Imperial College London

Topic 2

Current, Voltage and Power

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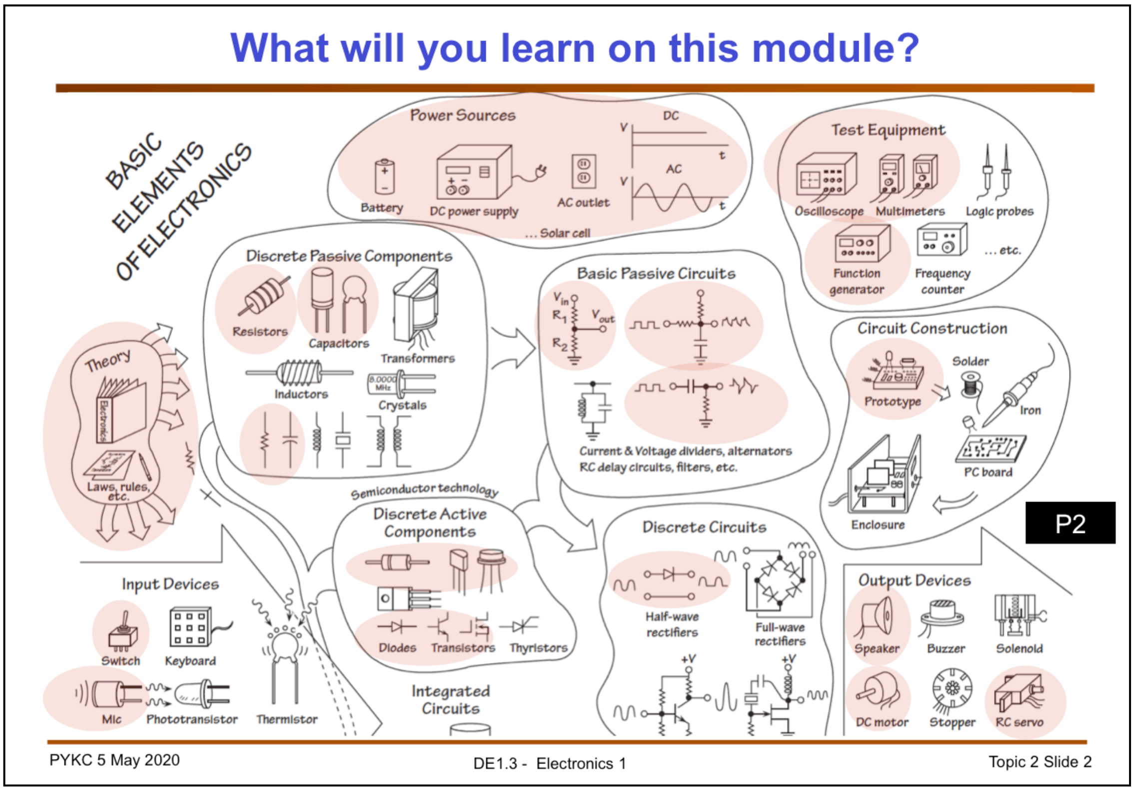
Let us kick off this module by considering three basic quantifies in electronics: current, voltage and power.



First, let us take an overview of the subject. Shown in pink are elements in electronics that will be covered in this module.

Electronics is based on some **fundamental theories**. Circuits obeys laws. As a result, we can calculate and predict behaviour of electronic circuits quite precisely.

For electronics to work, we need some form of **energy source** such as a battery, a power supply, and main supply (110V in N. America and 220/240V in the rest of the world).

