

POWERTRAIN & SUSTAINABILITY (Semester 2)

Fundamental Units – AGAIN!!

Dr Owen Williams – University of Wales TSD:

A number of times during the course, I have reiterated (banged on about) UNITS. These are fundamentally important in understanding the physical quantities that we deal with everyday... but are even more important in helping to develop our understanding of concepts or quantities that we are much less familiar with.

For the next part of this module, we will be looking to develop our understanding of electrical principles... and in our normal style, we will attempt to do this from the most fundamental principles, such that we have a comprehensive understanding of the key areas and concepts needed to understand the field of electricity and magnetism.

For now, let us start with the units themselves....

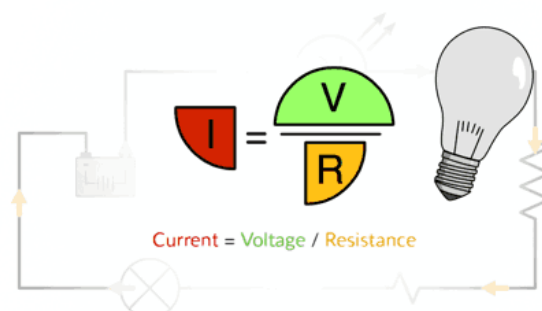
The SI system (Système International d'Unité) consists of 7 basic units. (Pre-Brexit 2020)

This rationalised system of units was adopted internationally in 1960.

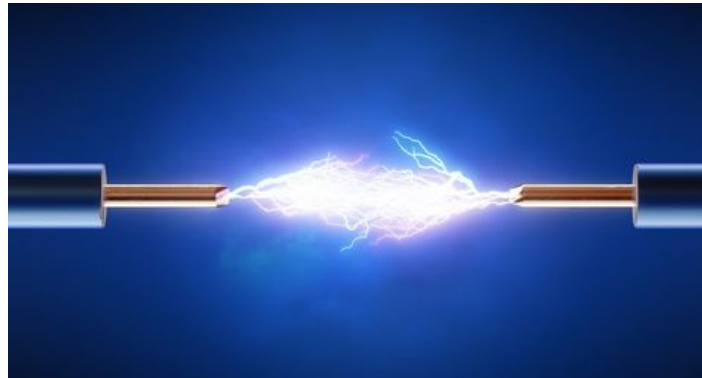
Unit	SI name	SI symbol
length	metre	m
mass	kilogramme	kg
time	second	s
electric current	Ampere	A
temperature difference	Kelvin	K
luminous intensity	candela	cd
quantity of substance	mole	mol

This may seem a little surprising, but these are the fundamental building blocks... and from these basic units, other useful derived units that we are familiar with have all been defined.

We need to think about the units we need to fully understand electricity and magnetism, and eventually the motor, electrical circuits, batteries and the hybrid or electric vehicle.



So, what about all the other units? And how do the electrical units that we know relate to the mechanical units with which we are already familiar? Is there a pattern? Are they 'the same'?



Well basically, all the electrical units we need to understand are combinations of all the things that we are already familiar with, but for the simple inclusion of the SI unit of the Ampere (A) ... So, what on earth actually is an Ampere, and how does it relate to our favourite stuff??

How complicated a question could this possibly be? An Amp??

The **ampere** or **amp** is named after André-Marie Ampère (1775–1836), French mathematician and physicist, considered the father of electrodynamics.

The International System of Units defines the ampere in terms of other base units by measuring the electromagnetic force between electrical conductors carrying electric current. The earlier CGS measurement system had two different definitions of current, one essentially the same as the SI's and the other using electric charge as the base unit, with the unit of charge defined by measuring the force between two charged metal plates.

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:

$$1A = 1 \frac{C}{s}$$

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

Constant, instantaneous and average current are expressed in amperes (as in "the charging current is 1.2 A") and the charge accumulated (or passed through a circuit) over a period of time is expressed in coulombs (as in "the battery charge is 30000 C").

The relation of the ampere (C/s) to the coulomb is the same as that of the watt (J/s) to the joule. But that can be confusing!

Out of interest, New definitions, in terms of invariant constants of nature, specifically the elementary charge, took effect on 20 May 2019.

The seven definitions we now know are rewritten below with the derived units (joule, coulomb, hertz, lumen, and watt) expressed in terms of the seven base units; second, metre, kilogram, ampere, kelvin, mole, and candela, according to the 9th SI Brochure.

