Units of Measure in Electrical Engineering

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Coulomb and Charge Number

Coulomb

	coulomb
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Unit of...	Electric charge
Symbol:	C
Named after:	Charles-Augustin de Coulomb
	Unit conversions
1 C in...	is equal to...
SI base units	1 A s
CGS units	2997924580 statC
Atomic units	$6.24150965(16) \times 10^{18}$ e

The **coulomb** (symbol: **C**) is the SI derived unit of electric charge, transported by a steady current of one ampere in one second.

$$1\mathrm{C} = 1\mathrm{A} \cdot 1\mathrm{s}$$

One coulomb is also the amount of excess charge on the positive side of a capacitance of one farad charged to a potential difference of one volt:

$$1\mathrm{C} = 1\mathrm{F} \cdot 1\mathrm{V}$$

Name and notation

The unit is named after Charles-Augustin de Coulomb.

This SI unit is named after Charles-Augustin de Coulomb. As with every SI unit whose name is derived from the proper name of a person, the first letter of its symbol is upper

case (**C**). When an SI unit is spelled out in English, it should always begin with a lower case letter (**coulomb**), except where *any* word would be capitalized, such as at the beginning of a sentence or in capitalized material such as a title. Note that "degree Celsius" conforms to this rule because the "d" is lowercase.
—Based on *The International System of Units*, section 5.2.

Definition

In the SI system, the coulomb is defined in terms of the ampere and second: 1C = 1A × 1s. The second is defined in terms of a frequency which is naturally emitted by caesium atoms. The ampere is defined using Ampere's force law; the definition relies in part on the mass of the International Prototype Kilogram, a metal cylinder housed in France. In practice, the watt balance is used to measure amperes with the highest possible accuracy.

SI prefixes

SI multiples for coulomb (C)

Submultiples			Multiples		
Value	**Symbol**	**Name**	**Value**	**Symbol**	**Name**
10^{-1} C	dC	decicoulomb	10^{1} C	daC	decacoulomb
10^{-2} C	cC	centicoulomb	10^{2} C	hC	hectocoulomb
10^{-3} C	**mC**	**millicoulomb**	10^{3} C	kC	kilocoulomb
10^{-6} C	**µC**	**microcoulomb**	10^{6} C	MC	megacoulomb
10^{-9} C	**nC**	**nanocoulomb**	10^{9} C	GC	gigacoulomb
10^{-12} C	**pC**	**picocoulomb**	10^{12} C	TC	teracoulomb
10^{-15} C	fC	femtocoulomb	10^{15} C	PC	petacoulomb
10^{-18} C	aC	attocoulomb	10^{18} C	EC	exacoulomb
10^{-21} C	zC	not used	10^{21} C	ZC	zettacoulomb
10^{-24} C	yC	not used	10^{24} C	YC	yottacoulomb

Common multiples are in bold face.

Conversions

- The magnitude of the electrical charge of one mole of elementary charges (approximately 6.022×10^{23}, or Avogadro's number) is known as a faraday unit of charge (closely related to the Faraday constant). One faraday is equal to 96485.3399 coulombs. In terms of Avogadro's number (N_A), one coulomb is equal to approximately $1.036 \times N_A \times 10^{-5}$ elementary charges.
- one ampere-hour = 3600 C, 1 mAh = 3.6 C
- The elementary charge is $1.602176487 \times 10^{-19}$ C
- One statcoulomb (statC), the CGS electrostatic unit of charge (esu), is approximately 3.3356×10^{-10} C or about 1/3 nC.

- One coulomb is the magnitude (absolute value) of electrical charge in $6.24150965(16)\times10^{18}$ protons or electrons.

Relation to elementary charge

The elementary charge, the charge of a proton (equivalently, the negative of the charge of an electron), is approximately $1.602176487(40)\times10^{-19}$ coulombs. In SI, the elementary charge in coulombs is an approximate value: No experiment can be infinitely accurate. However, in other unit systems, the elementary charge has an *exact* value by definition, and other charges are ultimately measured relative to the elementary charge. For example, in conventional electrical units, the values of the Josephson constant K_J and von Klitzing constant R_K are exact defined values (written $K_{J\text{-}90}$ and $R_{K\text{-}90}$), and it follows that the elementary charge $e = 2 / (K_J R_K)$ is also an exact defined value in this unit system. Specifically, $e_{90} = (2 \times 10^{-9})/(25812.807 \times 483597.9)C$ exactly. SI itself may someday change its definitions in a similar way. For example, one possible proposed redefinition is "the ampere...is [defined] such that the value of the elementary charge *e* (charge on a proton) is exactly $1.602176487\times10^{-19}$ coulomb" This proposal is not yet accepted as part of the SI system: The SI definitions are unlikely to change until at least 2015.

In everyday terms

- The charges in static electricity from rubbing materials together are typically a few microcoulombs.
- The amount of charge that travels through a lightning bolt is typically around 15 C, although large bolts can be up to 350 C.
- The amount of charge that travels through a typical alkaline AA battery is about 5 kC = 5000 C = 1400 mAh. After that charge has flowed, the battery must be discarded or recharged.
- According to Coulomb's Law, two point charges of +1 C, one meter apart, would experience a repulsive force of 9×10^9 N, a force roughly equal to the weight of 900,000 metric tons of mass.

Charge number

Charge number or just **valance** of an ion is the coefficient that, when multiplied by the elementary charge, gives the ions charge.

For example, the charge on a chloride ion, Cl^-, is $-1 \cdot e$, where e is the elementary charge. This means the charge number for the ion is − 1.

z is sometimes used as the symbol for the charge number. In that case, the charge of an ion could be written as $Q = ze$.

For an atomic nucleus, which can be regarded as an ion having stripped off all electrons, the charge number is identical with the atomic number Z (number of protons).

In particle physics the charge number is a (derived) flavour quantum number, mostly denoted by Q (regarded as 'electric charge in units of e') rather than z. For color charged particles with like quarks and hypothetical leptoquarks the charge number is a broken multiple of 1/3.

Chapter-2

Elementary Charge and Faraday Constant

Elementary charge

Elementary charge	
Definition:	Charge of a proton
Symbol	*e*
Value in Coulombs:	$1.602176487(40)\times10^{-19}$ C

The **elementary charge**, usually denoted as *e*, is the electric charge carried by a single proton, or equivalently, the absolute value of the electric charge carried by a single electron. This elementary charge is a fundamental physical constant. To avoid confusion over its sign, *e* is sometimes called the "elementary positive charge". This charge has a measured value of approximately $1.602176487(40)\times10^{-19}$ coulombs. In the cgs system, *e* is $4.80320427(12)\times10^{-10}$ statcoulombs.

The elementary charge as a unit

Elementary charge ***(as a unit of charge)***	
Unit system:	Atomic units
Unit of...	electric charge
Symbol:	e
Unit conversions	
1 e in...	is equal to...
coulomb	$1.602\ 176\ 487(40)\times10^{-19}$
statcoulomb	$4.803\ 204\ 27(12)\times10^{-10}$

In the system of atomic units as well as some other systems of natural units (e.g. the Stoney units), *e* functions as the unit of electric charge, i.e. *e* = 1 e in those system of units. The use of the elementary charge as a unit was first promoted by George Johnstone Stoney in 1874 for his Stoney units which was the first system of natural units. Later he proposed the name *electron* for this unit. At this time the particle we now call the electron was not yet discovered and the difference between the particle *electron* and the unit of charge *electron* was still blurred. Later, the name *electron* was assigned to the particle and the unit of charge e lost its name. However, the old unit of energy electronvolt reminds us that the elementary charge was once called *electron*.

The magnitude of the elementary charge was first measured in Robert A. Millikan's noted oil drop experiment in 1909.

Quantization

Charge quantization is the concept that every stable and independent object (meaning an object that can exist independently for a prolonged period of time) has a charge which is an integer multiple of the elementary charge *e*. Thus, e.g., a charge can be exactly 0 e, or exactly 1 e, −1 e, 2 e, etc., but not, say, $^1\!/_2$ e, or −3.8 e, etc. (This statement must not be interpreted to include quarks or quasiparticles, since neither quarks nor quasiparticles possess the ability to exist on their own for prolonged periods of time. Quarks have charges that are integer multiples of $^1\!/_3$ *e*.)

This is the reason for the terminology "elementary charge": it is meant to imply that it is an indivisible unit of charge.

Charges less than an elementary charge

There are two known sorts of exceptions to the indivisibility of the elementary charge: quarks and quasiparticles.

- Quarks, first posited in the 1960s, have quantized charge, but the charge is quantized into multiples of $^1\!/_3$ *e*. However, quarks cannot be seen as isolated particles; they only exist in groupings, and stable groupings of quarks (such as a proton, which consists of three quarks) all have charges that are integer multiples of *e*. For this reason, either 1 e or $^1\!/_3$ e can be justifiably considered to be "the quantum of charge", depending on the context.

- Quasiparticles are not particles as such, but rather an emergent entity in a complex material system that behaves like a particle. In 1982 Robert Laughlin explained the fractional quantum Hall effect by postulating the existence of fractionally-charged quasiparticles. This theory is now widely accepted, but this is not considered to be a violation of the principle of charge quantization, since quasiparticles are not elementary particles.

What is the quantum of charge?

All known elementary particles, including quarks, have charges that are integer multiples of $\frac{1}{3}$ e. Therefore, one can say that the "quantum of charge" is $\frac{1}{3}$ e. In this case, one says that the "elementary charge" is three times as large as the "quantum of charge".

On the other hand, all *isolatable* particles have charges that are integer multiples of *e*. (Quarks cannot be isolated, except in combinations like protons that have total charges which are integer multiples of *e*.) Therefore, one can say that the "quantum of charge" is *e*, with the proviso that quarks are not to be included. In this case, "elementary charge" would be synonymous with the "quantum of charge".

In fact, both terminologies are used. For this reason, phrases like "the quantum of charge" or "the indivisible unit of charge" can be ambiguous, unless further specification is given. On the other hand, the term "elementary charge" is unambiguous: It universally refers to the charge of a proton.

Experimental measurements of the elementary charge

In terms of the Avogadro constant and Faraday constant

If the Avogadro constant N_A and the Faraday constant F are independently known, the value of the elementary charge can be deduced, using the formula

$$e = \frac{F}{N_A}$$

(In other words, the charge of one mole of electrons, divided by the number of electrons in a mole, equals the charge of a single electron.)

In practice, this method is *not* how the *most accurate* values are measured today: nevertheless, it is a legitimate and still quite accurate method, and experimental methodologies are described below:

The value of the Avogadro constant N_A was first approximated by Johann Josef Loschmidt who, in 1865, estimated the average diameter of the molecules in air by a method that is equivalent to calculating the number of particles in a given volume of gas. Today the value of N_A can be measured at very high accuracy by taking an extremely pure crystal (in practice, often silicon), measuring how far apart the atoms are spaced using X-ray diffraction or another method, and accurately measuring the density of the crystal. From this information, one can deduce the mass (m) of a single atom; and since the molar mass (M) is known, the number of atoms in a mole can be calculated: $N_A = M/m$.

The value of F can be measured directly using Faraday's laws of electrolysis. Faraday's laws of electrolysis are quantitative relationships based on the electrochemical researches published by Michael Faraday in 1834. In an electrolysis experiment, there is a one-to-one correspondence between the electrons passing through the anode-to-cathode wire and the ions that plate onto or off of the anode or cathode. Measuring the mass change of the anode or cathode, and the total charge passing through the wire (which can be measured as the time-integral of electric current), and also taking into account the molar mass of the ions, one can deduce F.

The limit to the precision of the method is the measurement of F: the best experimental value has a relative uncertainty of 1.6 ppm, about thirty times higher than other modern methods of measuring or calculating the elementary charge.

Oil-drop experiment

A famous method for measuring e is Millikan's oil-drop experiment. A small drop of oil in an electric field would move at a rate that balanced the forces of gravity, viscosity (of traveling through the air), and electric force. The forces due to gravity and viscosity could be calculated based on the size and velocity of the oil drop, so electric force could be deduced. Since electric force, in turn, is the product of the electric charge and the known electric field, the electric charge of the oil drop could be accurately computed. By measuring the charges of many different oil drops, it can be seen that the charges are all integer multiples of a single small charge, namely e.

Shot noise

Any electric current will be associated with noise from a variety of sources, one of which is shot noise. Shot noise exists because a current is not a smooth continual flow; instead, a current is made up of discrete electrons which pass by one at a time. By carefully analyzing the noise of a current, the charge of an electron can be calculated. This method, first proposed by Walter H. Schottky, can only give a value of e accurate to a few percent. However, it was used in the first direct observation of Laughlin quasiparticles, implicated in the fractional quantum Hall effect.

From the Josephson and von Klitzing constants

Another accurate method for measuring the elementary charge is by inferring it from measurements of two effects in quantum mechanics: The Josephson effect, voltage oscillations that arise in certain superconducting structures; and the quantum Hall effect, a quantum effect of electrons at low temperatures, strong magnetic fields, and confinement into two dimensions. The Josephson constant is

$$K_{\mathrm{J}} = \frac{2e}{h}$$

(where h is the Planck constant). It can be measured directly using the Josephson effect.

The von Klitzing constant is

$$R_{\mathrm{K}} = \frac{h}{e^2}$$

It can be measured directly using the quantum Hall effect.

From these two constants, the elementary charge can be deduced:

$$e = \frac{2}{R_{\mathrm{K}} K_{\mathrm{J}}}$$

CODATA method

In the most recent CODATA adjustments, the elementary charge is not an independently refined quantity. Instead, a value is derived from the relation

$$e^2 = \frac{2h\alpha}{\mu_0 c_0}$$

where h is the Planck constant, α is the fine structure constant, μ_0 is the magnetic constant and c_0 is the speed of light. The uncertainty in the value of e is currently determined entirely by the uncertainty in the Planck constant.

The most precise values of the Planck constant come from watt balance experiments, which are currently used to measure the product $K2$ $_{J}R_{\mathrm{K}}$. The most precise values of the fine structure constant come from comparisons of the measured and calculated value of the gyromagnetic ratio of the electron.

Faraday Constant

In physics and chemistry, the **Faraday constant** (named after Michael Faraday) is the magnitude of electric charge per mole of electrons. It has the currently accepted value:

$$F = 96\,485.339\,9(24)\,\mathrm{C\ mol^{-1}}.$$

The constant F has a simple relation to two other physical constants:

$$F = eN_A$$

where

$$N_A = 6.022 \times 10^{23}\,\mathrm{mol^{-1}}$$
$$e = 1.602 \times 10^{-19}\,\mathrm{C}.$$

N_A is the Avogadro constant, and *e* is the elementary charge or the magnitude of the charge of an electron. This relation is true because the amount of charge of a mole of electrons is equal to the amount of charge in *one* electron multiplied by the number of electrons in a mole.

The value of *F* was first determined by weighing the amount of silver deposited in an electrochemical reaction in which a measured current was passed for a measured time, and using Faraday's law of electrolysis. Research is continuing into more accurate ways of determining the interrelated constants *F*, N_A, and *e*.

Other Common Units of Faraday's Constant

- 96.485 kJ per volt gram equivalent
- 23.061 kcal per volt gram equivalent

Faraday unit of charge

Related to Faraday's constant is the "Faraday", a unit of electrical charge. It is much less common than the coulomb, but sometimes used in electrochemistry. One Faraday of charge is the magnitude of the charge of one mole of electrons, i.e. 96,485.3399(24) C.

Expressed in Faradays, the Faraday constant F equals "1 faraday of charge per mole".

This Faraday unit is not to be confused with the farad, an unrelated unit of capacitance.

Chapter-3

Electric Charge

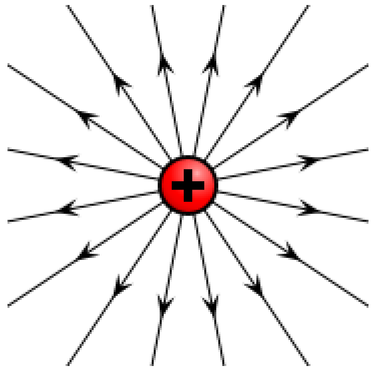
electric charge	
SI symbol:	*Q*
SI quantity dimension:	**Q**
SI unit:	coulomb
other units:	e
Derivations from other quantities:	$Q = I \cdot t$

Electric charge is a physical property of matter which causes it to experience a force when near other electrically charged matter. Electric charge comes in two types, called positive and negative. Two positively charged substances, or objects, experience a mutual repulsive force, as do two negatively charged objects. Positively charged objects and negatively charged objects experience an attractive force. The SI unit of electric charge is the coulomb (C), although in electrical engineering it is also common to use the ampere-hour (Ah). The study of how charged substances interact is classical electrodynamics, which is accurate insofar as quantum effects can be ignored.

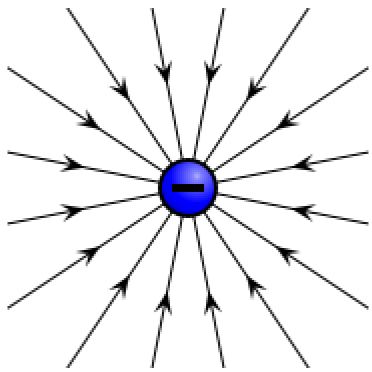
The *electric charge* is a fundamental conserved property of some subatomic particles, which determines their electromagnetic interaction. Electrically charged matter is influenced by, and produces, electromagnetic fields. The interaction between a moving charge and an electromagnetic field is the source of the electromagnetic force, which is one of the four fundamental forces.