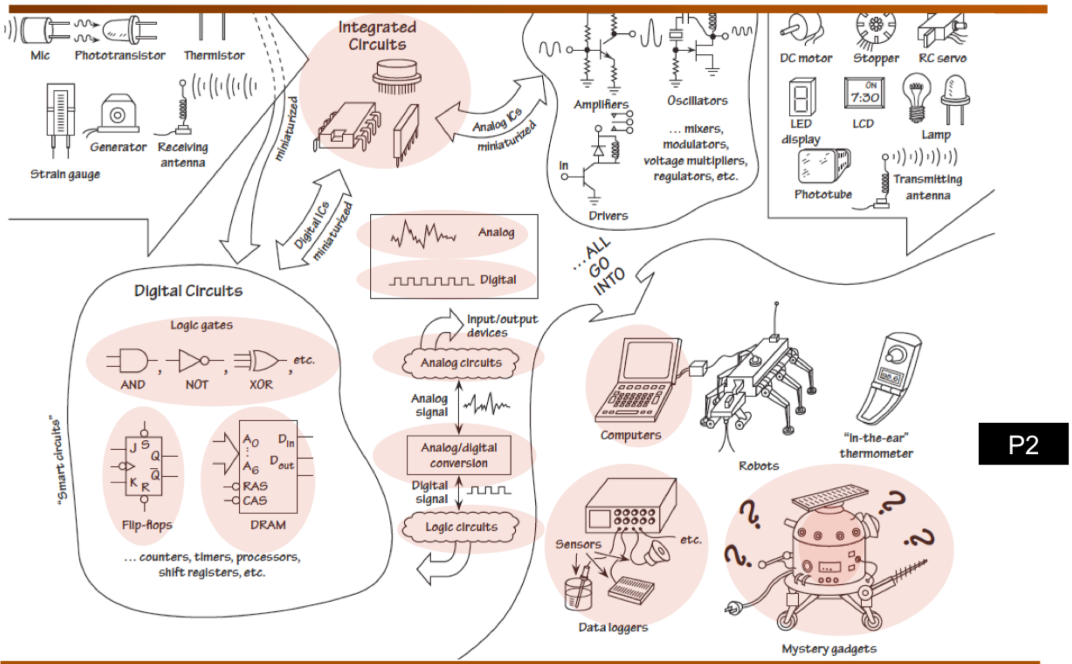
However, electronics on a whole is invisible to the naked eyes. When have you ever seen an electron in real life? Therefore, we need **test equipment** to measure and observe electrical currents and voltages.

Electronic **circuits** are built around **components**. **Passive components** are those that work without any energy source. Examples are resistors and capacitors. These components connected together to form circuits that behave in a certain way.

Another type of component are more sophisticated and need to be connected to sources for them to work. Examples are transistors and diodes. These are called **active components**.

We build circuits usually as a **prototype** on breadboard (what you will be using), then make PCBs and an entire system.

What will you learn on this module?



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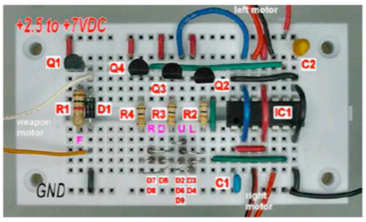
Electronic circuit may be miniaturized into integrated circuits such as microprocessors or amplifier chips.

Electronic circuits takes in external input signals through transducers, and they produce output to affect its surroundings, such as motors, lights and displays.

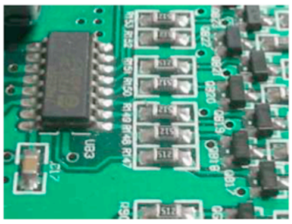
There are two types of electronic circuits: analogue and digital. Analogue circuits allow us to interact with the real physical world. Digital circuits is now the dominant type, and they make computers and provide "intelligence" and power of autonomy to machines. As a result, electronics allows us to design and build clever gadgets.

What are electrical circuits?

- A ***circuit*** consists of electrical or electronic components interconnected with metal wires.
- Every electrical or electronic device is a circuit.



Breadboard



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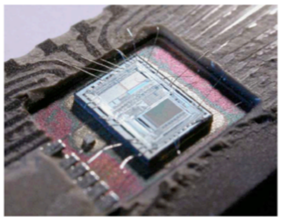


Integrated

- The function of the circuit is determined by which components are used and how they are interconnected: the physical positioning of the components usually has hardly any effect.