- $\Delta\nu_{\text{Cs}} = \Delta\nu(^{133}\text{Cs})_{\text{hfs}} = 9192631770 \text{ s}^{-1}$
- $c = 299792458 \text{ m}\cdot\text{s}^{-1}$
- $h = 6.62607015 \times 10^{-34} \text{ kg}\cdot\text{m}^2\cdot\text{s}^{-1}$
- $e = 1.602176634 \times 10^{-19} \text{ A}\cdot\text{s}$
- $k = 1.380649 \times 10^{-23} \text{ kg}\cdot\text{m}^2\cdot\text{K}^{-1}\cdot\text{s}^{-2}$
- $N_{\text{A}} = 6.02214076 \times 10^{23} \text{ mol}^{-1}$
- $K_{\text{cd}} = 683 \text{ cd}\cdot\text{sr}\cdot\text{s}^3\cdot\text{kg}^{-1}\cdot\text{m}^{-2}$

As part of the redefinition, the international prototype kilogram was retired and definitions of the kilogram, the ampere, and the kelvin were replaced. The definition of the mole was revised. These changes have the effect of redefining the SI base units, though the definitions of the SI derived units in terms of the base units remain the same.

Implications for the Kilogram (We have discussed this before)

The definition of the kilogram changed fundamentally; the previous definition defined the kilogram as the mass of the international prototype kilogram, which is an artefact rather than a constant of nature. The new definition relates the kilogram to, amongst things, the equivalent mass of the energy of a photon given its frequency, via the Planck constant.

- Previous definition: The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.
- 2019 definition: The kilogram, symbol kg, is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant h to be $6.62607015 \times 10^{-34}$ when expressed in the unit $\text{J}\cdot\text{s}$, which is equal to $\text{kg}\cdot\text{m}^2\cdot\text{s}^{-1}$, where the metre and the second are defined in terms of c and $\Delta\nu_{\text{Cs}}$.

Implications for the Kelvin

The definition of the kelvin underwent a fundamental change. Rather than using the triple point of water to fix the temperature scale, the new definition uses the energy equivalent as given by Boltzmann's equation.

- Previous definition: The kelvin, unit of thermodynamic temperature, is $1/273.16$ of the thermodynamic temperature of the triple point of water.
- 2019 definition: The kelvin, symbol K, is the SI unit of thermodynamic temperature. It is defined by taking the fixed numerical value of the Boltzmann constant k to be 1.380649×10^{-23} when expressed in the unit $\text{J}\cdot\text{K}^{-1}$, which is equal to $\text{kg}\cdot\text{m}^2\cdot\text{s}^{-2}\cdot\text{K}^{-1}$, where the kilogram, metre and second are defined in terms of h , c and $\Delta\nu_{\text{Cs}}$.

Revisions of the definition of the Mole

The previous definition of the mole linked it to the kilogram. The revised definition breaks that link by making a mole a specific number of entities of the substance in question.

- **Previous definition:** The mole is the amount of substance of a system that contains as many elementary entities as there are atoms in 0.012 kilogram of carbon-12. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.
- **2019 definition:** The mole, symbol mol, is the SI unit of amount of substance. One mole contains exactly $6.02214076 \times 10^{23}$ elementary entities. This number is the fixed numerical value of the Avogadro constant, N_A , when expressed in the unit mol^{-1} and is called the Avogadro number. The amount of substance, symbol n , of a system is a measure of the number of specified elementary entities. An elementary entity may be an atom, a molecule, an ion, an electron, any other particle or specified group of particles.

Implications for the Ampere

The definition of the ampere underwent a major revision. The previous definition, which is difficult to realise with high precision in practice, was replaced by a definition that is more intuitive and easier to realise.

- **Previous definition:** The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 m apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per metre of length.
- **2019 definition:** The ampere, symbol A, is the SI unit of electric current. It is defined by taking the fixed numerical value of the elementary charge e to be $1.602176634 \times 10^{-19}$ when expressed in the unit C, which is equal to $\text{A} \cdot \text{s}$, where the second is defined in terms of $\Delta\nu_{\text{Cs}}$, the unperturbed ground state hyperfine transition frequency of the caesium-133 atom

Because the previous definition contains a reference to force, which has the dimensions MLT^{-2} , it follows that in the previous SI the kilogram, metre, and second – the base units representing these dimensions – had to be defined before the ampere could be defined.