Twentieth-century experiments demonstrated that electric charge is *quantized*; that is, it comes in multiples of individual small units called the elementary charge, *e*, approximately equal to 1.602×10^{-19} coulombs (except for particles called quarks which have charges that are multiples of $\frac{1}{3}e$). The proton has a charge of *e*, and the electron has a charge of $-e$. The study of charged particles, and how their interactions are mediated by photons, is quantum electrodynamics.

Overview



Electric field induced by a positive electric charge



Electric field induced by a negative electric charge

Charge is the fundamental property of forms of matter that exhibit electrostatic attraction or repulsion in the presence of other matter. Electric charge is a characteristic property of many subatomic particles. The charges of free-standing particles are integer multiples of the elementary charge *e*; we say that electric charge is *quantized*. Michael Faraday, in his electrolysis experiments, was the first to note the discrete nature of electric charge. Robert Millikan's oil-drop experiment demonstrated this fact directly, and measured the elementary charge.

By convention, the charge of an electron is −1, while that of a proton is +1. Charged particles whose charges have the same sign repel one another, and particles whose charges have different signs attract. Coulomb's law quantifies the electrostatic force between two particles by asserting that the force is proportional to the product of their charges, and inversely proportional to the square of the distance between them.

The charge of an antiparticle equals that of the corresponding particle, but with opposite sign. Quarks have fractional charges of either $-\frac{1}{3}$ or $+\frac{2}{3}$, but free-standing quarks have never been observed (the theoretical reason for this fact is asymptotic freedom).

The electric charge of a macroscopic object is the sum of the electric charges of the particles that make it up. This charge is often small, because matter is made of atoms, and atoms typically have equal numbers of protons and electrons, in which case their charges cancel out, yielding a net charge of zero, thus making the atom neutral.

An *ion* is an atom (or group of atoms) that has lost one or more electrons, giving it a net positive charge (cation), or that has gained one or more electrons, giving it a net negative charge (anion). *Monatomic ions* are formed from single atoms, while *polyatomic ions* are formed from two or more atoms that have been bonded together, in each case yielding an ion with a positive or negative net charge.

During the formation of macroscopic objects, usually the constituent atoms and ions will combine in such a manner that they form structures composed of neutral *ionic compounds* electrically bound to neutral atoms. Thus macroscopic objects tend toward being neutral overall, but macroscopic objects are rarely perfectly net neutral.

There are times when macroscopic objects contain ions distributed throughout the material, rigidly bound in place, giving an overall net positive or negative charge to the object. Also, macroscopic objects made of conductive elements, can more or less easily (depending on the element) take on or give off electrons, and then maintain a net negative or positive charge indefinitely. When the net electric charge of an object is non-zero and motionless, the phenomenon is known as static electricity. This can easily be produced by rubbing two dissimilar materials together, such as rubbing amber with fur or glass with silk. In this way non-conductive materials can be charged to a significant degree, either positively or negatively. Of course, charge taken from one material is simply moved to the other material, leaving an opposite charge of the same magnitude behind. The law of *conservation of charge* always applies, giving the object from which a negative charge has been taken a positive charge of the same magnitude, and vice-versa.

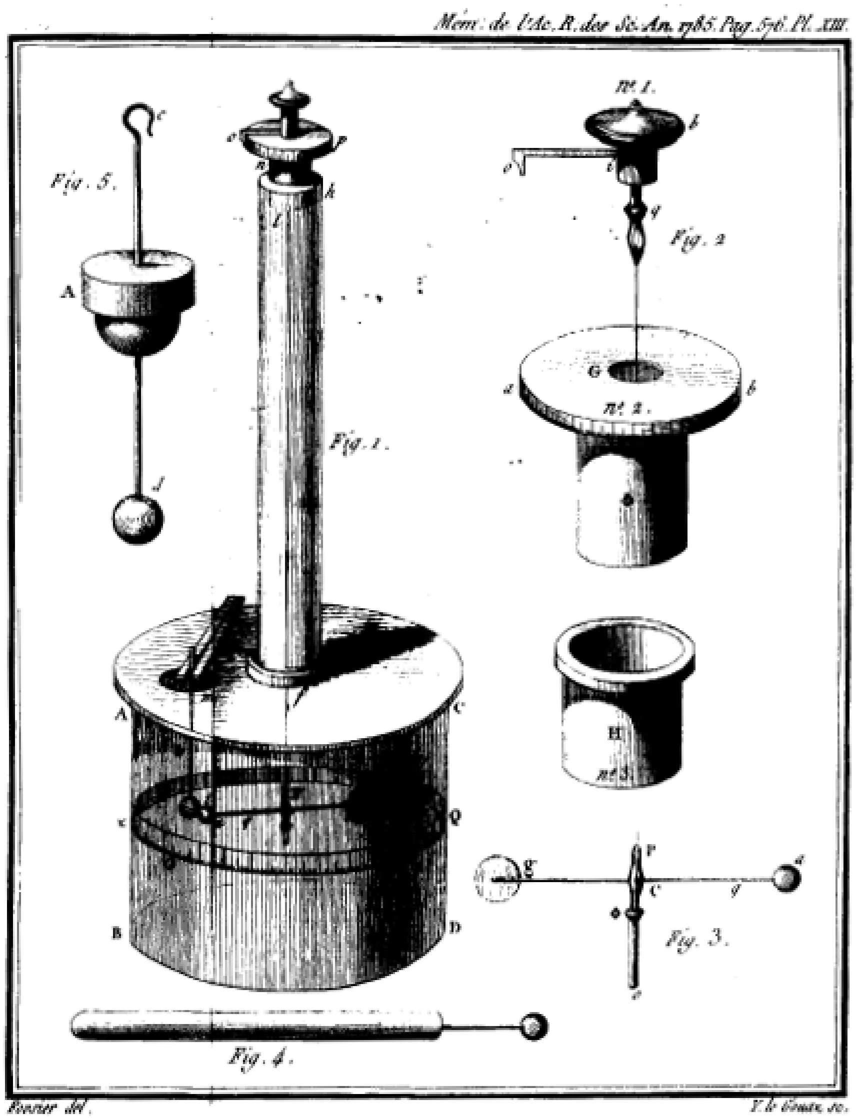
Even when an object's net charge is zero, charge can be distributed non-uniformly in the object (e.g., due to an external electromagnetic field, or bound polar molecules). In such cases the object is said to be polarized. The charge due to polarization is known as bound charge, while charge on an object produced by electrons gained or lost from outside the object is called *free charge*. The motion of electrons in conductive metals in a specific direction is known as electric current.

Units

The SI unit of quantity of electric charge is the coulomb, which is equivalent to about 6.242×10^{18} *e* (*e* is the charge of a proton). Hence, the charge of an electron is approximately -1.602×10^{-19} C. The coulomb is defined as the quantity of charge that has passed through the cross section of an electrical conductor carrying one ampere within one second. The symbol *Q* is often used to denote a quantity of electricity or charge. The quantity of electric charge can be directly measured with an electrometer, or indirectly measured with a ballistic galvanometer.

After finding the quantized character of charge, in 1891 George Stoney proposed the unit 'electron' for this fundamental unit of electrical charge. This was before the discovery of the particle by J.J. Thomson in 1897. The unit is today treated as nameless, referred to as "elementary charge", "fundamental unit of charge", or simply as "e". A measure of charge should be a multiple of the elementary charge *e*, even if at large scales, charge seems to behave as a real quantity. In some contexts it is meaningful to speak of fractions of a charge; for example in the charging of a capacitor, or in the fractional quantum Hall effect.

History



Coulomb's torsion balance

As reported by the ancient Greek philosopher Thales of Miletus around 600 BC, charge (or *electricity*) could be accumulated by rubbing fur on various substances, such as amber. The Greeks noted that the charged amber buttons could attract light objects such as hair. They also noted that if they rubbed the amber for long enough, they could even get an electric spark to jump. This property derives from the triboelectric effect.

In 1600, the English scientist William Gilbert returned to the subject in *De Magnete*, and coined the New Latin word *electricus* from *ηλεκτρον* (*elektron*), the Greek word for "amber", which soon gave rise to the English words "electric" and "electricity." He was followed in 1660 by Otto von Guericke, who invented what was probably the first electrostatic generator. Other European pioneers were Robert Boyle, who in 1675 stated that electric attraction and repulsion can act across a vacuum; Stephen Gray, who in 1729 classified materials as conductors and insulators; and C. F. du Fay, who proposed in 1733 that electricity came in two varieties which cancelled each other, and expressed this in terms of a two-fluid theory. When glass was rubbed with silk, du Fay said that the glass was charged with *vitreous electricity*, and when amber was rubbed with fur, the amber was said to be charged with *resinous electricity*. In 1839, Michael Faraday showed that the apparent division between static electricity, current electricity and bioelectricity was incorrect, and all were a consequence of the behavior of a single kind of electricity appearing in opposite polarities. It is arbitrary which polarity you call positive and which you call negative. Positive charge can be defined as the charge left on a glass rod after being rubbed with silk.

One of the foremost experts on electricity in the 18th century was Benjamin Franklin, who argued in favour of a one-fluid theory of electricity. Franklin imagined electricity as being a type of invisible fluid present in all matter; for example he believed that it was the glass in a Leyden jar that held the accumulated charge. He posited that rubbing insulating surfaces together caused this fluid to change location, and that a flow of this fluid constitutes an electric current. He also posited that when matter contained too little of the fluid it was "negatively" charged, and when it had an excess it was "positively" charged. Arbitrarily (or for a reason that was not recorded) he identified the term "positive" with vitreous electricity and "negative" with resinous electricity. William Watson arrived at the same explanation at about the same time.

Static electricity and electric current

Static electricity and electric current are two separate phenomena, both involving electric charge, and may occur simultaneously in the same object. Static electricity is a reference to the electric charge of an object and the related electrostatic discharge when two objects are brought together that are not at equilibrium. An electrostatic discharge creates a change in the charge of each of the two objects. In contrast, electric current is the flow of electric charge through an object, which produces no net loss or gain of electric charge. Although charge flows between two objects during an electrostatic discharge, time is too short for current to be maintained.

Electrification by friction

Experiment I

Let a piece of glass and a piece of resin, neither of which exhibits any electrical properties, be rubbed together and left with the rubbed surfaces in contact. They will still exhibit no electrical properties. Let them be separated. They will now attract each other.

If a second piece of glass be rubbed with a second piece of resin, and if the piece be then separated and suspended in the neighbourhood of the former pieces of glass and resin, it may be observed:

1. that the two pieces of glass repel each other.
2. that each piece of glass attracts each piece of resin.
3. that the two pieces of resin repel each other.

These phenomena of attraction and repulsion are called electrical phenomena and the bodies which exhibit them are said to be 'electrified', or to be 'charged with electricity'.

Bodies may be electrified in many other ways, as well as by friction.

The electrical properties of the two pieces of glass are similar to each other but opposite to those of the two pieces of resin: the glass attracts what the resin repels and repels what the resin attracts.

If a body electrified in any manner whatever behaves as the glass does, that is, if it repels the glass and attracts the resin, the body is said to be 'vitreously' electrified, and if it attracts the glass and repels the resin it is said to be 'resinously' electrified. All electrified bodies are found to be either vitreously or resinously electrified.

It is the established convention of the scientific community to define the vitreous electrification as positive, and the resinous electrification as negative. The exactly opposite properties of the two kinds of electrification justify us in indicating them by opposite signs, but the application of the positive sign to one rather than to the other kind must be considered as a matter of arbitrary convention, just as it is a matter of convention in mathematical diagram to reckon positive distances towards the right hand.

No force, either of attraction or of repulsion, can be observed between an electrified body and a body not electrified.

We now know that the Franklin/Watson model was fundamentally correct. There is only one kind of electrical charge, and only one variable is required to keep track of the amount of charge. On the other hand, just knowing the charge is not a complete description of the situation. Matter is composed of several kinds of electrically charged particles, and these particles have many properties, not just charge.

The most common charge carriers are the positively charged proton and the negatively charged electron. The movement of any of these charged particles constitutes an electric current. In many situations, it suffices to speak of the *conventional current* without regard to whether it is carried by positive charges moving in the direction of the conventional current and/or by negative charges moving in the opposite direction. This macroscopic viewpoint is an approximation that simplifies electromagnetic concepts and calculations.

At the opposite extreme, if one looks at the microscopic situation, one sees there are many ways of carrying an electric current, including: a flow of electrons; a flow of electron "holes" which act like positive particles; and both negative and positive particles (ions or other charged particles) flowing in opposite directions in an electrolytic solution or a plasma).

Beware that in the common and important case of metallic wires, the direction of the conventional current is opposite to the drift velocity of the actual charge carriers, i.e. the electrons. This is a source of confusion for beginners.

Properties

Aside from the properties described in articles about electromagnetism, charge is a relativistic invariant. This means that any particle that has charge Q, no matter how fast it goes, always has charge Q. This property has been experimentally verified by showing that the charge of *one* helium nucleus (two protons and two neutrons bound together in a nucleus and moving around at high speeds) is the same as *two* deuterium nuclei (one proton and one neutron bound together, but moving much more slowly than they would if they were in a helium nucleus).

Conservation of electric charge

The total electric charge of an isolated system remains constant regardless of changes within the system itself. This law is inherent to all processes known to physics and can be derived in a local form from gauge invariance of the wave function. The conservation of charge results in the charge-current continuity equation. More generally, the net change in charge density ρ within a volume of integration V is equal to the area integral over the current density $\mathbf{J}$ through the closed surface $S = \partial V$, which is in turn equal to the net current I:

$$-\frac{d}{dt}\int_V \rho \, \mathrm{d}V = \oint\!\!\!\oint_{\partial V} \mathbf{J} \cdot \mathrm{d}\mathbf{S} = \int J dS \cos\theta = I.$$

Thus, the conservation of electric charge, as expressed by the continuity equation, gives the result:

$$I = \frac{dQ}{dt}.$$

The charge transferred between times t_i and t_f is obtained by integrating both sides:

$$Q = \int_{t_\mathrm{i}}^{t_\mathrm{f}} I \, \mathrm{d}t$$

where I is the net outward current through a closed surface and Q is the electric charge contained within the volume defined by the surface.

Chapter-4

Planck Charge, Abcoulomb and Statcoulomb

Planck charge

In physics, the **Planck charge** (***q_P***), is one of the base units in the system of natural units called Planck units. It is a quantity of electric charge defined in terms of fundamental physical constants.

The Planck charge is defined as:

$$q_P = \sqrt{4\pi\epsilon_0\hbar c} = \sqrt{2ch\epsilon_0} = \frac{e}{\sqrt{\alpha}} = 1.8755459 \times 10^{-18}$$ coulombs,

where:

c is the speed of light in the vacuum,
h is Planck's constant,
$\hbar \equiv \frac{h}{2\pi}$ is the reduced Planck constant,
ϵ_0 is the permittivity of free space
e is the elementary charge
$\alpha = (137.03599911)^{-1}$ is the fine structure constant.

The Planck charge is $\alpha^{-1/2} \approx 11.706$ times greater than the elementary charge *e* carried by an electron.

The Gaussian cgs units are defined so that $4\pi\varepsilon_0 = 1$, in which case q_P has the following simple form:

$$q_P = \sqrt{\hbar c}.$$

Abcoulomb

The **abcoulomb** (**abC** or **aC**) or **electromagnetic unit of charge** (**emu of charge**) is the basic physical unit of electric charge in the cgs-emu system of units. One abcoulomb is equal to ten coulombs.

CGS-emu (or "electromagnetic cgs") units are one of several systems of electromagnetic units within the centimetre gram second system of units; others include cgs-esu, Gaussian units, and Lorentz-Heaviside units. In these other systems, the abcoulomb is *not* one of the units; the statcoulomb is instead.

In the electromagnetic cgs system, electrical current is a fundamental quantity defined via Ampère's law and takes the permeability as a dimensionless quantity (relative permeability) whose value in a vacuum is unity. As a consequence, the square of the speed of light appears explicitly in some of the equations interrelating quantities in this system.

The definition of the abcoulomb follows from that of the abampere: given two parallel currents of one abampere separated by one centimetre, the force per distance of wire is 2 dyn/cm. The abcoulomb is the charge flowing in 1 second given a current of 1 abampere.

Statcoulomb

The **statcoulomb** (**statC**) or **franklin** (**Fr**) or **electrostatic unit of charge** (**esu**) is the physical unit for electrical charge used in the centimetre-gram-second (cgs) electrostatic system of units. It is a derived unit given by

$$1\ \text{statC} = 1\ \text{g}^{1/2}\ \text{cm}^{3/2}\ \text{s}^{-1} = 1\ \text{erg}^{1/2}\ \text{cm}^{1/2}.$$

The SI system of units uses the coulomb (C) instead. The conversion is

$$1\ \text{C} \leftrightarrow 2997924580\ \text{statC}.$$

This conversion is *exact*. However, the symbol "↔" is used instead of "=" because of the dimensional-analysis complications discussed below. The number on the right-hand side is 10 times the value of the speed of light expressed in meters/second. The approximate conversions in both directions are:

$$1\ \text{C} \leftrightarrow 3.00\times10^{9}\ \text{statC},$$
$$1\ \text{statC} \leftrightarrow 3.34\times10^{-10}\ \text{C}.$$

The statcoulomb is defined as follows: if two stationary objects each carry a charge of 1 statC and are 1 cm apart, they will electrically repel each other with a force of 1 dyne. This repulsion is governed by Coulomb's law, which in the Gaussian-cgs system states:

$$F = \frac{q_1 q_2}{r^2}$$

where F is the force, q_1 and q_2 are the two charges, and r is the distance between the charges. Performing dimensional analysis on Coulomb's law, the dimension of electrical charge in cgs must be $[\text{mass}]^{1/2}\,[\text{length}]^{3/2}\,[\text{time}]^{-1}$. We can be more specific in light of the definition above: Plugging in F=1 dyne, q_1=q_2=1 statC, and r = 1 cm, we get:

$$1\ \text{statC} = \text{g}^{1/2}\,\text{cm}^{3/2}\,\text{s}^{-1}$$

as expected.