P1-3

This course is about electronics circuits and how to use them. In this course, you will be building some simple electronic circuits using prototyping board known as a **breadboard** (shown on the left). This is how we normally try out some simple circuits to see if they work. Eventually, we put all components on a printed circuit board (PCB). Most electronics systems come in this form. You are not going to build any PCB on this course, but you will be using an ARM microcontroller on such a board later.

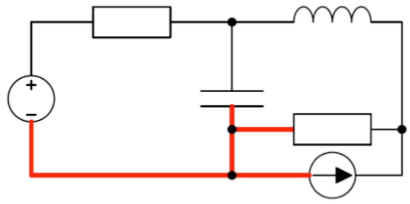
Finally, most electronics circuits are also integrated inside a chip. In fact is amazing how much you will find included in a single chip package nowadays.

Note that I also put the relevant page numbers in the textbook on the bottom right corner where appropriate. This is meant to help you to read up on the topic if you found that my notes are not sufficient.

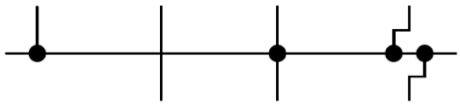
Circuit Diagrams

A ***circuit diagram*** shows the way in which the components are connected.

- Each component has a special symbol
- The interconnecting wires are shown as lines



A ***node*** in a circuit is all the points that are connected together via the interconnecting wires. One of the four nodes in the diagram is coloured red. Assumption: Interconnecting wires have zero resistance so everywhere along a node has the same voltage.



Indicate three meeting wires with a • and crossovers without one.

Avoid having four meeting wires in case the • disappears; stagger the wires instead.

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We often represent electronic circuits in the form of circuit schematic in a diagram form. Here is a circuit with components connected together. The lines connecting the components together are called “Nodes”. In this circuit, we have four nodes. The one shown in red is quite large, but we assume that no matter where you are on this red node, you will have the same electrical voltage. In other words, the wires associated with this node is assumed to have zero resistance.

You should be careful with nodes that are complex and could be connected together in different ways.

Electrical charge

- ***Charge*** is an electrical property possessed by some atomic particles.
- Charge is measured in Coulombs (abbreviated C).
- An electron has a charge -1.6×10^{-19}C, a proton $+1.6 \times 10^{-19}$C.
- Unlike charges attract; like charges repel.
- The force is fantastically huge:

Two people 384,000 km apart
Each with 1% extra electrons
Force = 2×10^{-8} N
= 360, 000 × their weight

- Consequence: Charge never accumulates in a conductor: everywhere in a conducting path stays electrically neutral at all times.

P5-6

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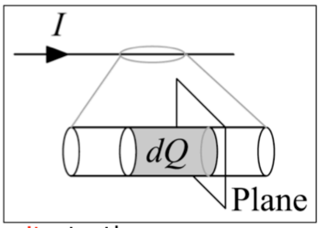
The foundation of electronics is of course the electrons you found inside atoms. Each electron has electrical charge, which is measured in Coulombs (C). An electron's charge is negative, and is measured as -1.6 x 10^{-19} C, which is pretty small. This is balanced out by the proton in the atom, which has a positive charge of +16 x 10^{-19} C.

Charge particles with same sign repel each other; those with different signs attract each other. The force exerted by charge is amazingly large. Two people, one on the month and one on earth, each somehow acquires 1% extra electrons would exert a force of 360,000 times their weight! This can be calculated.

The key take away message here is that due to this force between electrons, charge particulars never accumulates in a conductor.

Electrical Current

- ***Current*** is the flow of charged particles past a measurement boundary.
- Using an ammeter, we measure current in Ampères (usually abbreviated to Amps or A): 1 A = 1 C/s.
- Analogy: the flow of water in a pipe or river is measured in litres per second.
- The arrow in a circuit diagram indicates the direction we choose to measure the current:



> I = +1 A ⇒ 1 C of +ve charge passes each point every second in the direction of the arrow (or else 1 C of −ve charge in the opposite direction)

$I = -1$ A ⇒ 1 C of +ve charge in the direction opposite to the arrow.