A consequence of the revised definition is that the ampere no longer depends on the definitions of the kilogram and the metre; it does, however, still depend on the definition of the second. I

Confusing.... But very interesting!!

Now, back to more sensible things.... What are the other units, in terms of the 7 base units?

Unit	SI name	SI symbol	Relationship	SI basic units
frequency	hertz	Hz		s^{-1}
speed, velocity				m / s
plane angle	radian	rad		$m \times m^{-1} = 1$
angular velocity			rad / s	s^{-1}
acceleration				m / s^2
angular acceleration			rad / s^2	s^{-2}
area				m^2
volume				m^3
mass density				kg / m^3
specific volume				m^3 / kg
force	newton	N		$kg \times m \times s^{-2}$
work, energy, heat	joule	J	N x m	$kg \times m^2 \times s^{-2}$
pressure, stress	pascal	Pa	N / m^2	$kg \times m^{-1} \times s^{-2}$
power	watt	W	J / s	$kg \times m^2 \times s^{-3}$
electric potential difference, EMF	volt	V	W / A	$kg \times m^2 \times s^{-3} \times A^{-1}$
electric resistance	ohm	Ω	V / A	$kg \times m^2 \times s^{-3} \times A^{-2}$
electric conductance	siemens	S	A / V	$kg^{-1} \times m^{-2} \times s^3 \times A^2$
current density				A / m^2
electric charge	coulomb	C		$A \times s$
capacitance	farad	F	C / V	$kg^{-1} \times m^{-2} \times s^4 \times A^2$
magnetic flux	weber	Wb	V x s	$kg \times m^2 \times s^{-2} \times A^{-1}$
magnetic flux density	tesla	T	Wb / m^2	$kg \times s^{-2} \times A^{-1}$
magnetic field strength				A / m
inductance	henry	H	Wb / A	$kg \times m^2 \times s^{-2} \times A^{-2}$
Celsius temperature	degree Celsius	$^{\circ}C$		K

Fun Questions about Electricity

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How fast does electricity flow?

The electromagnetic wave rippling through the electrons propagates at close to the speed of light. The dimensions of the wire and electrical properties like its inductance affect the exact propagation speed, but usually it will be around 90 per cent of the speed of light – about 270,000 km/s.

How fast do electrons travel when moving as an electrical current through copper wire?

The actual velocity of electrons through a conductor is measured as an average speed called drift velocity. This is because individual electrons do not continue through the conductor in straight line paths, but instead they move in a random zig-zag motion, changing directions as they collide with atoms in the conductor. Thus, the actual drift velocity of these electrons through the conductor is very small in the direction of current.

For example, the drift speed through a copper wire of cross-sectional area $3.00 \times 10^{-6} \text{ m}^2$, with a current of 10 A will be approximately $2.5 \times 10^{-4} \text{ m/s}$ or about a quarter of a millimetre per second.

Generally, we say ‘about a mm per second’ ..

So how does an electrical device turn on near instantaneously? If you think of a copper wire as a pipe completely filled with marbles, then forcing one in one end will result in one at the other end being pushed out very quickly. This is analogous to initiating an electric field in a conductor.

How exactly does electricity kill you?

At low currents, AC electricity can disrupt the nerve signals from the natural pacemaker in your heart and cause fibrillation. This is a rapid fluttering vibration, too weak to pump blood. If the rhythm isn’t restarted with a defibrillator, it’s usually fatal. At higher currents, DC electricity can have the same effect by causing the entire heart muscle to contract at once, which also breaks the pacemaker rhythm.

The highest currents (more than one amp) cause burns through resistive heating as the current passes through the body. If this path crosses the heart or brain, then the burn may be fatal.

How much voltage do certain things produce?

Spark Plug? Electric eel? Lightning Strike?

Voltage

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In SI units, work per unit charge is expressed as joules per coulomb, where 1 volt = 1 joule (of work) per 1 coulomb (of charge).

The official SI definition for volt uses power and current, where 1 volt = 1 watt (of power) per 1 ampere (of current).

This definition is equivalent to the more commonly used 'joules per coulomb'.

One volt is defined as the difference in electric potential between two points of a conducting wire when an electric current of one ampere dissipates one watt of power between those points.

It is also equal to the potential difference between two parallel, infinite planes spaced one meter apart that create an electric field of one newton per coulomb.

Additionally, it is the potential difference between two points that will impart one joule of energy per coulomb of charge that passes through it.