The coulomb is an extremely large charge rarely encountered in electrostatics, while the statcoulomb is closer to everyday charges.

Dimensional relation between Statcoulomb and Coulomb

In the cgs-Gaussian unit system, as mentioned above, Coulomb's law states

$$F = \frac{q_1 q_2}{r^2}$$

To be consistent with this equation, the statcoulomb must be (and is) dimensionally equivalent to $[\text{mass}]^{1/2}\,[\text{length}]^{3/2}\,[\text{time}]^{-1}$.

On the other hand, in SI units, Coulomb's law is different:

$$F = \frac{q_1 q_2}{4\pi\epsilon_0 r^2}$$

Since ε_0, the vacuum permittivity, is *not* dimensionless, the coulomb (the SI unit of charge) is *not* dimensionally equivalent to $[\text{mass}]^{1/2}\,[\text{length}]^{3/2}\,[\text{time}]^{-1}$, unlike the statcoulomb. In fact, it is impossible to express the Coulomb in terms of mass, length, and time alone.

Consequently, the equation "1 C = 2997924580 statC" can be misleading: the units on the two sides are not consistent. One *cannot* freely switch between Coulombs and statcoulombs within a formula or equation, as one would freely switch between centimeters and meters. A clearer statement is to say "1 C *corresponds to* 2997924580 statC", instead of "1 coulomb *equals* 2997924580 statcoulombs". In other words, if a physical object has a charge of 1 coulomb, it also has a charge of 2997924580 statcoulombs.

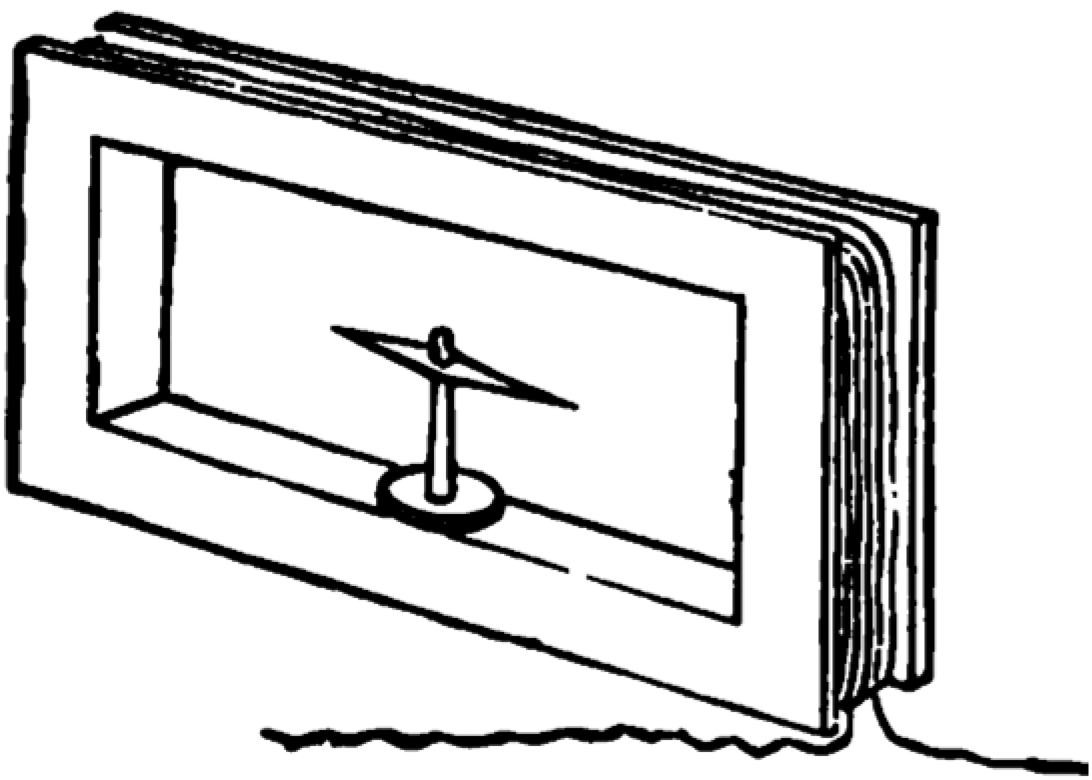
On the other hand, the following conversion *is* fully dimensionally consistent, and often useful for switching between SI and cgs formulae:

$$1\ \mathrm{C}/\sqrt{4\pi\epsilon_0} = 2997924580\,\mathrm{statC}$$

where ε_0 is the vacuum permittivity, ≈ $8.85\times10^{-12}\ \mathrm{A^2\ s^4 kg^{-1} m^{-3}}$ = $8.85\times10^{-21}\ \mathrm{A^2 s^4 g^{-1} cm^{-3}}$.

Chapter-5

Ampere



Current can be measured by a galvanometer, via the deflection of a magnetic needle in the magnetic field created by the current.

The **ampere** (symbol: A) is the SI unit of electric current (symbol: I) and is one of the seven SI base units. It is named after André-Marie Ampère (1775–1836), French mathematician and physicist, considered the father of electrodynamics. In practice, its name is often shortened to **amp**.

In practical terms, the ampere is a measure of the amount of electric charge passing a point per unit time. Around 6.241×10^{18} electrons, or one coulomb, passing a given point each second constitutes one ampere.

Definition

Ampère's force law states that there is an attractive force between two parallel wires carrying an electric current. This force is used in the formal definition of the ampere which states that it is "the constant current which will produce an attractive force of 2×10^{-7} newton per metre of length between two straight, parallel conductors of infinite length and negligible circular cross section placed one metre apart in a vacuum".

In terms of Ampère's force law,

$$2 \times 10^{-7}\ \tfrac{\mathrm{N}}{\mathrm{m}} = 2 \times k_A \frac{\mathrm{A} \cdot \mathrm{A}}{\mathrm{m}}$$

so

$$1\ \mathrm{A} = \sqrt{\frac{2 \times 10^{-7}\ \mathrm{N}}{2 \times k_A}}$$

The SI unit of charge, the coulomb, "is the quantity of electricity carried in 1 second by a current of 1 ampere." Conversely, a current of one ampere is one coulomb of charge going past a given point per second**:**

$$1\ \mathrm{A} = 1 \tfrac{\mathrm{C}}{\mathrm{s}}$$

That is, in general, charge Q is determined by steady current I flowing for a time t as $Q = It$.

History

The ampere was originally defined as one tenth of the CGS system electromagnetic unit of current (now known as the abampere), the amount of current which generates a force of two dynes per centimetre of length between two wires one centimetre apart. The size of the unit was chosen so that the units derived from it in the MKSA system would be conveniently sized.

The "international ampere" was an early realisation of the ampere, defined as the current that would deposit 0.001118000 grams of silver per second from a silver nitrate solution. Later, more accurate measurements revealed that this current is 0.99985 A.

Realisation

The ampere is most accurately realised using a watt balance, but is in practice maintained via Ohm's Law from the units of electromotive force and resistance, the volt and the ohm, since the latter two can be tied to physical phenomena that are relatively easy to reproduce, the Josephson junction and the quantum Hall effect, respectively.

At present, techniques to establish the realisation of an ampere have a relative uncertainty of approximately a few parts in 10^7, and involve realisations of the watt, the ohm and the volt.

Proposed future definition

Rather than a definition in terms of the force between two current-carrying wires, it has been proposed to define the ampere in terms of the rate of flow of elementary charges. Since a coulomb is approximately equal to $6.24150948 \times 10^{18}$ elementary charges, one ampere is approximately equivalent to $6.24150948 \times 10^{18}$ elementary charges per second, such as electrons, moving past a boundary in one second. The proposed change would define 1 A as being the current in the direction of flow of a particular number of elementary charges per second. In 2005, the International Committee for Weights and Measures (CIPM) agreed to study the proposed change. The new definition is expected to be formally proposed at the 25th General Conference on Weights and Measures (CGPM) in 2015.

Everyday examples

The current drawn by typical systems is usually dictated by the power (watts) consumed by the system and voltage supplied. For this reason the examples given below are grouped by voltage level.

Portable gadgets

- Hearing aid (typically 1 mW at 1.4 V): 0.7 mA

Motorcars - 12 V DC

A typical motor car has a 12 V battery. The various accessories that are powered by the battery might include:

- Headlights (typically 60 W): 5 A each.
- Instrument panel light (typically 2 W): 166 mA.
- Starter Motor (typically 1-2 kW): 80-160 A

US domestic supply - 120 V AC

Most United States domestic power suppliers run at 120 V.

Household circuit breakers typically provide a maximum of 15A or 20A of current to a given set of outlets.

European domestic supply - 230 V AC

Most European domestic power supplies run at 230 V, so the current drawn for a particular appliance will be less than for an equivalent United States appliance. This means that lighter (and cheaper) cabling can be used.

The current drawn by a number of typical appliances are:

- Toaster, kettle (2 kW): 9 A
- Immersion heater (16 kW): 20 A
- Tungsten light bulb (60 W - 100 W): 250 mA - 450 mA
- 22 inch/56 cm Portable Television (35 W): 150 mA

Chapter-6

Siemens, Planck Current and Abampere

Siemens (unit)

The **siemens** (symbol: S) is the SI derived unit of electric conductance and electric admittance. Conductance and admittance are the reciprocals of resistance and impedance respectively, hence one siemens is equal to the reciprocal of one ohm, and is sometimes referred to as the *mho*. It is named after the German inventor and industrialist Ernst Werner von Siemens. In English, the term *siemens* is used both for the singular and plural. The 14th General Conference on Weights and Measures approved the addition of the siemens as an SI derived unit in 1971.

This SI unit is named after Ernst Werner von Siemens. As with every SI unit whose name is derived from the proper name of a person, the first letter of its symbol is upper case (**S**). When an SI unit is spelled out in English, it should always begin with a lower case letter (**siemens**), except where *any* word would be capitalized, such as at the beginning of a sentence or in capitalized material such as a title. Note that "degree Celsius" conforms to this rule because the "d" is lowercase.
—Based on *The International System of Units*, section 5.2.

Definition

For a conducting or semiconducting element with electrical resistance *R*, the conductance *G* is defined as

$$G = \frac{1}{R} = \frac{I}{V}$$

where *I* is the electric current through the object and *V* is the voltage (electrical potential difference) across the object.

The unit **siemens** for the conductance *G* is defined by

$$S = \Omega^{-1} = \frac{A}{V}$$

where Ω is the ohm, A is the ampere, and V is the volt.

For a device with a conductance of one siemens, the electric current through the device will increase by one ampere for every increase of one volt of electric potential difference across the device.

Example: The conductance of a resistor with resistance six ohms is $G = 1/(6\ \Omega) \approx 0.167$ S ≈ 167 mS.

Historical/Deprecated

Since 1860 to the middle of 20th century, **siemens** or siemens mercury unit, was the unit of electrical resistance. It was defined as the resistance of a mercury column 1 meter long and uniform 1 mm^2 cross sectional area at 0 degrees Celsius. It was equivalent to 0.953 Ohm approximately. Officially, it ceased usage after 1881, but was widely used in telegraph and telephone services until World War II.

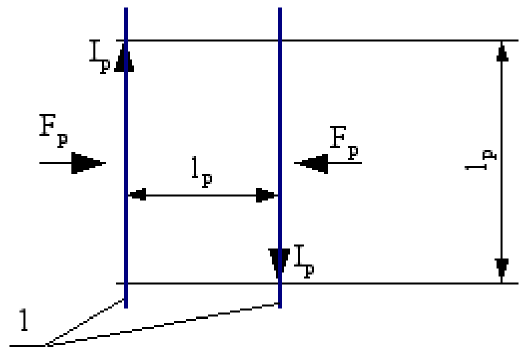
Mho

Mho is an alternate, non-SI unit of conductivity which is equivalent to 1 siemens. Mho is derived from spelling *ohm* backwards and is written with an upside-down capital Greek letter Omega: ℧, Unicode symbol U+2127 (℧). According to Maver the term *mho* was suggested by Sir William Thomson.

The term *siemens*, as it is an SI unit, is used universally in science and often in electrical applications, while *mho* is still used primarily in electronic applications. Two reasons are usually given for using *mho* instead of *siemens* in electronic applications:

- The inverted Omega and the *mho*, while not an official SI abbreviation, has the advantage of being less likely to be confused with a variable than the letter S when doing algebraic calculations by hand, where the usual typographical distinctions (such as italic for variables and Roman for unit names) are difficult to maintain. Likewise, it is difficult to distinguish the symbol *S* from the lower case *s* where *second* is meant, potentially causing confusion.
- The term *siemens* could be confused with the large multinational electronics company Siemens.

Planck current



1 - conductors, F_p - Planck force, l_p - Planck length, I_p - Planck current.

The **Planck current** is the unit of electric current, denoted by I_p, in the system of natural units known as Planck units.

$$I_p = q_p/t_p = (c^6 4\pi\varepsilon_0/G)^{\frac{1}{2}} \approx 3.479 \times 10^{25} \text{ A}$$

where:

$q_p = (c\hbar 4\pi\varepsilon_0)^{\frac{1}{2}}$ is the Planck charge

$t_p = (\hbar G/c^5)^{\frac{1}{2}}$ is the Planck time

ε_0 = permittivity in vacuum

$\hbar$ is the reduced Planck constant

G is the gravitational constant

c is the speed of light in vacuum.

The Planck current is that current which, in a conductor, carries a Planck charge in Planck time.

Alternately, the Planck current is that constant current which, if maintained in two straight parallel conductors of infinite length and negligible circular cross-section, and placed a Planck length apart in vacuum, would produce between these conductors a force equal to a Planck force per Planck length.

Abampere

The **abampere** (**aA**), also called the biot after Jean-Baptiste Biot, is the basic electromagnetic unit of electric current in the emu-cgs system of units (electromagnetic cgs). One abampere is equal to ten amperes in the SI system of units. An abampere of current in a circular path of one centimeter radius produces a magnetic field of 2π oersteds at the center of the circle.

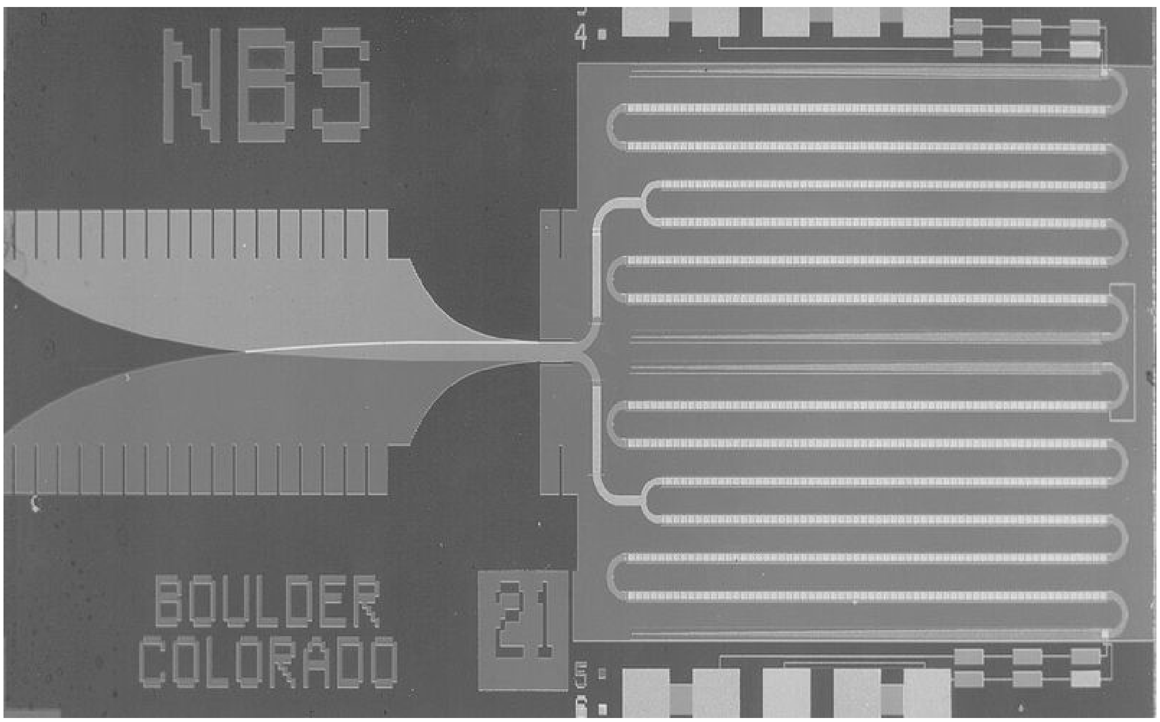
The emu-cgs (or "electromagnetic cgs") units are one of several systems of electromagnetic units within the centimetre gram second system of units; others include esu-cgs, Gaussian units, and Lorentz-Heaviside units. In these other systems, the abampere is *not* one of the units; the "statcoulomb per second" or *statampere* is used instead.