- Average electron velocity is surprisingly slow (e.g. 1 mm/s) but (like a water pipe) the signal travels much faster.
- In metals the charge carriers (electrons) are actually −ve: in this course you should ignore this always.

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Electrical circuits would not be doing anything useful unless current flows in them. Electrical current is the flow of charge (electrons) as measure at a certain cross section. This is really similar to water molecules flowing through a pipe.

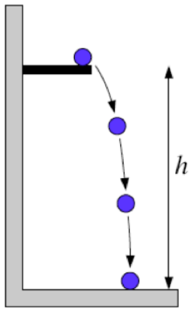
Current is measured in Amperes, or A. We always use an arrow to denote the direction of the flow of positive charge. One Ampere (1A) is the flow of 1 Coulomb of positive charge flowing passing through the cross section every second. The direction of the arrow is not important. If you get it wrong, then the current (positive charge) flow is -1A, which indicates that it is in the oppose direction.

One interesting fact: while electrical SIGNAL travels at, say, 50% of speed of light (depending on many factors such as whether is it through air or conductor cable or optical fibre), electrons travel very slowly (around 1mm/s). Why? Have a discussion among yourselves.

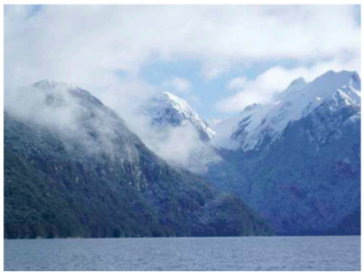
In reality, what actually flows in metal are negative charge, i.e. electrons. Therefore current is flow is always negative. But we will ignore this throughout our course – we only consider positive charge flowing.

Potential Energy

- When a ball falls from a shelf, it loses ***potential energy*** of mg or, equivalently, gh per kg.
- The potential energy per kg of any point on a mountain range is equal to gh where h is measured relative to an equipotential reference surface (e.g. the surface of a lake).



> The potential energy difference between any two points is the energy needed to move 1 kg from one point to the other.
>
> The potential energy difference **does not depend on the route** taken between the points.
>
> The potential energy difference **does not depend on your choice of reference** surface (e.g. lake surface or sea level).



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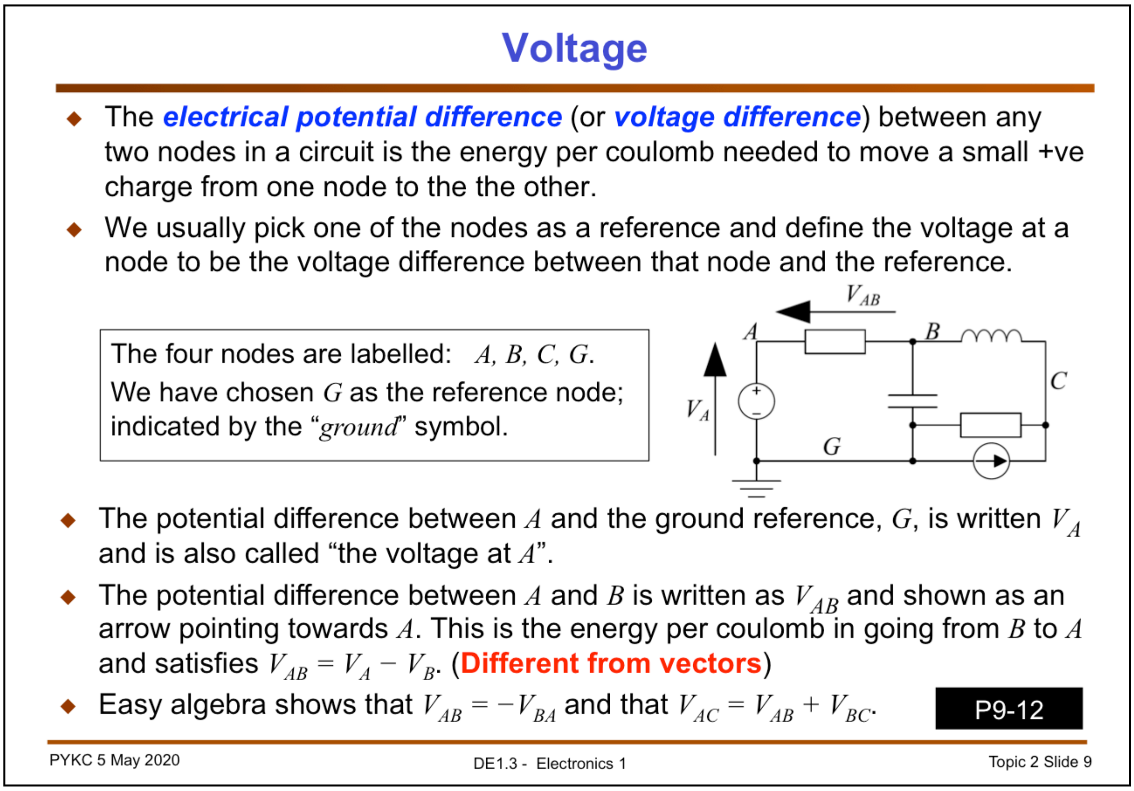
You are all familiar with gravity which relates to potential energy of objects. The lost of potential energy of an object of mass m, dropping a distance of h, is *mgh*.

