nautical mile	length
Oe	oersted	magnetic field strength
Ω	ohm	electric resistance
oz	ounce	mass
P	poise	dynamic viscosity
P	peta	prefix for 10^{15}
p	pico	prefix for 10^{-12}
Pa	pascal	pressure, sound pressure
pdl	poundal	force
pk	peck	volume
PS	horsepower	power
pt	pint	volume
q	quintal	mass
qt	quart	volume
R	roentgen	ion dose
rad	radian	plane angle
rd	rad	absorbed dose
rem	rem	equivalent dose
rood	rood	area
S	siemens	electric conductance
s	second	time
sb	stilb	illuminance
sh cwt	short hundredweight (US)	mass
sh ton	short ton (US)	mass
sq (in, ft, yd)	square ...	aera

red = SI base unit
bold = SI derived unit, SI prefixes
regular = non SI unit, but legally regulated unit
italic = legally non regulated unit or non metric unit (US or UK unit)

Symbol	Unit	Quantity
sr	steradian	space angle
St	stokes	kinematc viscosity
Sv	sievert	equivalent dose
T	tesla	magnetic induction
T	tera	prefix for 10^{12}
t	ton	mass
tex	tex	mass per length
ton	ton	mass
tonf	ton-force	force
Torr	torr	pressure
u	atomic mass unit	mass
ua	astronomical unit	length
V	volt	electrical voltage
W	watt	power, heat flux, sound power
Wb	weber	magnetic flux
Y	yotta	prefix for 10^{24}
y	yocto	prefix for 10^{-24}
yd	yard	length
Z	zetta	prefix for 10^{21}
z	zepto	prefix for 10^{-21}
°C	degree celsius	temperature
°F	degree fahrenheit	temperature
°	degree (angle)	plane angle
'	minute (angle)	plane angle
"	second (angle)	plane angle

METAS: the National Metrology Institute of Switzerland

The Metre Convention of 1875 brought international agreement on the standardisation of the metric system and its further development. As a result the *General Conference on Weights and Measures* was founded and the *International Bureau of Weights and Measures* was created in Paris.

The respective national metrology institutes have the tasks of disseminating units of measure and ensuring the compliance of the metrological infrastructure with the system of units.

The Federal Office of Metrology (METAS) is the national metrological institute of Switzerland. It realises the national reference measures for Switzerland, ensures international recognition of these reference measures and provides the accuracy required by research, industry and society.

METAS satisfies the prerequisite that in Switzerland measurements are made with the necessary accuracy and can be verified, as is demanded by research, industry and society.

METAS oversees the introduction, use and testing of measuring equipment in the fields of trade, transport, public safety, health and environmental protection and ensures that the measurements necessary for the protection and safety of humans and the environment are made correctly and in accordance with legal prescriptions.

Advancing into New Dimensions

New scientific fields and technologies are to a great degree reliant on corresponding measurement bases and techniques. Technologies such as nanotechnology, pushing understanding and techniques into the smallest dimensions, play an ever more important role. Our daily lives are coming ever more into contact with technical equipment which is based on micro- and nanometre-scale structures. To manufacture and test this equipment, our industry needs measurement techniques with accuracies down to the nanometre range (millionth of a millimetre) or less. The measurement of corresponding quantities places high demands on science and instrumentation.

METAS, as the national metrology institute, must therefore continuously review and adapt its services, to be able to provide research, industry and society with access to the needed metrological know-how and facilities in good time.

Metrology

Metrology is the science and technique of measurement (the word derives from the Greek *metron* – measure). *Metrology* is often confused with *Meteorology*. The two terms are, however, unrelated. *Meteorology* means the study of weather phenomena (from the Greek *meteoros* – suspended in air).

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Services
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