The other units in this system related to the abampere are:

- abcoulomb -- the charge that passes in one second through any cross section of a conductor carrying a steady current of one abampere
- abhenry -- the self-inductance of a circuit or the mutual inductance of two circuits in which the variation of current at the rate of one abampere per second results in an induced electromotive force of one abvolt
- abohm -- the resistance of a conductor that, with a constant current of one abampere through it, maintains between its terminals a potential difference of one abvolt

Chapter-7

Volt



Josephson junction array chip developed by NIST as a standard volt.

The **volt** (symbol: **V**) is the SI derived unit of electromotive force, commonly called "voltage". It is also the unit for the related but slightly different quantity electric potential in a point (voltage as related to a reference ground) and electric potential difference (also called "electrostatic potential difference"). It is named in honor of the Italian physicist Alessandro Volta (1745–1827), who invented the voltaic pile, possibly the first chemical battery.

Definition

The volt is defined as the value of the voltage across a conductor when a current of one ampere dissipates one watt of power in the conductor. It can be written in terms of SI base units as: $m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$. It is also equal to one joule of energy per coulomb of charge, J/C.

$$V = \frac{W}{A} = \sqrt{W \cdot \Omega} = \frac{J}{A \cdot s} = \frac{N \cdot m}{A \cdot s} = \frac{kg \cdot m^2}{A \cdot s^3} = \frac{kg \cdot m^2}{C \cdot s^2} = \frac{N \cdot m}{C} = \frac{J}{C}$$

Josephson junction definition

Between 1990 and 1997 the volt was calibrated using the Josephson effect for exact voltage-to-frequency conversion, combined with cesium-133 time reference, as decided by the 18th General Conference on Weights and Measures. The following value for the Josephson constant is used:

$K_{\{J\text{-}90\}} = 2e/h = 0.4835979$ GHz/μV.

This is typically used with an array of several thousand or tens of thousands of junctions, excited by microwave signals between 10 and 80 GHz (depending on the array design). Empirically, several experiments have shown that the method is independent of device design, material, measurement setup, etc, and no correction terms are required in a practical implementation. However, as of July 2007, this is not the official BIPM definition of Volt.]

Water flow analogy

In the *water flow analogy* sometimes used to explain electric circuits by comparing them to water-filled pipes, voltage difference is likened to water pressure difference–the difference determines how quickly the electrons will travel through the circuit. Current (in amperes), in the same analogy, is a measure of the volume of water that flows past a given point per unit time (volumetric flow rate). The flow rate is determined by the width of the pipe (analogous to electrical conductivity), and the pressure difference between the front end of the pipe and the exit (analogous to voltage). The analogy extends to power dissipation: the power given up by the water flow is equal to flow rate times pressure, just as the power dissipated in a resistor is equal to current times the voltage drop across the resistor (watts = amperes × volts).

The relationship between voltage and current (in ohmic devices) is defined by Ohm's Law.

Common voltages

A multimeter can be used to measure the voltage between two positions.

1.5 V C-cell batteries

Nominal voltages of familiar sources:

- Nerve cell resting potential: around −75 mV
- Single-cell, rechargeable NiMH or NiCd battery: 1.2 V
- Mercury battery: 1.355 V
- Single-cell, non-rechargeable alkaline battery (e.g., AAA, AA, C and D cells): 1.5 V
- $LiFePO_4$ rechargeable battery: 3.3 V
- Lithium polymer rechargeable battery: 3.75 V
- Transistor-transistor logic/CMOS (TTL) power supply: 5 V
- PP3 battery: 9 V
- Automobile electrical system: nominal 12 V, about 11.8 V discharged, 12.8 V charged, and 13.8–14.4 V while charging (vehicle running).

- Household mains electricity: 230 V RMS in Europe, Asia and Africa, 120 V RMS in North America, 100 V RMS in Japan
- Trucks/lorries: 24 V DC
- Rapid transit third rail: 600–750 V
- High speed train overhead power lines: 25 kV RMS at 50 Hz
- High voltage electric power transmission lines: 110 kV RMS and up (1.15 MV RMS was the record as of 2005)
- Lightning: Varies greatly, often around 100 MV.

Note: Where *RMS* (root mean square) is stated above, the peak voltage is $\sqrt{2}$times greater than the RMS voltage for a sinusoidal signal centered around zero voltage.

History of the volt

In 1800, as the result of a professional disagreement over the galvanic response advocated by Luigi Galvani, Alessandro Volta developed the so-called Voltaic pile, a forerunner of the battery, which produced a steady electric current. Volta had determined that the most effective pair of dissimilar metals to produce electricity was zinc and silver. In the 1880s, the International Electrical Congress, now the International Electrotechnical Commission (IEC), approved the volt as the unit for electromotive force. At that time, the volt was defined as the potential difference [i.e., what is nowadays called the "voltage (difference)"] across a conductor when a current of one ampere dissipates one watt of power.

The international volt was defined in 1893 as 1/1.434 of the emf of a Clark cell. This definition was abandoned in 1908 in favor of a definition based on the international ohm and international ampere until the entire set of "reproducible units" was abandoned in 1948.

Prior to the development of the Josephson junction voltage standard, the volt was maintained in national laboratories using specially constructed batteries called **standard cells**. The United States used a design called the Weston cell from 1905 to 1972.

This SI unit is named after Alessandro Volta. As with every SI unit whose name is derived from the proper name of a person, the first letter of its symbol is upper case (**V**). When an SI unit is spelled out in English, it should always begin with a lower case letter (**volt**), except where *any* word would be capitalized, such as at the beginning of a sentence or in capitalized material such as a title. Note that "degree Celsius" conforms to this rule because the "d" is lowercase.
—Based on *The International System of Units*, section 5.2.

Chapter-8

Ohm and Abohm

Ohm

A multimeter can be used to measure resistance in ohms. It can also be used to measure capacitance, voltage, current, and other electrical characteristics.

The **ohm** (symbol: Ω) is the SI unit of electrical resistance, named after Georg Simon Ohm.

Definition

Several resistors. Their resistance, in ohms, is marked using a color code.

The ohm is defined as a resistance between two points of a conductor when a constant potential difference of 1 volt, applied to these points, produces in the conductor a current of 1 ampere, the conductor not being the seat of any electromotive force.

$$\Omega = \frac{\mathrm{V}}{\mathrm{A}} = \frac{\mathrm{m}^2 \cdot \mathrm{kg}}{\mathrm{s} \cdot \mathrm{C}^2} = \frac{\mathrm{J}}{\mathrm{s} \cdot \mathrm{A}^2} = \frac{\mathrm{kg} \cdot \mathrm{m}^2}{\mathrm{s}^3 \cdot \mathrm{A}^2} = \frac{\mathrm{J} \cdot \mathrm{s}}{\mathrm{C}^2}$$

In many cases the resistance of a conductor in ohms is approximately constant within a certain range of voltages, temperatures, and other parameters; one speaks of linear resistors. In other cases resistance varies (e.g., thermistors).

Commonly used multiples and submultiples in electrical and electronic usage are the milliohm, ohm, kilohm, megohm, and gigaohm.

In alternating current circuits, electrical impedance is also measured in ohms.

Power as a function of resistance

The power dissipated by a linear resistor may be calculated from its resistance, and voltage or current. The formula is a combination of Ohm's law and Joule's laws:

$$P = V \cdot I = \frac{V^2}{R} = I^2 \cdot R$$

where **P** is the power in watts, **R** the resistance in ohms, **V** the voltage across the resistor, and **I** the current through it.

This formula is applicable to devices whose resistance varies with current.

Use of the Ω symbol in electronic documents

Care should be taken when preparing documents (including HTML documents) which make use of the symbol Ω. Some document editing software will attempt to use the symbol typeface to render the character. Where the font is not supported, a W is displayed instead (a "10 W" resistor instead of a "10 Ω" resistor, for instance). As this represents the SI unit of power, not resistance, this can lead to confusion.

Unicode encodes an ohm symbol (U+2126, Ω) distinct from Greek omega among letterlike symbols, but it is only included for backwards compatibility and the Greek uppercase omega character (U+03A9, Ω) is preferred.

Abohm

The **abohm** is the basic unit of electrical resistance in the emu-cgs system of units (emu stands for "electromagnetic units"). One abohm is equal to 10^{-9} ohms in the SI system of units; one abohm is a nanoohm.

The emu-cgs (or "electromagnetic cgs") units are one of several systems of electromagnetic units within the centimetre gram second system of units; others include esu-cgs, Gaussian units, and Lorentz-Heaviside units. In these other systems, the abohm is *not* one of the units.

When a current of one abampere (1 abA) flows through a resistance of 1 abohm, the resulting potential difference across the component is one abvolt (1 abV).

Chapter-9

Kilowatt Hour and Rydberg Constant

Kilowatt hour

Residential electricity meter located in Canada

The **kilowatt hour**, or *kilowatt-hour*, (symbol **kW·h**, **kW h** or **kWh**) is a unit of energy equal to 1000 watt hours or 3.6 megajoules. Related units are: **megawatt hour** (as 1 million W·h, symbol MW·h, **MWh**) or **milliwatt hour** (as 1/1000 W·h, symbol mW·h, **mWh**), and such. For constant power, energy in watt hours is the multiplication of power in watts and time in hours.

The kilowatt hour is most commonly known as a billing unit for energy delivered to consumers by electric utility or electric utilities.

Definition

The standard unit of energy in the International System of Units (SI) is the joule (J), equal to one watt second.

Inversely, one watt is equal to 1 J/s. One kilowatt hour is 3.6 megajoules, which is the amount of energy converted if work is done at an average rate of one thousand watts for one hour.

Examples

A heater rated at 1000 watts (1 kilowatt), operating for one hour uses one kilowatt hour (equivalent to 3.6 megajoules) of energy.

Using a 60 watt light bulb for one hour consumes 0.06 kilowatt hours of electricity. Using a 60 watt light bulb for one thousand hours consumes 60 kilowatt hours of electricity.

Symbol and abbreviation for kilowatt hour

The international standard for SI states that in a forming a compound unit symbol, "Multiplication must be indicated by a space or a half-high (centered) dot (·), since otherwise some prefixes could be misinterpreted as a unit symbol" (i.e., kW h or kW·h). This is supported by a voluntary standard issued jointly by an international (IEEE) and national (ASTM) organization. However, at least one major usage guide and the IEEE/ASTM standard allow "kWh" (but do not mention other multiples of the watt hour). One guide published by NIST specifically recommends avoiding "kWh" "to avoid possible confusion". Nonetheless, it is commonly used in commercial, educational, scientific and media publications.

Conversions

To convert a quantity measured in a unit in the left column to the units in the top row, multiply by the factor in the cell where the row and column intersect.

	joule	watt hour	electronvolt	calorie
1 J = 1 kg·m^2 s^{-2} =	1	2.77778×10^{-4}	6.241×10^{18}	0.239
1 W·h =	3600	1	2.247×10^{22}	859.8
1 eV =	1.602×10^{-19}	4.45×10^{-23}	1	3.827×10^{-20}
1 cal =	4.1868	1.163×10^{-3}	2.613×10^{19}	1

Watt hour multiples and billing units

The kilowatt hour is commonly used by electrical distribution providers for purposes of billing, since the monthly energy consumption of a typical residential customer ranges from a few hundred to a few thousand kilowatt hours. Megawatt hours, gigawatt hours, and terawatt hours are often used for metering larger amounts of electrical energy to industrial customers and in power generation.

SI multiples for watt hour (W·h)					
Submultiples			**Multiples**		
Value	**Symbol**	**Name**	**Value**	**Symbol**	**Name**
10^{-3}	mW·h	milliwatt hour	10^{3}	kW·h	kilowatt hour
10^{-6}	µW·h	microwatt hour	10^{6}	MW·h	megawatt hour
			10^{9}	GW·h	gigawatt hour
			10^{12}	TW·h	terawatt hour
			10^{15}	PW·h	petawatt hour

In India, the kilowatt hour is often simply called a *Unit* of energy. A million units, designated *MU*, is a gigawatt hour and a BU (billion units) is a terawatt hour.

Other energy-related units

Several other units are commonly used to indicate power or energy capacity or use in specific application areas.

Average annual power production or consumption can be expressed in kilowatt hours per year; for example, when comparing the energy efficiency of household appliances whose power consumption varies with time or the season of the year, or the energy produced by a distributed power source. One kilowatt hour per year equals about 114.08 milliwatts applied constantly during one year.

The energy capacity of a battery is usually expressed indirectly in ampere hours; to convert watt hours (W·h) to ampere hour (A·h), the watt hour value must be divided by the voltage of the power source. This value is approximate since the voltage is not constant during discharge of a battery.

The *Board of Trade unit* (BOTU) is an obsolete UK synonym for kilowatt hour. The term derives from the name of the Board of Trade that regulated the electricity industry. The B.O.T.U. should not be confused with the British thermal unit or BTU, which is a much smaller quantity of thermal energy. To further the confusion, at least as late as 1937, Board of Trade unit was simply abbreviated *BTU*.

Burnup of nuclear fuel is normally quoted in megawatt-days per tonne (MWd/MTU), where tonne refers to a metric ton of uranium metal or its equivalent, and megawatt refers to the entire thermal output, not the fraction which is converted to electricity.

Confusion of kilowatt hours and kilowatts per hour

The terms power and energy are frequently confused. Power is the rate at which energy is generated or consumed. Power therefore has the unit *watts*, which is *joules per second*. A unit of energy is *kilowatt hour*.

For example, when a light bulb with a power rating of 100W is turned on for one hour, the energy used is 100 watt hours (W·h), 0.1 kilowatt hour, or 360 kJ. This same amount of energy would light a 40-watt bulb for 2.5 hours, or a 50-watt bulb for 2 hours. A power station would be rated in multiples of watts, but its annual energy sales would be in multiples of watt hours. A kilowatt hour is the amount of energy equivalent to a steady power of 1 kilowatt running for 1 hour, or 3.6 MJ.

Power units measure the rate of energy per unit time. Many compound units for rates explicitly mention units of time, for example, miles per hour, kilometers per hour, dollars per hour. Kilowatt hours are a product of power and time, not a rate of change of power with time. Terms such as *watts per hour* are often misused. Watts per hour (W/h) is a unit of a *change* of power per hour. It might be used to characterize the ramp-up behavior of power plants. For example, a power plant that reaches a power output of 1 MW from 0 MW in 15 minutes has a ramp-up rate of 4 MW/h. Hydroelectric power plants have a very high ramp-up rate, which makes them particularly useful in peak load and emergency situations.

Major energy production or consumption is often expressed as terawatt hours for a given period that is often a calendar year or financial year. One terawatt hour is equal to a sustained power of approximately 114 megawatts for a period of one year.

Rydberg constant

The **Rydberg constant**, symbol R_∞, named after the Swedish physicist Johannes Rydberg, is a physical constant relating to atomic spectra in the science of spectroscopy. Rydberg initially determined its value empirically from spectroscopy, but Niels Bohr later showed that its value could be calculated from more fundamental constants by using quantum mechanics. As of 2010, it is the most accurately measured fundamental physical constant.

The Rydberg constant represents the limiting value of the highest wavenumber (the inverse wavelength) of any photon that can be emitted from the hydrogen atom, or, alternatively, the wavenumber of the lowest-energy photon capable of ionizing the hydrogen atom from its ground state. The spectrum of hydrogen can be expressed simply in terms of the Rydberg constant, using the Rydberg formula.

The **Rydberg unit of energy**, symbol Ry, is closely related to the Rydberg constant. It corresponds to the *energy* of the photon whose wavenumber is the Rydberg constant, i.e. the ionization energy of the hydrogen atom.

Value of the Rydberg constant and Rydberg unit of energy

Making use of the simplifying assumption that the mass of the atomic nucleus is infinite compared to the mass of the electron, according to the 2006 CODATA the constant is:

$$R_\infty = \frac{m_e e^4}{8\varepsilon_0^2 h^3 c} = 1.097\ 373\ 156\ 852\ 5\ (73) \times 10^7\ \mathrm{m}^{-1},$$

where m_e is the rest mass of the electron, e is the elementary charge, ε_0 is the permittivity of free space, h is the Planck constant, and c is the speed of light in a vacuum.

This constant is often used in atomic physics in the form of the Rydberg unit of energy:

$$hcR_\infty = 13.605\ 6923(12)\ \mathrm{eV} \equiv 1\ \mathrm{Ry}.$$

Two complications arise. One is that one may wish to discuss a hydrogen-like ion; that is, an atom with atomic number Z that has only one electron, such as C^{5+}. In this case, the wavenumbers and photon energies are scaled up by a factor of Z^2, neglecting relativistic effects. The other is that the mass of the atomic nucleus is not actually infinite compared to the mass of the electron. The predicted spectrum must then be corrected by substituting the reduced mass for the mass of the electron. The Rydberg constant R_M for an atom with one electron is then given by

$$R_M = \frac{R_\infty}{1 + m_e/M},$$

where m_e is the rest mass of the electron, and M is the mass of the atomic nucleus.