It can be expressed in terms of SI base units (m, kg, s, and A) as:

$$V = \frac{\text{Potential Energy}}{\text{Charge}} = \frac{J}{C} = \frac{kg \cdot m^2}{A \cdot s^3}$$

It can also be expressed as amperes times ohms (current times resistance, Ohm's law), webers per second (magnetic flux per time), watts per ampere (power per unit current, definition of electric power), or joules per coulomb (energy per unit charge), which is also equivalent to electronvolts per elementary charge:

$$V = A \cdot \Omega = \frac{Wb}{s} = \frac{W}{A} = \frac{J}{C} = \frac{eV}{e}$$

But let's stick with....

$$\text{Volts} = \frac{\text{Joules}}{\text{Coulomb}} = \frac{\text{Watts}}{\text{Amp}}$$

From this, it is obvious to see the relationship between Power, Voltage and Current

$$\text{Power} = \text{Voltage} \times \text{Current}$$

For example, our trusty kettle....

$$\begin{aligned}\text{Power} &= 240V \times 13A \\ \text{Power} &= 3120W = 3.12kW\end{aligned}$$

So, what actually is a coulomb??

The coulomb (symbol: C) is the International System of Units (SI) unit of electric charge. It is the charge (symbol: Q or q) transported by a constant current of one ampere in one second:

$$1C = 1A \times 1s$$

Under the 2019 redefinition of the SI base units, which took effect on 20 May 2019, the elementary charge (the charge of the proton) is exactly $1.602176634 \times 10^{-19}$ coulombs.

Thus the coulomb is exactly the charge of $1/(1.602176634 \times 10^{-19})$ protons, which is approximately $6.2415090744 \times 10^{18}$ protons (1.036×10^{-5} mol).

The same number of electrons has the same magnitude but opposite sign of charge, that is, a charge of -1 C.

And an Amp when it's at home??

Wait, we did that already.... Watch a video....

Voltage – <https://youtu.be/z8qfhFXjsrw>

Current - <https://youtu.be/kYwNj9uauJ4>

So, the important concepts we need to remember are really...

$$\text{Volts} = \frac{\text{Potential Energy}}{\text{Charge}} = \frac{J}{C} = \frac{kg \cdot m^2}{A \cdot s^3}$$

$$\text{Amps} = \frac{\text{Charge}}{\text{Second}} = \frac{C}{s} = \frac{A \cdot s}{s}$$

$$\text{Electrical Power} = \text{Voltage} \cdot \text{Current}$$

$$\text{Electrical Power} = \frac{\text{Energy}}{\text{Charge}} \cdot \frac{\text{Charge}}{\text{Second}} = \frac{J}{s} = \text{Watts}$$

Some Examples:

Team MCR Kettle



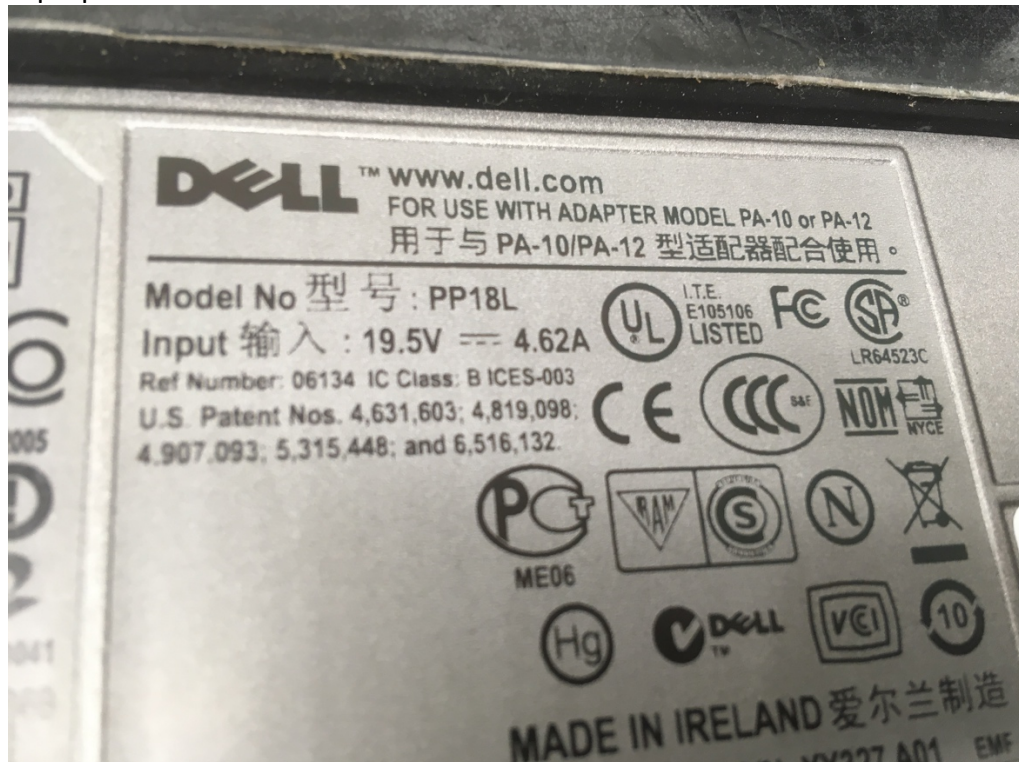
How many Amps?