Measurement

The Rydberg constant is *the* most well-determined physical constant, with a relative experimental uncertainty of less than 7 parts in 10^{12}. The ability to measure it directly to such a high precision constrains the proportions of the values of the other physical constants that define it.

The Rydberg constant is inferred from measurements of atomic transition frequencies in three atoms (hydrogen, deuterium, and antiprotonic helium). These measurements are interpreted using detailed theoretical calculations in the framework of quantum electrodynamics.

Alternative expressions

The Rydberg constant can also be expressed as the following equations.

$$R_\infty = \frac{\alpha^2 m_e c}{4\pi\hbar} = \frac{\alpha^2}{2\lambda_e}$$

and

$$hcR_\infty = m_e c^2 \frac{\alpha^2}{2} = \frac{hc\alpha^2}{2\lambda_e} = \frac{hf_C\alpha^2}{2} = \frac{\hbar\omega_C}{2}\alpha^2 = \frac{\hbar^2}{2m_e a_0^2}.$$

where

h is the Planck constant
$\hbar = h/2\pi$ is the reduced Planck constant,
c is the speed of light in a vacuum,
α is the fine-structure constant,
$\lambda_e = h/m_e c$ is the Compton wavelength of the electron,
$f_C = m_e c^2/h$ is the Compton frequency of the electron,
$\omega_C = 2\pi f_C$ is the Compton angular frequency of the electron,
$a_0 = \frac{4\pi\varepsilon_0\hbar^2}{e^2 m_e}$ is the Bohr radius.

The second equation is relevant because it is the coefficient for the energy of the atomic orbitals of a hydrogen atom: $E_n = -hcR_\infty \frac{1}{n^2}$.

The derivation of Rydberg constant from quantum mechanics

Historically, the Rydberg formula was found *empirically* (experimentally), and it predated the development of quantum theory. To understand its significance in terms of the quantum theory, we can start from the equation

$$E_{\text{total}} = \frac{-m_e e^4}{8\epsilon_0^2 h^2} \cdot \frac{1}{n^2}$$

for the energy of an atom with one electron and a nucleus with a charge of +1 and an infinite mass. Of course, atomic nuclei do not have infinite masses in real life, but even the lightest nucleus, a single proton, is over 1800 times heavier than an electron, so this is reasonable as a first approximation. This energy formula can be derived either from the Bohr model or from a fully quantum-mechanical treatment of a hydrogen-like atom. Therefore the change in energy due to the electron changing from one value of *n* to another is

$$\Delta E = \frac{m_e e^4}{8\epsilon_0^2 h^2} \left(\frac{1}{n_{\text{initial}}^2} - \frac{1}{n_{\text{final}}^2} \right).$$

We simply change the units to wavenumbers $\left(\frac{1}{\lambda} = \frac{E}{hc} \rightarrow \Delta E = hc\Delta \left(\frac{1}{\lambda} \right) \right)$ and we get

$$\Delta \left(\frac{1}{\lambda} \right) = \frac{m_e e^4}{8\epsilon_0^2 h^3 c} \left(\frac{1}{n_{\text{initial}}^2} - \frac{1}{n_{\text{final}}^2} \right)$$

where

h is Planck's constant,
m_e is the rest mass of the electron,
e is the elementary charge,
c is the speed of light in vacuum, and
ϵ_0 is the permittivity of free space.
n_{initial} and n_{final} being the electron shell number of the hydrogen atom.

We have therefore found the Rydberg constant for our hypothetical system of a nucleus with infinite mass, a +1 charge, and a single electron to be

$$R_\infty = \frac{m_e e^4}{8\epsilon_0^2 h^3 c}.$$

Chapter-10

Gasoline Gallon Equivalent and Foot-pound

Gasoline gallon equivalent

Gasoline gallon equivalent (GGE) or gasoline-equivalent gallon (GEG) is the amount of alternative fuel it takes to equal the energy content of one liquid gallon of gasoline. In 1994, the U.S. National Institute of Standards and Technology or NIST defined "gasoline gallon equivalent (GGE) means 5.660 pounds of natural gas."

GGE allows consumers to compare the energy content of competing fuels against a commonly known fuel—gasoline. Compressed natural gas (CNG), for example, is a gas rather than a liquid. It can be measured by its volume in cubic feet (ft^3), by its weight in pounds (lb) or by its energy content in joules (J) or British thermal units (BTU) or kilowatt-hours (kW·h) It is difficult to compare the cost of gasoline with other fuels if they are sold in different units. GGE solves this. A GGE of CNG and a GGE of electricity all have the same energy content as one gallon of gasoline. CNG sold at filling stations is priced in dollars per GGE.

One important point that somewhat clouds the practical utility of a GGE for comparing different fuels to each other is that machines which run on them produce usable energy from different fuels at different efficiencies.

Table of GGE

Fuel	GGE	BTU/unit
Gasoline (base)	1 US gallon	114,000 BTU/gal
Gasoline (conventional, summer)	0.996 US gallon *	114,500 BTU/gal
Gasoline (conventional, winter)	1.013 US gallon *	112,500 BTU/gal
Gasoline (reformulated gasoline, ethanol)	1.019 US gallon *	111,836 BTU/gal

Gasoline (reformulated gasoline, ETBE)	1.019 US gallon *	111,811 BTU/gal
Gasoline (reformulated gasoline, MTBE)	1.020 US gallon *	111,745 BTU/gal
Gasoline (10% MBTE)	1.02 US gallon	112,000 BTU/gallon
Gasoline (regular unleaded)	1 US gallon	114,100 BTU/gal
Diesel #2	0.88 US gallons	129,500 BTU/gal
Biodiesel (B100)	0.96 US gallons	118,300 BTU/gal
Bio Diesel (B20)	0.90 US gallons	127,250 BTU/gal
Liquid natural gas (LNG)	1.52 US gallons	75,000 BTU/gal
Compressed natural gas (CNG)	126.67 cu ft (3.587 m^3)	900 BTU/cu ft
Hydrogen at 101.325 kPa	357.37 cu ft	319 BTU/cu ft
Hydrogen by weight	0.997 kg (2.198 lb)	119.9 MJ/kg (51,500 BTU/lb)
Liquefied petroleum gas(propane) (LPG)	1.35 US gallons	84,300 BTU/gal
Methanol fuel (M100)	2.01 US gallons	56,800 BTU/gal
Ethanol fuel (E100)	1.500 US gallons	76,100 BTU/gal
Ethanol (E85)	1.39 US gallons	81,800 BTU/gal
Jet fuel (naphtha)	0.97 US gallons	118,700 BTU/gal
Jet fuel (kerosene)	0.90 US gallons	128,100 BTU/gal
Electricity	33.40 kilowatt-hours *	3,413 BTU/(kW·h)

*calculated based on 114,000 BTU/gal base gasoline

Compressed natural gas

One GGE of natural gas is 126.67 cubic feet (3.587 m^3) at standard conditions. This volume of natural gas has the same energy content as one US gallon of gasoline (based on lower heating values: 900 BTU/cu ft of natural gas and 115,000 BTU/gal of gasoline).

One GGE of CNG pressurized at 2,400 psi (17 MPa) is 0.77 cubic foot (21.8 liters). This volume of CNG at 2,400 psi has the same energy content as one US gallon of gasoline (based on lower heating values: 148,144 BTU/cu ft of CNG and 115,000 BTU/gal of gasoline. Using Boyle's Law, the equivalent GGE at 3,600 psi (25 MPa) is 0.51 cubic foot (14.4 L or 3.82 actual US gal).

The National Conference of Weights & Measurements (NCWM) has developed a standard unit of measurement for compressed natural gas, defined in the NIST Handbook 44 Appendix D as follows: "1 Gasoline [US] gallon equivalent (GGE) means 2.567 kg (5.660 lb) of natural gas."

When consumers refuel their CNG vehicles in the USA, the CNG is usually measured and sold in GGE units. This is fairly helpful as a comparison to gallons of gasoline.

Ethanol

One GGE of ethanol is 1.5 gallons. This volume of ethanol has the same energy content as one US gallon of gasoline. This is because a gallon of ethanol has a lower heat value or energy content (76,100 BTU) when compared to a gallon of gasoline (114,100 BTU).

E85

Ordinary consumers driving a "flex-fuel" vehicle can expect a substantial drop in fuel mileage when using 85% ethanol products (the compression ratio is fixed mechanically, and electronic sensors can only modify the timing of the spark and allow the electronic fuel injectors to provide more of the reduced energy-content fuel).

Foot-pound

The **foot-pound force**, or simply **foot-pound** (symbol: ft-lb_f or ft-lb) is a unit of work or energy in the Engineering and Gravitational Systems in United States customary and Imperial units of measure. It is the energy transferred on applying a force of 1 pound-force (lb_f) through a displacement of 1 foot. The corresponding SI unit is the joule.

Usage

The foot-pound is often used to specify the muzzle energy of a bullet in small arms ballistics, particularly in the United States.

"Foot-pound" is sometimes also used as a unit of torque. In the United States this unit is often used to specify, for example, the tightness of a bolt or the output of an engine. Although they are dimensionally equivalent, energy (a scalar), and torque (a vector) are distinct physical quantities. Both energy and torque can be expressed as a product of a force vector with a displacement vector (hence pounds and feet); energy is the dot product of the two, and torque is the cross product.

Conversion to other units

Energy units

1 foot-pound is equivalent to:

- 1.3558179483314 joules
- 13,558,179.483314 ergs

- 0.001285067 British Thermal Units
- 0.323832 gram calories
- 0.000323832 kilogram calories or food calories

Power Units

- 1 watt ≈ 44.25372896 ft-lb_f/min
- 1 horsepower (mechanical) = 33,000 ft-lb_f/min = 550 ft-lb_f/s

Chapter-11

British Thermal Unit and Calorie

British thermal unit

The **British thermal unit** (BTU or Btu) is a traditional unit of energy equal to about 1 055.05585 joules. It is approximately the amount of energy needed to heat 1 pound (0.454 kg) of water from 39 °F (3.9 °C) to 40 °F (4.4 °C) . The unit is most often used in the power, steam generation, heating and air conditioning industries. In scientific contexts the BTU has largely been replaced by the SI unit of energy, the joule, though it may be used as a measure of agricultural energy production (BTU/kg). It is still used unofficially in metric English-speaking countries (such as Canada), and remains the standard unit of classification for air conditioning units manufactured and sold in many non-English-speaking metric countries.

In North America, the term "BTU" is used to describe the heat value (energy content) of fuels, and also to describe the power of heating and cooling systems, such as furnaces, stoves, barbecue grills, and air conditioners. When used as a unit of power, BTU *per hour* (BTU/h) is the correct unit, though this is often abbreviated to just "BTU".

The unit **MBTU** was defined as one thousand BTU, presumably from the Roman numeral system where "M" stands for one thousand (1,000). This is easily confused with the SI mega (M) prefix, which multiplies by a factor of one million (1,000,000). To avoid confusion many companies and engineers use **MMBTU** to represent one million BTU. Alternatively a *therm* is used representing 100,000 or 10^5 BTU, and a *quad* as 10^{15} BTU.

Definitions

A BTU is defined as amount of heat required to raise the temperature of one 1 pound (0.454 kg) of liquid water by 1 °F (0.556 °C) at a constant pressure of one atmosphere. As is the case with the calorie, several different definitions of the BTU exist, which are based on different water temperatures and therefore vary by up to 0.5%: A BTU can be approximated as the heat produced by burning a single wooden match or as the amount of energy it would take to lift a one-pound weight to a height of 778 feet (237 m).

Nominal temperature	BTU equivalent in joules	Notes
39 °F (3.9 °C)	≈ 1059.67	Uses the calorie value of water at its maximum density (4 °C or 39.2 °F)
Mean	≈ 1055.87	Uses a calorie averaged over water temperatures 0 to 100 °C (32 to 212 °F)
IT	≡ 1055.05585262	The most widespread BTU, uses the International [Steam] Table (IT) calorie, which was defined by the *Fifth International Conference on the Properties of Steam* (London, July 1956) to be exactly 4.1868 J
ISO	≡ 1055.056	International standard ISO 31-4 on *Quantities and units—Part 4: Heat*, Appendix A. This value uses the IT calorie and is rounded to a realistic accuracy
59 °F (15.0 °C)	≡ 1054.804	Chiefly American. Uses the 15 °C calorie, itself now defined as exactly 4.1855 J (*Comité international* 1950; PV, 1950, 22, 79–80)
60 °F (15.6 °C)	≈ 1054.68	Chiefly Canadian
63 °F (17.2 °C)	≈ 1054.6	
Thermochemical	≡ 1054.35026444	Uses the "thermochemical calorie" of exactly 4.184 J

Conversions

One BTU is approximately:

- 1.054 to 1.060 kJ (kilojoules)
- 0.293071 W·h (watt hours)
- 252 to 253 cal (calories, or "little calories")
- 0.25 kcal (kilocalories, "large calories," or "food calories")
- 25 031 to 25 160 ft·pdl (foot-poundal)
- 778 to 782 ft·lbf (foot-pounds-force)

Other conversions:

- In natural gas, by convention 1 MMBtu (1 million BTU, sometimes written "mmBTU") = 1.054615 GJ. Conversely, 1 gigajoule is equivalent to 26.8 m^3 of natural gas at defined temperature and pressure. So, 1 MMBtu = 28.263682 m^3 of natural gas at defined temperature and pressure.
- 1 standard cubic foot of natural gas yields ≈ 1030 BTU (between 1010 BTU and 1070 BTU, depending on quality, when burned)

Associated units

The BTU per hour (BTU/h) is the unit of power most commonly associated with the BTU. The term is sometimes shortened to BTU hour (BTU.h) but both have the same meaning.

- 1 watt is approximately 3.41214 BTU/h
- 1000 BTU/h is approximately 293.071 W
- 1 horsepower is approximately 2,544 BTU/h
- 1 "ton of cooling," a common unit in North American refrigeration and air conditioning applications, is 12,000 BTU/h. It is the amount of power needed to melt one short ton of ice in 24 hours, and is approximately 3.51 kW.
- 1 *therm* is defined in the United States and European Union as 100,000 BTU—but the U.S. uses the $BTU_{59\,°F}$ whilst the EU uses the BTU_{IT}.
- 1 *quad (energy)* (short for quadrillion BTU) is defined as 10^{15} BTU, which is about one exajoule (1.055×10^{18} J). Quads are used in the United States for representing the annual energy consumption of large economies: for example, the U.S. economy used 99.75 quads/year in 2005. One quad/year is about 33.43 gigawatts.

The BTU should not be confused with the Board of Trade Unit (B.O.T.U.), which is a much larger quantity of energy (1 kW·h, or about 3412 BTU).

The BTU is often used to express the conversion-efficiency of heat into electrical energy in power plants. Figures are quoted in terms of the quantity of heat in BTU required to generate 1 kWh of electrical energy. A typical coal-fired power plant works at 10,500 BTU/kWh, an efficiency of 32-33%.

Calorie

The **calorie** is a pre-SI metric unit of energy. It was first defined by Nicolas Clément in 1824 as a unit of heat, entering French and English dictionaries between 1841 and 1867. In most fields its use is archaic, having been replaced by the SI unit of energy, the joule. However, in many countries it remains in common use as a unit of food energy.

Definitions of a calorie fall into two classes:

- The **small calorie** or **gram calorie** (symbol: cal) approximates the energy needed to increase the temperature of 1 gram of water by 1 °C. This is about 4.18 joules.
- The **large calorie**, **kilogram calorie**, **dietary calorie** or **food calorie** (symbol: Cal) approximates the energy needed to increase the temperature of 1 kilogram of water by 1 °C. This is exactly 1000 small calories or about 4.18 kilojoules.

In an attempt to avoid confusion the large calorie is sometimes written as *Calorie* (with a capital *C*). This convention, however, is not always followed, and not explained to the average person clearly (and is sometimes impossible). Whether the large or small calorie is intended often must be inferred from context. When used in scientific contexts, the term *calorie* refers to the small calorie.

The gram calorie, however, is a very small a unit for use in nutritional contexts. Larger units are therefore used. The **kilocalorie** (symbol: **kcal**), being 1000 small calories, is one such unit. The large calorie, usually refered to simply as *calorie*, is also used. These are equivalent (1 kcal = 1 Cal). Therefore, in nutritional contexts the *calorie* and *kilocalorie* are the same size.

Variations

The energy needed to increase the temperature of a gram of water by 1 °C depends on the starting temperature and is difficult to measure precisely. Accordingly, there have been several definitions of the calorie. The two perhaps most popular definitions used in older literature are the 15 °C calorie and the thermochemical calorie.

The factors used to convert measurements in calories to their equivalents in joules are numerically equivalent to expressions of the specific heat capacity of water in joules per gram or kilojoules per kilogram.

Name	Symbol	Equivalent in Joules	Notes
Thermochemical calorie	cal_{th}	≡ 4.184 J	
4 °C calorie	cal_4	≈ 4.204 J	the amount of energy required to warm one gram of air-free water from 3.5 °C to 4.5 °C at standard atmospheric pressure.
15 °C calorie	cal_{15}	≈ 4.1855 J	the amount of energy required to warm one gram of air-free water from 14.5 °C to 15.5 °C at standard atmospheric pressure (101.325 kPa). Experimental values of this calorie ranged from 4.1852 J to 4.1858 J. The CIPM in 1950 published a mean experimental value of 4.1855 J, noting an uncertainty of 0.0005 J.
20 °C calorie	cal_{20}	≈ 4.182 J	the amount of energy required to warm one gram of air-free water from 19.5 °C to 20.5 °C at standard atmospheric pressure.

Mean calorie	cal_{mean}	≈ 4.190 J	$^1/_{100}$ of the amount of energy required to warm one gram of air-free water from 0 °C to 100 °C at standard atmospheric pressure.
International Steam Table calorie (1929)		≈ 4.1868 J	$^1/_{860}$ *international watt hours* = $^{180}/_{43}$ *international joules* exactly.
International Steam Table calorie (1956)	cal_{IT}	≡ 4.1868 J	1.163 mW·h = 4.1868 J exactly. This definition was adopted by the Fifth International Conference on Properties of Steam (London, July 1956).
IUNS calorie		≡ 4.182 J	This is a ratio adopted by the Committee on Nomenclature of the International Union of Nutritional Sciences.

Conversions

The conversion factor between calories and joules is numerically equivalent to the specific heat capacity of liquid water (in SI units).

One **gram** calorie is approximately:

- 4.184 J (joules)
- 0.003964 BTU (British thermal units)
- 1.163×10^{-6} kW·h (kilowatt hours)
- 2.611×10^{19} eV (electron volts)

One **kilogram** calorie (food calorie) is approximately:

- 4.184 kJ
- 3.964 BTU
- 0.001163 kW·h
- 2.611×10^{22} eV

Chapter-12

Cubic Mile of Oil

The **cubic mile of oil** (CMO) is a unit of energy. It was created by Hew Crane of SRI International to aid in public understanding of global-scale energy consumption and resources.

Significant sources of energy include oil, coal, natural gas, nuclear, hydroelectric, and biomass (primarily the burning of wood). Other energy sources include geothermal, wind, photovoltaic, and solar thermal. The various energy units commonly used to measure these sources (e.g., joules, BTUs, kilowatt hours, therms) are only somewhat familiar to the general public, and their relationships can be confusing. These common energy units are sized for everyday activities (a joule is the energy required to lift a small apple one meter vertically). For regional, national, and global scales, larger energy units, such as the exajoule, the billion barrels of oil equivalent (BBOE) and the quad are used. Derived by multiplying the small common units by large powers of ten these larger units pose additional conceptual difficulties for many citizens.

Crane intended the cubic mile of oil to provide a tangible scale for comparing the contributions of these diverse energy components as a percentage of total worldwide, energy use.

The global economy consumes approximately 30 billion barrels of oil (1.2 trillion U.S. gallons or 4.8×10^9 m^3) each year. Numbers of this magnitude are difficult to conceive by most educated people. The volume occupied by one trillion U.S. gallons is about one cubic mile. Crane felt that a cubic mile would be an easier concept for the general public than a trillion gallons.

Definition and energy equivalents

The CMO is the energy released by burning a cubic mile of oil. Conversions to other units may be calculated based on the barrel of oil equivalent (BOE), an approximation of the energy released by burning one 42-US-gallon barrel of crude oil. Since one BOE is about 5.8×10^{6} BTU and one cubic mile is about 2.62×10^{10} barrels:

1 CMO $\approx 1.6\times10^{20}$ joules

= 160 exajoules

$\approx 4.454\times10^{13}$ kilowatt-hours

= 44.54 petawatt-hours

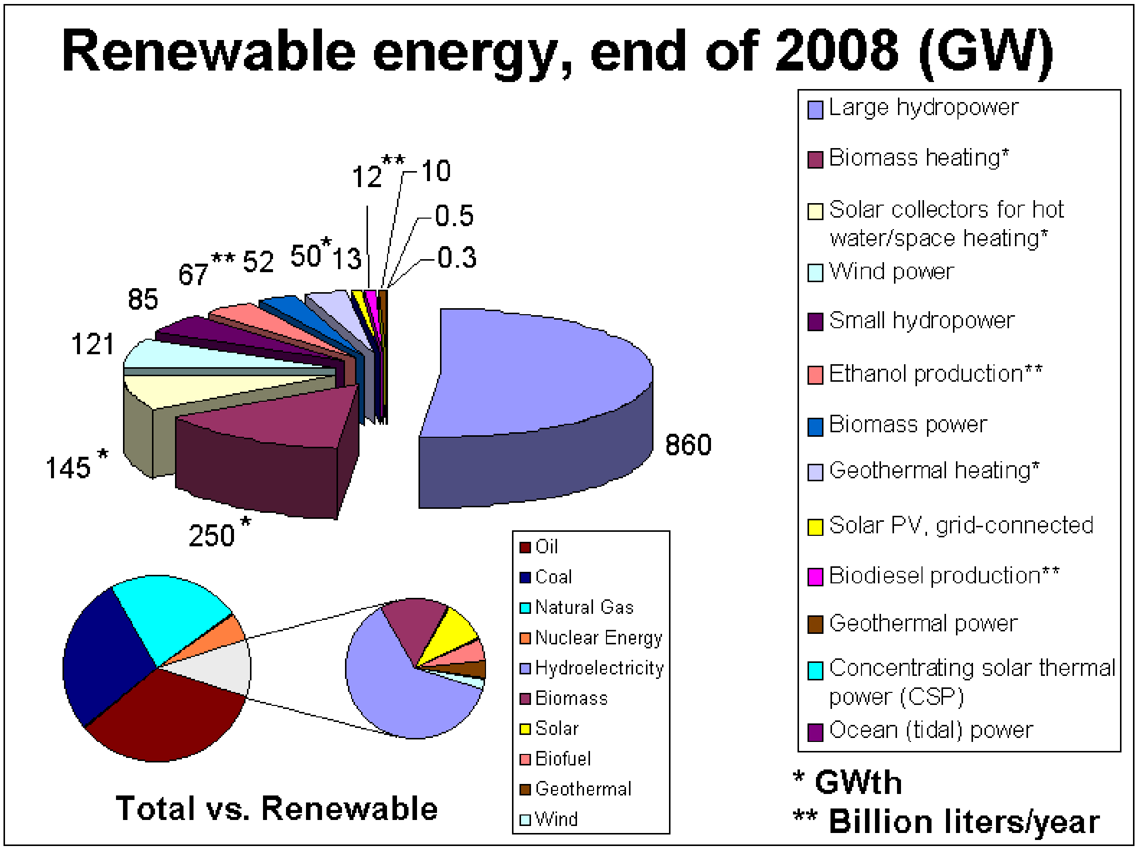
$\approx 1.52\times10^{17}$ BTU

= 152 quads

≈ 150 trillion (10^{12}) cubic feet of natural gas

$\approx 2.62\times10^{10}$ BOE

Annual energy consumption by source



2008 worldwide renewable-energy sources. *Source: REN21*

The world consumes approximately 3 CMO annually from all sources. The table emphasizes the small contribution from alternative energies in 2006.

Source	CMO/yr
Oil	1.06
Coal	0.81
Natural gas	0.61
Biomass	0.19
Nuclear	0.15
Hydroelectric	0.17
Geothermal	<0.01
Wind+Photovoltaic+Solar thermal	<0.005

Global energy reserves

Proved oil reserves are those that can be extracted with reasonable certainty under existing conditions using existing technology. Global proved oil reserves are estimated at approximately 1,300 billion barrels (210×10^9 m^3). This corresponds to roughly 43 cubic miles, or 43 CMO. At the current rate of use, this would last about 40 years. Technological advances, new discoveries, and political changes may lead to additional proved oil reserves in the future. Concurrently, the International Energy Agency predicted in its 2005 World Energy Outlook that the annual consumption will increase by 50% by 2030. Other fossil fuels provide additional reserves needed to provide the 1.42 CMO they currently supply:

- Natural gas reserves total 42 CMOs (69 years at current consumption)
- Coal reserves total 121 CMOs (150 years at current consumption)
- Tar sands and other unconventional fossil sources have unknown reserves

Replacement of oil by alternative sources

While oil has many other important uses (lubrication, plastics, roadways, roofing) this section considers only its use as an energy source.

The CMO is a powerful means of understanding the difficulty of replacing oil energy by other sources. SRI International chemist Ripudaman Malhotra, working with Crane and colleague Ed Kinderman, used it to describe the looming energy crisis in sobering terms. Malhotra illustrates the problem of replacing one cubic mile of oil with energy from five different alternative sources. Such a replacement requires long and significant development.

Allowing fifty years to develop each replacement, one cubic mile of oil could be replaced by any one of these developments:

- 4 Three Gorges Dams, developed each year for 50 years, *or*
- 52 nuclear power plants, developed each year for 50 years, *or*
- 104 coal-fired power plants, developed each year for 50 years, *or*
- 32,850 wind turbines, developed each year for 50 years, *or*
- 91,250,000 rooftop solar photovoltaic panels developed each year for 50 years

The energy produced is the power rating of the source multiplied by the duration it is operational. These comparisons take into account the variability of available power (solar panels work only during the day, turbines work only when the wind blows).

The environmental, social, and financial costs of such development projects are immense:

- The Three Gorges Dam is the world's largest, flooding 632 km^2, displacing 1.25 million people, and costing roughly US$30 billion.

- A nuclear power plant produces hazardous radioactive waste, raises fears of radiation or nuclear proliferation, requires 10 years to construct for a 40 year lifetime, occupies about 4 km^2, and may cost upwards of US$5 billion.
- A 500 MW coal-fired power plant may contribute to acid rain, global warming, and air pollution, occupies about 2 km^2, may obtain its fuel via controversial methods such as mountaintop removal, and costs about US$650 million.
- A large wind turbine requires a location with an abundance of steady wind, may be visually obtrusive, can interfere with aviation, needs about 0.16 km^2 to avoid interfering with adjacent turbines, and costs about US$2 million.
- A 2.1 kW rooftop solar array requires technical skills for installation, needs a sunny location, presents few aesthetic or environmental problems, covers about 14 m^2, but costs around US$15,000.

Alternative Replacements for one CMO

Source	Number	Cost (US$1 trillion)	Area	
			(km^2)	(sq mi)
Dams	200	6	1,264,400	488,200
Nuclear plants	2,600	13	10,400	4,000
Coal plants	5,200	3.4	10,400	4,000
Wind turbines	1,642,000	3.3	273,667	105,663
Rooftop photovoltaics	4,562,500,000	68	63,875	24,662

For comparison, US$3.2 trillion is the approximate gross domestic product of Germany, China, or the United Kingdom. The total land area of New Zealand is approximately 270,000 square kilometres (100,000 sq mi).

At a 2008 market price of US$120 per barrel (US$750/m^3), the cost of one CMO was about US$3 trillion.

Chapter-13

Electronvolt

In physics, the **electron volt** (symbol **eV**; also written **electronvolt**) is a unit of energy equal to approximately 1.602×10^{-19} J. By definition, it is equal to the amount of kinetic energy gained by a single unbound electron when it accelerates through an electric potential difference of one volt. Thus it is 1 volt (1 joule per coulomb) multiplied by the electron charge (1 e, or $1.60217653(14) \times 10^{-19}$ C). Therefore, one electron volt is equal to $1.60217653(14) \times 10^{-19}$ J. Historically, the electron volt was devised as a standard unit of measure through its usefulness in electrostatic particle accelerator sciences because a particle with charge q has an energy E=qV after passing through the potential V; if q is quoted in integer units of the elementary charge and the terminal bias in volts, one gets an energy in eV.

The electron volt is not an SI unit and its value must be obtained experimentally. It is a common unit of energy within physics, widely used in solid state, atomic, nuclear, and particle physics. It is commonly used with the SI prefixes milli-, kilo-, mega-, giga-, tera-, or peta- (meV, keV, MeV, GeV, TeV and PeV respectively). Thus meV stands for milli-electron volt.

In chemistry, it is often useful to have the molar equivalent, that is the kinetic energy that would be gained by one mole of electrons ($6.02214179(30) \times 10^{23}$) passing through a potential difference of one volt. This is equal to 96.48534(2) kJ/mol. Atomic properties like the ionization energy are often quoted in electron volts.

As a unit of energy

Conversion factors:

- 1 eV = $1.602176487(40) \times 10^{-19}$ J (the conversion factor is numerically equal to the elementary charge expressed in coulombs).
- 1 eV (per atom) is 96.485 kJ/mol.

For comparison:

- ~624 EeV (624,000,000 TeV): energy needed to power a single 100 watt light bulb for one second. (100W = 100J/s = ~6.24x10^20 eV/s).
- 300 EeV (300,000 PeV) : the so-called Oh-My-God particle (the most energetic cosmic ray particle ever observed).
- 14 TeV: the design proton collision energy at the Large Hadron Collider (which has operated at half of the energy since March 30, 2010).
- 1 TeV: A trillion electronvolts, or 1.602×10^{-7} J, about the kinetic energy of a flying mosquito.
- 210 MeV: The average energy released in fission of one Pu-239 atom.
- 200 MeV: The total energy released in nuclear fission of one U-235 atom (on average; depends on the precise break up).
- 17.6 MeV: The total energy released in the fusion of deuterium and tritium to form He-4 (also on average); this is 0.41 PJ per kilogram of product produced.
- 1 MeV: Or, 1.602×10^{-13} J, about twice the rest mass-energy of an electron.
- 13.6 eV: The energy required to ionize atomic hydrogen. Molecular bond energies are on the order of one eV per molecule.
- 1.6 to 3.4 eV: the photon energy of visible light.
- 1/40 eV: The thermal energy at room temperature. A single molecule in the air has an average kinetic energy 3/80 eV.

In some older documents, and in the name Bevatron, the symbol BeV is used, which stands for billion electron volts; it is equivalent to the GeV.

As a unit of momentum

In high-energy physics, electron-volt is often used as a unit of momentum. A potential difference of 1 Volt causes an electron to gain a discrete amount of energy (i.e., 1 eV). This gives rise to usage of eV (and keV, MeV, GeV or TeV) as units of momentum, for the energy supplied results in acceleration of the particle.

The dimensions of momentum units are $M^1 L^1 T^{-1}$. The dimensions of energy units are $M^1 L^2 T^{-2}$. Then, dividing the units of energy (such as eV) by a fundamental constant that has units of velocity ($M^0 L^1 T^{-1}$), facilitates the required conversion of using energy units to describe momentum. In the field of high-energy particle physics, the fundamental velocity unit is the speed of light c. Thus, dividing energy in eV by the speed of light in vacuum, one can describe the momentum of an electron as eV/c.

The fundamental velocity constant c can be *dropped* from the units of momentum by way of defining units of length such that the value of c is unity. For example, if the momentum p of an electron is said to be 1 GeV, then the conversion to MKS can be achieved by:

$$p = 1\ GeV/c = \frac{(1 \times 10^9) \times (1.60217646 \times 10^{-19}\ C)\ \cdot\ V}{(2.99792458 \times 10^8\ m/s)} = 5.344286{\times}10^{-19}\ kg{\cdot}m/s$$

As a unit of mass

By mass-energy equivalence, the electron volt is also a unit of mass. It is common in particle physics, where mass and energy are often interchanged, to use eV/c^2, where c is the speed of light in a vacuum (from $E = mc^2$). Even more common is to use a system of natural units with c set to 1 (hence, $E = m$), and simply use eV as a unit of mass.

For example, an electron and a positron, each with a mass of 0.511 MeV/c^2, can annihilate to yield 1.022 MeV of energy. The proton has a mass of 0.938 GeV/c^2, making a gigaelectronvolt a very convenient unit of mass for particle physics.

1 GeV/c^2 = $1.783{\times}10^{-27}$ kg

The atomic mass unit, 1 gram divided by Avogadro's number, is almost the mass of a hydrogen atom, which is mostly the mass of the proton. To convert to megaelectronvolts, use the formula:

1 amu = 931.46 MeV/c^2 = 0.93146 GeV/c^2
1 MeV/c^2 = $1.074{\times}10^{-3}$ amu

Relation to units of time and distance

In particle physics, a system of units in which the speed of light in a vacuum c and the reduced Planck constant $\hbar$ are dimensionless and equal to unity is widely used: $c = \hbar = 1$. In these units, both distances and times are expressed in inverse energy units. In particular, particle scattering lengths are often presented in units of inverse particle masses.

Outside this system of units, the conversion factors between electronvolt, second, and nanometer are the following:

$$\hbar = \frac{h}{2\pi} = 1.054\ 571\ 628(53) \times 10^{-34}\ \mathrm{J\ s} = 6.582\ 118\ 99(16) \times 10^{-16}\ \mathrm{eV\ s.}$$

The above relations also allow expressing the mean lifetime τ of an unstable particle (in seconds) in terms of its decay width Γ (in eV) via $\Gamma = \hbar/\tau$. For example, the B^0 meson has a lifetime of 1.530(9) picoseconds, mean decay length is $c\tau$ = 459.7 µm, or a decay width of 4.302±25×10−4
eV.

Conversely, the tiny meson mass mass differences responsible for meson oscillations are often expressed in the more convenient inverse picoseconds.