Shitty Dell Desktop Computer



How many Amps?

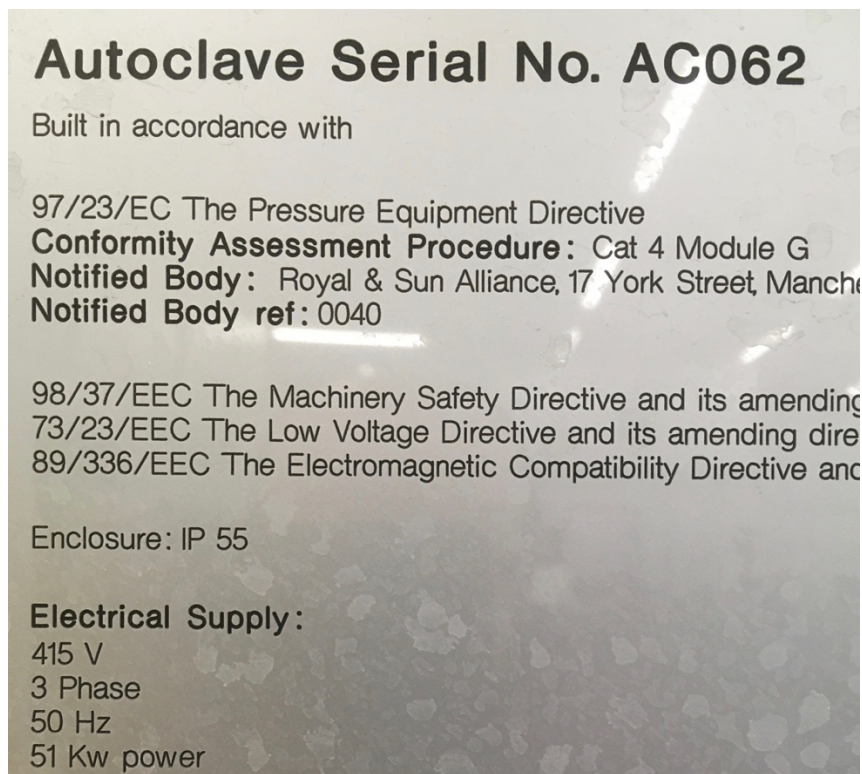
Laptop



How much power could it use?

If it was 240V with the same Current?

The Yellow Submarine



What Fuse does it need??

Lemons ??



How much 'Electricity' do you get from a Lemon?

*The average **lemon** output is 0.9 volts at 0.00024 **amps** — or about 0.000216 watt.*

0.2 mA and 0.2mW

Making a battery out of a lemon has been a popular school science experiment for decades, in part because it doesn't take an inordinate amount of effort. Simply adding copper and zinc will let the lemon juice act as an electrolyte and set off an electrochemical reaction that can power small objects like a clock. But if one lemon can do that, then how much power can 1,000 lemons provide?



Former NASA engineer Mark Rober recently explored that question when he was tasked to find a way to power Volkswagen's I.D. R, a fully-electric racing car. While making the attempt, Rober and his collaborators created the world's largest lemon battery.



Rober partnered with electrical engineer and fellow YouTube host William Osman, as they assembled the record-breaking lemon battery. And while the battery was an impressive creation, its output was less so. Even the combined power of 1,000 lemons could only offer a minuscule charge for the race car. Basically, there's no way that this particular battery could ever meet that challenge.

This realistically gives about 0.2KW.. before resistive losses!!

<https://youtu.be/a1D-fZP8qJk>