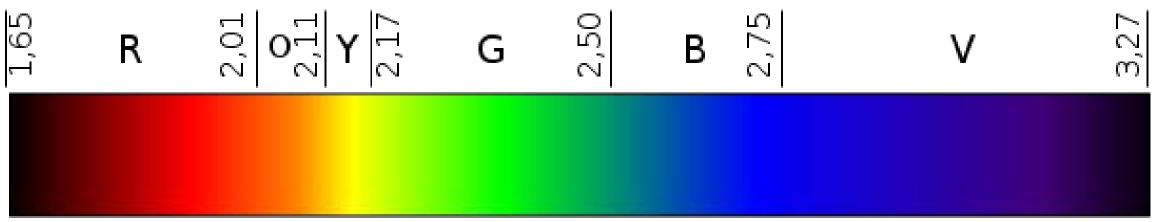
As a unit of temperature

In certain fields, such as plasma physics, it is convenient to use the electronvolt as a unit of temperature. The conversion to kelvins (symbol: uppercase K) is defined by using k_B, the Boltzmann constant:

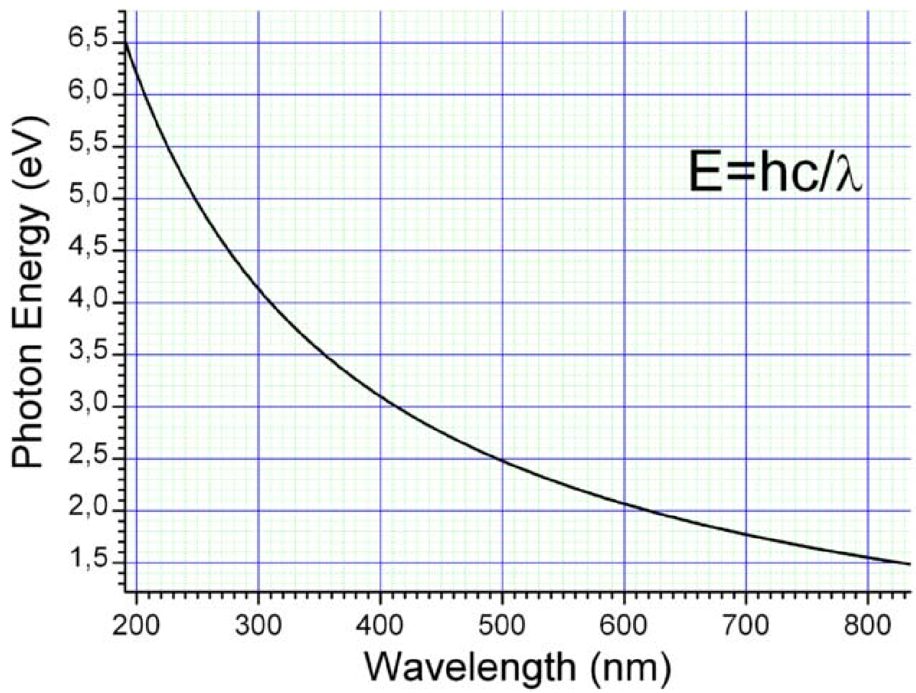
$$\frac{1\ \mathrm{eV}}{k_{\mathrm{B}}} = \frac{1.602\,176\,53(14) \times 10^{-19}\ \mathrm{J}}{1.380\,6505(24) \times 10^{-23}\ \mathrm{J/K}} = 11\,604.505(20)\ \mathrm{K}.$$

For example, a typical magnetic confinement fusion plasma is 15 keV, or 170 megakelvins.

Photon properties



Energy of photons in the visible spectrum



The energy *E*, frequency *v*, and wavelength λ of a photon are related by

$$E = h\nu = \frac{hc}{\lambda} = \frac{(4.13566733 \times 10^{-15}\,\mathrm{eV\,s})(299\,792\,458\,\mathrm{m/s})}{\lambda}$$

where *h* is Planck's constant, *c* is the speed of light. For quick calculations, this reduces to

$$E(\mathrm{eV}) \approx \frac{1240\,\mathrm{eV\,nm}}{\lambda\ (\mathrm{nm})}$$

A photon with a wavelength of 532 nm (green light) would have an energy of approximately 2.33 eV. Similarly, 1 eV would correspond to an infrared photon of wavelength 1240 nm, and so on.

In scattering experiments

In a low-energy nuclear scattering experiment, it is conventional to refer to the nuclear recoil energy in units of eVr, keVr, etc. This distinguishes the nuclear recoil energy from the "electron equivalent" recoil energy (eVee, keVee, etc.) measured by scintillation light. For example, the yield of a phototube is measured in phe/keVee (photoelectrons per keV electron-equivalent energy). The relationship between eV, eVr, and eVee depends on the medium the scattering takes place in, and must be established empirically for each material.

Chapter-14

Joule

	Joule
Unit system:	SI derived unit
Unit of...	Energy
Symbol:	J
Named after:	James Prescott Joule
Unit conversions	
1 J in...	is equal to...
SI base units	1 kg·m^2/s^2
CGS units	1×107 erg
kilocalories	2.39×10−4 kcal

The **joule (**symbol **J**) is a derived unit of energy or work in the International System of Units. It is equal to the energy expended (or work done) in applying a force of one newton through a distance of one metre (1 newton metre or N·m), or in passing an electric current of one ampere through a resistance of one ohm for one second. It is named after the English physicist James Prescott Joule (1818–1889).

In terms firstly of base SI units and then in terms of other SI units:

$$\mathrm{J} = \frac{\mathrm{kg} \cdot \mathrm{m}^2}{\mathrm{s}^2} = \mathrm{N} \cdot \mathrm{m} = \mathrm{Pa} \cdot \mathrm{m}^3 = \mathrm{W} \cdot \mathrm{s}$$

where N is the newton, m is the metre, kg is the kilogram, s is the second, Pa is the pascal, and W is the watt.

One joule can also be defined as:

- The work required to move an electric charge of one coulomb through an electrical potential difference of one volt, or one '"coulomb volt" (C·V). This relationship can be used to define the volt.
- The work required to produce one watt of power for one second, or one "watt second" (W·s) (compare kilowatt hour). This relationship can be used to define the watt.

Usage

This SI unit is named after James Prescott Joule. As with every SI unit whose name is derived from the proper name of a person, the first letter of its symbol is upper case (**J**). When an SI unit is spelled out in English, it should always begin with a lower case letter (**joule**), except where *any* word would be capitalized, such as at the beginning of a sentence or in capitalized material such as a title. Note that "degree Celsius" conforms to this rule because the "d" is lowercase.
—Based on *The International System of Units*, section 5.2.

Confusion with newton metre

It is dimensionally correct to say that 1 joule equals 1 newton metre (1 J = 1 N·m = 1 $kg \cdot m^2 \cdot s^{-2}$); however, these units are *not* interchangeable in practice. Instead, the SI authority recommends using newton metres (N·m) as the unit of torque, and joules as the unit of energy. Since torque and energy are very different, this convention is useful to help avoid misunderstandings and miscommunications.

To understand the difference, consider that the distance part of a Joule is parallel to the force, while the distance part of a N·m is perpendicular to the force. In a topological sense, these distances are not equivalent, even though they carry the same unit.

Practical examples

One joule in everyday life is approximately:

- the energy required to lift a small apple one metre straight up. (A mass of about 102 g = $\frac{1}{9.81}$ kg)
- the energy released when that same apple falls one metre to the ground.
- the energy released as heat by a person at rest, every hundredth of a second.
- the kinetic energy of a 50 kg human moving very slowly (0.2 m/s or 720 m/h).
- the kinetic energy of a tennis ball moving at 23 km/h (14 mph).

Multiples

SI multiples for joule (J)

Submultiples			Multiples		
Value	**Symbol**	**Name**	**Value**	**Symbol**	**Name**
10^{-1} J	dJ	decijoule	10^{1} J	daJ	decajoule

10^{-2} J	cJ	centijoule	10^{2} J	hJ	hectojoule
10^{-3} J	**mJ**	**millijoule**	10^{3} J	**kJ**	**kilojoule**
10^{-6} J	**µJ**	**microjoule**	10^{6} J	**MJ**	**megajoule**
10^{-9} J	**nJ**	**nanojoule**	10^{9} J	**GJ**	**gigajoule**
10^{-12} J	**pJ**	**picojoule**	10^{12} J	**TJ**	**terajoule**
10^{-15} J	fJ	femtojoule	10^{15} J	PJ	petajoule
10^{-18} J	aJ	attojoule	10^{18} J	EJ	exajoule
10^{-21} J	zJ	zeptojoule	10^{21} J	ZJ	zettajoule
10^{-24} J	yJ	yoctojoule	10^{24} J	YJ	yottajoule

Common multiples are in bold face

Nanojoule

The nanojoule (nJ) is equal to one billionth of one joule. One nanojoule is about 1/160 of the kinetic energy of a flying mosquito.

Microjoule

The microjoule (µJ) is equal to one millionth of one joule. The Large Hadron Collider (LHC) is expected to produce collisions on the order of 1 microjoule (7 TeV) per particle.

Millijoule

The millijoule (mJ) is equal to one thousandth of one joule.

Kilojoule

The kilojoule (kJ) is equal to one thousand joules. Food labels in some countries express food energy in kilojoules.

One kilojoule per second (1000 watts) is approximately the amount of solar radiation received by one square metre of the Earth in full daylight.

Megajoule

The megajoule (MJ) is equal to one million joules, or approximately the kinetic energy of a one-tonne vehicle moving at 160 km/h (100 mph).

Gigajoule

The gigajoule (GJ) is equal to one billion joules. Six gigajoules is about the amount of potential chemical energy in a barrel of oil, when combusted.

Terajoule

The terajoule (TJ) is equal to one trillion joules. About 63 terajoules were released by the atomic bomb that exploded over Hiroshima. The International Space Station, at completion, with a mass of 450,000kg and orbital velocity of 7.7 km/s, will have a kinetic energy of roughly 13 terajoules.

Exajoule

The exajoule (EJ) is equal to 10^{18} joules. The 2011 Tōhoku earthquake and tsunami in Japan had 1.41 EJ of energy according to its 9.0 on the Richter magnitude scale. Energy in the United States used per year is roughly 105 EJ.

Zettajoule

The zettajoule (ZJ) is equal to 10^{21} joules. Annual global energy consumption is approximately 0.5 ZJ

Yottajoule

The yottajoule (YJ) is equal to 10^{24} joules. This is approximately the amount of energy required to heat the entire volume of water on Earth by 1˚Celsius.

Conversions

1 joule is equal to:

- 1×10^{7} ergs (exactly)
- 6.24150974×10^{18} eV (electronvolts)
- 0.2390 cal (thermochemical gram calories or small calories)
- 2.3901×10^{-4} kcal (thermochemical kilocalories, kilogram calories, large calories or food calories)
- 9.4782×10^{-4} BTU (British thermal unit)
- 0.7376 ft·lbf (foot-pounds force)
- 23.7 ft·pdl (foot-poundals)
- 2.7778×10^{-7} kilowatt-hour
- 2.7778×10^{-4} watt-hour
- 9.8692×10^{-3} litre-atmosphere

- 1×10^{-44} foe (exactly)

Units defined exactly in terms of the joule include:

- 1 thermochemical calorie = 4.184 J
- 1 International Table calorie = 4.1868 J
- 1 watt hour = 3600 J
- 1 kilowatt hour = 3.6×10^{6} J (or 3.6 MJ)
- 1 ton TNT = 4.184 GJ

Chapter-15

Horsepower

Horsepower (**HP**) is the name of several units of measurement of power. The most common definitions equal between 735.5 and 750 watts. Horsepower was originally defined to compare the output of steam engines with the power of draft horses. The unit was widely adopted to measure the output of piston engines, turbines, electric motors, and other machinery. The definition of the unit varied between geographical regions. Most countries now use the SI unit *watt* for measurement of power. With the implementation of the EU Directive 80/181/EEC on January 1, 2010, the use of horsepower in the EU is only permitted as supplementary unit.

The definition of the horsepower also has varied between different applications:

- The *mechanical horsepower*, also known as *imperial horsepower*, of exactly 550 foot-pounds per second is approximately equivalent to 745.7 watts.
- The *metric horsepower* of 75 kgf-m per second is approximately equivalent to 735.499 watts.
- The *boiler horsepower* is used for rating steam boilers and is equivalent to 34.5 pounds of water evaporated per hour at 212 degrees Fahrenheit, or 9,809.5 watts.
- One horsepower for rating electric motors is equal to 746 watts.
- Continental European electric motors used to have dual ratings, using conversion rate 0.735 kW for 1 HP
- The *Pferdestärke* PS (German translation of horsepower) is a name for a group of similar power measurements used in Germany around the end of the 19th century, all of about one metric horsepower in size.
- The Royal Automobile Club (RAC) horsepower or British tax horsepower is an estimate based on several engine dimensions.

History of the unit

The development of the steam engine provided a reason to compare the output of horses with that of the engines that could replace them. In 1702, Thomas Savery wrote in The Miner's Friend: "So that an engine which will raise as much water as two horses, working together at one time in such a work, can do, and for which there must be constantly kept ten or twelve horses for doing the same. Then I say, such an engine may be made large enough to do the work required in employing eight, ten, fifteen, or twenty horses to be constantly maintained and kept for doing such a work…" The idea was later used by James Watt to help market his improved steam engine. He had previously agreed to take royalties of one third of the savings in coal from the older Newcomen steam engines. This royalty scheme did not work with customers who did not have existing steam engines but used horses instead. Watt determined that a horse could turn a mill wheel 144 times in an hour (or 2.4 times a minute). The wheel was 12 feet in radius; therefore, the horse travelled 2.4 × 2π × 12 feet in one minute. Watt judged that the horse could pull with a force of 180 pounds. So:

$$power = \frac{work}{time} = \frac{force \times distance}{time} = \frac{(180\ \mathrm{lbf})(2.4 \times 2\pi \times 12\ \mathrm{ft})}{1\ \mathrm{min}} = 32,572\frac{\mathrm{ft} \cdot \mathrm{lbf}}{\mathrm{min}}.$$

This was rounded to an even 33,000 ft·lbf/min.

Others recount that Watt determined that a pony could lift an average 220 lbf (0.98 kN) 100 ft (30 m) per minute over a four-hour working shift. Watt then judged a horse was 50% more powerful than a pony and thus arrived at the 33,000 ft·lbf/min figure.

Engineering in History recounts that John Smeaton initially estimated that a horse could produce 22,916 foot-pounds per minute. John Desaguliers increased that to 27,500 foot-pounds per minute. "Watt found by experiment in 1782 that a 'brewery horse' was able to produce 32,400 foot-pounds per minute." James Watt and Matthew Boulton standardized that figure at 33,000 the next year.

Most observers familiar with horses and their capabilities estimate that Watt was either a bit optimistic or intended to underpromise and overdeliver; few horses can maintain that effort for long. Regardless, comparison with a horse proved to be an enduring marketing tool.

A healthy human can produce about 1.2 hp briefly and sustain about 0.1 hp indefinitely; trained athletes can manage up to about 2.5 hp briefly and 0.3 hp for a period of several hours.

Horsepower from a horse

In 1993, R. D. Stevenson and R. J. Wassersug published an article calculating the upper limit to an animal's power output. The peak power over a few seconds has been measured to be as high as 14.9 hp. However, Stevenson and Wassersug observe that for sustained activity, a work rate of about 1 hp per horse is consistent with agricultural advice from both 19th and 20th century sources.

Current definitions

The following definitions have been widely used:

Mechanical horsepower hp(I)	≡ 33,000 ft-lb_f/min
	= 550 ft·lb_f/s
	= 745.699872 W
Metric horsepower hp(M)	≡ 75 kg_f·m/s
	≡ 735.49875 W
Electrical horsepower hp(E)	≡ 746 W
Boiler horsepower hp(S)	≡ 33,475 BTU/h
	= 9,809.5 W
Hydraulic horsepower	= flow rate (US gal/min) × pressure (psi) × 7/12,000
	or
	= flow rate (US gal/min) × pressure (psi) / 1714
	= 550 ft·lb_f/s
	= 745.699872 W

In certain situations it is necessary to distinguish between the various definitions of horsepower and thus a suffix is added: hp(I) for mechanical (or imperial) horsepower, hp(M) for metric horsepower, hp(S) for boiler (or steam) horsepower and hp(E) for electrical horsepower.

Hydraulic horsepower is equivalent to mechanical horsepower. The formula given above is for conversion to mechanical horsepower from the factors acting on a hydraulic system.

Mechanical horsepower

Assuming the third CGPM (1901, CR 70) definition of standard gravity, g_n=9.80665 m/s^2, is used to define the pound-force as well as the kilogram force, and the international avoirdupois pound (1959), one mechanical horsepower is:

1 HP	≡ 33,000 ft·lb_f/min	by definition
	= 550 ft·lb_f/s	since 1 min = 60 s
	= 550×0.3048×0.45359237 m·kg_f/s	since 1 ft = 0.3048 m and
	= 76.0402249068 kg_f·m/s	1 lb = 0.45359237 kg
	= 76.0402249068×9.80665 kg·m^2/s^3	g = 9.80665 m/s^2
	= 745.69987158227022 W	since 1 W ≡ 1 J/s = 1 N·m/s = 1 (kg·m/s^2)·(m/s)

Or given that 1 hp = 550 ft·lb_f/s, 1 ft = 0.3048 m, 1 $lb_f \approx$ 4.448 N, 1 J = 1 N·m, 1 W = 1 J/s: 1 hp = 746 W

Metric horsepower

Metric horsepower began in Germany in the 19th century and became popular across Europe and Asia. The various units used to indicate this definition (*PS*, *CV*, *hk*, *pk*, *ks* and *ch*) all translate to *horse power* in English, so it is common to see these values referred to as *horsepower* or *hp* in the press releases or media coverage of the German, French, Italian, and Japanese automobile companies. British manufacturers often intermix metric horsepower and mechanical horsepower depending on the origin of the engine in question. Sometimes the metric horsepower rating of an engine is conservative enough so that the same figure can be used for both 80/1269/EEC with metric hp and SAE J1349 with imperial hp.

Metric horsepower, as a rule, is defined as 0.73549875 kW, or roughly 98.6% of mechanical horsepower. This was a minor issue in the days when measurement systems varied widely and engines produced less power, but has become a major sticking point today. Exotic cars from Europe like the McLaren F1 and Bugatti Veyron are often quoted using the wrong definition, and their power output is sometimes even converted twice because of confusion over whether the original *horsepower* number was metric or mechanical.

PS

This unit (German: *Pferdestärke* = horse strength) is no longer a statutory unit, but is still commonly used in Europe, South America, Japan and India especially by the automotive and motorcycle industry. It was adopted throughout continental Europe with designations equivalent to the English *horsepower*, but mathematically different from the British unit.

DIN 66036 defines one horsepower to lift a mass of 75 kilograms within one second against the earth gravitation over a distance of one metre. Similar definitions were already common to the time of James Watt.

The PS was adopted by the Deutsches Institut für Normung (DIN) and then by the automotive industry throughout most of Europe, under varying names. In 1992, the PS was rendered obsolete by EEC directives, when it was replaced by the kilowatt as the official power measuring unit. It is still in use for commercial and advertising purposes, in addition to the kW rating, as many customers are still not familiar with the use of kilowatts for engines.

pk, ch, hk, hv, LE, k/ks, KS, KM, CP, PS

The Dutch *paardenkracht* (pk), the French *chevaux* (ch), the Swedish *hästkraft* (hk), the Finnish *hevosvoima* (hv), the Norwegian and Danish *hestekraft* (hk), the Hungarian *lóerő* (LE), the Czech *koňská síla* and Slovak *koňská sila* (k or ks), the Croatian and Serbian *konjska snaga* (KS), the Macedonian *Којнска сила* (KC), the Polish *koń mechaniczny* and Slovenian *konjska moč* (KM) and the Romanian *cal-putere* (CP) all equal the German *Pferdestärke* (PS), and are approximately equal to 735.5 W.

CV and cv

In Italian (*Cavalli*), Spanish (*Caballos de vapor*), and Portuguese (*Cavalo-vapor*), *CV* is the equivalent to the German, *PS*. It is also used as the French term for the Pferdestärke, but in French, this should be written in lowercase letters as *cv*.

In addition, the capital form *CV* is used in Italy and France as a unit for tax horsepower, short for, respectively, *cavalli vapore* and *chevaux vapeur* (*steam horses*). CV is a non-linear rating of a motor vehicle for tax purposes. The CV rating, or fiscal power, is $\left(\frac{P}{40}\right)^{1.6}+\frac{U}{45}$, where *P* is the maximum power in kilowatts and *U* is the amount of CO_2 emitted in grams per kilometre. The term for CO_2 measurements has only been included in the definition since 1998, so older ratings in CV are not directly comparable. The fiscal power has found its way into naming of automobile models, such as the popular Citroën deux-chevaux. The cheval-vapeur (ch) unit should not be confused with the French cheval fiscal (CV).

In the 19th century, the French had their own unit, which they used instead of the CV or horsepower. It was called the poncelet and was abbreviated *p*.

Boiler horsepower

A boiler horsepower is used for boilers in various industrial applications; however, it is considered an antiquated term and is not used in modern power plants except in North America, where it persists in industrial boiler engineering. One boiler horse power unit or BHP is equal to a boiler thermal output of 33,475 BTU/h (9.8095 kW), which is the energy rate needed to evaporate 34.5 lb (15.65 kg) of water at 212 °F (100 °C) in one hour.

The term was originally developed at the Philadelphia Centennial Exhibition in 1876, where the best steam engines of that period were tested. The average steam consumption of those engines (per output horsepower) was determined to be the evaporation of 30 lb/h of water, based on feedwater at 100 °F (38 °C), and saturated steam generated at 70 psi (480 kPa) gauge pressure. This original definition is equivalent to a boiler heat output of 33,485 BTU/h. In 1884, the ASME redefined the boiler horsepower as the thermal output equal to the evaporation of 34.5 lb/h of water "from and at" 212 °F. This considerably simplified boiler testing, and provided more accurate comparisons of the boilers at that time. This revised definition is equivalent to a boiler heat output of 33,469 BTU/hr. Present industrial practice is to define *boiler horsepower* as a boiler thermal output equal to 33,475 BTU/h, which is very close to the original and revised definitions.

The amount of power that can be obtained by a steam engine or steam turbine based on *boiler horsepower* varies so widely that use of the term is entirely obsolete for these purposes. The term makes no distinction as to the steam pressure or temperature which is produced (both of which significantly influence engine/turbine output); it merely defines a thermal output of a boiler. Smaller steam engines often require several *boiler horsepower* to make one horsepower, and modern steam turbines can make power with as little as about 0.15 hp (boiler) thermal output per actual horsepower developed.

Electrical horsepower

The horsepower used for electrical machines is defined as exactly 746 W. The nameplates on electrical motors show their power output, not their power input

Relationship with torque

For a given torque and speed, the power may be calculated; the relationship between torque in foot-pounds, rotational speed in rpm and horsepower is:

$$P/\mathrm{hp} = \frac{\tau/(\mathrm{ft{\cdot}lbf}) \times f/(\mathrm{rpm})}{5252}$$

Where *P* is power, τ is torque, and *f* is rotations per minute. The constant 5252 comes from (33,000 ft·lbf/min)/(2π rad/rev).

The standard equation relating torque in inch pounds, rotational speed in rpm and horsepower is:

$$P/\mathrm{hp} = \frac{\tau/(\mathrm{in{\cdot}lbf}) \times f/(\mathrm{rpm})}{63{,}025}$$

Where *P* is power, τ is torque, and *f* is rotations per minute. The constant 63,025 comes from (33,000 ft·lbf/min) × (12 in/ft)/(2π rad/rev).

Drawbar horsepower

Drawbar horsepower (dbhp) is the power a railway locomotive has available to haul a train or an agricultural tractor to pull an implement. This is a measured figure rather than a calculated one. A special railway car called a dynamometer car coupled behind the locomotive keeps a continuous record of the drawbar pull exerted, and the speed. From these, the power generated can be calculated. To determine the maximum power available, a controllable load is required; it is normally a second locomotive with its brakes applied, in addition to a static load.

If the drawbar force (*F*) is measured in pounds-force (lbf) and speed (*v*) is measured in miles per hour (mph), then the drawbar power (*P*) in horsepower (hp) is:

$$P/\mathrm{hp} = \frac{(F/\mathrm{lbf})(v/\mathrm{mph})}{375}$$

Example: How much power is needed to pull a drawbar load of 2,025 pounds-force at 5 miles per hour?

$$P/\mathrm{hp} = \frac{2025 \times 5}{375} = 27$$

The constant 375 is because 1 hp = 375 lbf·mph. If other units are used, the constant is different. When using a coherent system of units, such as SI (watts, newtons, and metres per second), no constant is needed, and the formula becomes $P = Fv$.

RAC horsepower (taxable horsepower)

This measure was instituted by the Royal Automobile Club in Britain and was used to denote the power of early 20th century British cars. Many cars took their names from this figure (hence the Austin Seven and Riley Nine), while others had names such as "40/50 hp", which indicated the RAC figure followed by the true measured power.

Taxable horsepower does not reflect developed horsepower; rather, it is a calculated figure based on the engine's bore size, number of cylinders, and a (now archaic) presumption of engine efficiency. As new engines were designed with ever-increasing efficiency, it was no longer a useful measure, but was kept in use by UK regulations which used the rating for tax purposes.

$$RACh.p. = D^2 * n/2.5$$

where
D is the diameter (or bore) of the cylinder in inches
n is the number of cylinders

This is equal to the displacement in cubic inches divided by 10π then divided again by the stroke in inches.

Since taxable horsepower was computed based on bore and number of cylinders, not based on actual displacement, it gave rise to engines with 'undersquare' dimensions (i.e., relatively narrow bore), but long stroke; this tended to impose an artificially low limit on rotational speed (rpm), hampering the potential power output and efficiency of the engine.

The situation persisted for several generations of four- and six-cylinder British engines: for example, Jaguar's 3.4-litre XK engine of the 1950s had six cylinders with a bore of 83 mm (3.27 in) and a stroke of 106 mm (4.17 in), where most American automakers had long since moved to oversquare (wide bore, short stroke) V-8s (see, for example, the early Chrysler Hemi).

Measurement

The power of an engine may be measured or estimated at several points in the transmission of the power from its generation to its application. A number of names are used for the power developed at various stages in this process, but none is a clear indicator of either the measurement system or definition used.

In the case of an engine dynamometer, power is measured at the engine's flywheel (i.e., at the crankshaft output). With a chassis dynamometer or *rolling road*, power output is measured at the driving wheels. This accounts for the significant power loss through the drive train.

In general:

Nominal is derived from the size of the engine and the piston speed and is only accurate at a pressure of 48 kPa (7 psi).
Indicated or gross horsepower (theoretical capability of the engine) [PLAN/ 33000]
minus frictional losses within the engine (bearing drag, rod and crankshaft windage losses, oil film drag, etc.), equals
Brake / net / crankshaft horsepower (power delivered directly to and measured at the engine's crankshaft)
minus frictional losses in the transmission (bearings, gears, oil drag, windage, etc.), equals
Shaft horsepower (power delivered to and measured at the output shaft of the transmission, when present in the system)
minus frictional losses in the universal joint/s, differential, wheel bearings, tire and chain, (if present), equals
Effective, True (thp) or commonly referred to as wheel horsepower (whp)

All the above assumes that no power inflation factors have been applied to any of the readings.

Engine designers use expressions other than horsepower to denote objective targets or performance, such as brake mean effective pressure (BMEP). This is a coefficient of theoretical brake horsepower and cylinder pressures during combustion.

Nominal horsepower

Nominal horsepower (nhp) is an early Nineteenth Century rule of thumb used to estimate the power of steam engines.

nhp = 7 x area of piston x equivalent piston speed/33,000

For paddle ships the piston speed was estimated as 129.7 x $(\text{stroke})^{1/3.35}$

For the nominal horsepower to equal the actual power it would be necessary for the mean steam pressure in the cylinder during the stroke to be 48 kPa (7 psi) and for the piston speed to be of the order of 54–75 m/min.

Indicated horsepower

Indicated horsepower (ihp) is the theoretical power of a reciprocating engine if it is completely frictionless in converting the expanding gas energy (piston pressure × displacement) in the cylinders. It is calculated from the pressures developed in the cylinders, measured by a device called an *engine indicator* – hence indicated horsepower. As the piston advances throughout its stroke, the pressure against the piston generally decreases, and the indicator device usually generates a graph of pressure vs stroke within the working cylinder. From this graph the amount of work performed during the piston stroke may be calculated. It was the figure normally used for steam engines in the 19th century but is misleading because the actual power output may only be 70% to 90% of the indicated horsepower.

Brake horsepower

Brake horsepower (bhp) is the measure of an engine's horsepower before the loss in power caused by the gearbox, alternator, differential, water pump, and other auxiliary components such as power steering pump, muffled exhaust system, etc. *Brake* refers to a device which was used to load an engine and hold it at a desired RPM. During testing, the output torque and rotational speed were measured to determine the *brake horsepower*. Horsepower was originally measured and calculated by use of the indicator (a James Watt invention of the late 18th century), and later by means of a De Prony brake connected to the engine's output shaft. More recently, an engine dynamometer is used instead of a De Prony brake. The output delivered to the driving wheels is less than that obtainable at the engine's crankshaft.

British horsepower

The abbreviation *bhp* may also be used for *British horsepower* (though the usual use is Brake Horse Power), which has the same definition as the American SAE gross brake horsepower: 33,000 lb·ft/min. More information on American SAE horsepower measurements is below.

Shaft horsepower

Shaft horsepower (shp) is the power delivered to the propeller shafts of a steamship (or one powered by diesel engines or nuclear power), or an aircraft powered by a piston engine or a gas turbine engine. This shaft horsepower can be measured with instruments, or estimated from the indicated horsepower and a standard figure for the losses in the transmission (typical figures are around 10%). This measure is uncommonly used in the automobile industry, because there, drive train losses can become significant.

Engine power test codes

Engine power test codes determine how the power and torque of an automobile engine is measured and corrected. Correction factors are used to adjust power and torque measurements to standard atmospheric conditions to provide a more accurate comparison between engines as they are affected by the pressure, humidity, and temperature of ambient air. There exist several standards for this purpose, some described below.

Society of Automotive Engineers

SAE gross power

Prior to the 1972 model year, American automakers rated and advertised their engines in brake horsepower (bhp), frequently referred to as SAE gross horsepower, because it was measured in accord with the protocols defined in SAE standards J245 and J1995. As with other brake horsepower test protocols, SAE gross hp was measured using a stock test engine, generally running with few belt-driven accessories and sometimes fitted with long tube (test headers) in lieu of the OEM exhaust manifolds. The atmospheric correction standards for barometric pressure, humidity and temperature for testing were relatively idealistic.

SAE net power

In the United States, the term *bhp* fell into disuse in 1971-72, as automakers began to quote power in terms of SAE net horsepower in accord with SAE standard J1349. Like SAE gross and other brake horsepower protocols, SAE Net hp is measured at the engine's crankshaft, and so does not account for transmission losses. However, the SAE net power testing protocol calls for standard production-type belt-driven accessories, air cleaner, emission controls, exhaust system, and other power-consuming accessories. This produces ratings in closer alignment with the power produced by the engine as it is actually configured and sold.

SAE certified power

In 2005, the SAE introduced "SAE Certified Power" with SAE J2723. This test is voluntary and is in itself not a separate engine test code but a certification of either J1349 or J1995 after which the manufacturer is allowed to advertise "Certified to SAE J1349" or "Certified to SAE J1995" depending on which test standard have been followed. To attain certification the test must follow the SAE standard in question, take place in a ISO9000/9002 certified facility and be witnessed by an SAE approved third party.

A few manufacturers such as Honda and Toyota switched to the new ratings immediately, with multi-directional results; the rated output of Cadillac's supercharged Northstar V8 jumped from 440 to 469 hp (330 to 350 kW) under the new tests, while the rating for Toyota's Camry 3.0 L *1MZ-FE* V6 fell from 210 to 190 hp (160 to 140 kW). The ES330 and Camry SE V6 were previously rated at 225 hp but the ES330 dropped to 218 hp

(163 kW) while the Camry declined to 210 hp (160 kW). The first engine certified under the new program was the 7.0 L LS7 used in the 2006 Chevrolet Corvette Z06. Certified power rose slightly from 500 to 505 hp (370 to 377 kW).

While Toyota and Honda are retesting their entire vehicle lineups, other automakers generally are retesting only those with updated powertrains. For example, the 2006 Ford Five Hundred is rated at 203 horsepower, the same as that of 2005 model. However, the 2006 rating does not reflect the new SAE testing procedure as Ford is not going to spend the extra expense of retesting its existing engines. Over time, most automakers are expected to comply with the new guidelines.

SAE tightened its horsepower rules after some engineers noticed parts of the old test could be subjected to different interpretations. Under the old testing procedures, there were small factors that required a judgment call: how much oil was in the crankcase, how the engine controls were calibrated and whether a vehicle was tested with premium fuel. In some cases, such can add up to a change in horsepower ratings. A road test editor at Edmunds.com, John Di Pietro, said decreases in horsepower ratings for some '06 models are not that dramatic. For vehicles like a midsize family sedan, it is likely that the reputation of the manufacturer will be more important.

Deutsches Institut für Normung 70020

DIN 70020 is a standard from German DIN regarding road vehicles. Because the German word for *horsepower* is ***P**ferde**s**tärke*, in Germany it is commonly abbreviated to *PS*. DIN hp is measured at the engine's output shaft, and is usually expressed in metric (Pferdestärke) rather than mechanical horsepower.

Economic Commission for Europe R24

ECE R24 is a European standard for the approval of compression ignition engine emissions, installation and measurement of engine power. It is similar to DIN 70020 standard, but with different requirements for connecting an engine's fan during testing causing it to absorb less power from the engine.

80/1269/EEC

80/1269/EEC of 16 December 1980 is a European Union standard for road vehicle engine power.

International Organization for Standardization

- ISO 14396 specifies the additional and method requirement for determinating the power of reciprocating internal combustion engines when presented for an ISO 8178 exhaust emission test. It applies to reciprocating internal combustion engines for land, rail and marine use excluding engines of motor vehicles primarily designed for road use.

- ISO 1585 is an engine net power test code intended for road vehicles.
- ISO 2534 is an engine gross power test code intended for road vehicles
- ISO 4164 is an engine net power test code intended for mopeds.
- ISO 4106 is an engine net power test code intended for motorcycles.
- ISO 9249 is an engine net power test code intended for earth moving machines.

Japanese Industrial Standard D 1001

JIS D 1001 is a Japanese net, and gross, engine power test code for automobiles or trucks having a spark ignition, diesel engine, or fuel injection engine.