The key takeaway points here are:

1. The difference in potential energy due to gravity does **NOT** depend on the **route taken between two points**.

2. The potential energy difference is independent of the **reference point** (i.e. you can take the sea level as the reference or the bottom of the hill as a reference).



Voltage is the electrical **potential difference** between any two nodes in a circuit. It is the energy required to move 1 Coulomb of positive change charge between the two nodes.

In the circuit shown here, we pick node G as the reference . We normally call this the "ground" node, and it is associated with the special symbol shown. Node G is the node that is "common" (i.e. shared) by most components. It is usually the best node to be used as the reference node. However, just like gravitational potential energy, YOU CAN USE ANY NODE AS A REFERENCE NODE. It would make no difference to any calculations, except that the calculations may be more complex as a result. The answers to any analysis would remain the same.

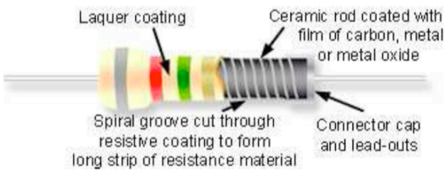
The voltage at node A is V_A, and it is assumed to be relative to the ground node G. We call this "the voltage at A".

The potential difference between A and B (with B being the reference) is V_{AB}.

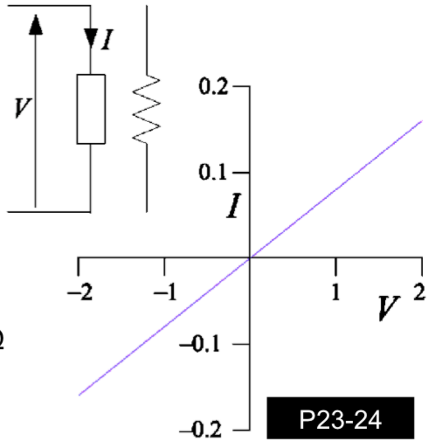
The arrow always points away from the reference node.

Resistors – the link between current and voltage

- A ***resistor*** is made from a thin strip of metal film deposited onto an insulating ceramic base.



- The ***characteristic*** of a component is a graph showing how the voltage and current are related. We always choose the current and voltage arrows in opposite directions.
- For a resistor, $I \propto V$ and $\frac{V}{I} = R$ its ***resistance*** which is measured in Ohms (Ω). **This is Ohm's Law**. Sometimes it is more convenient to work in terms of the ***conductance***, $G = \frac{1}{R} = \frac{I}{V}$ measured in Siemens (S).
- The graph shows the characteristic of a 12.5 Ω resistor. The gradient of the graph equals the conductance $G = 80$ mS. Alternative zigzag symbol.



The most basic component in electronics is the resistor. Its value, the resistance R provides the simple relationship between voltage and current through Ohm's law.

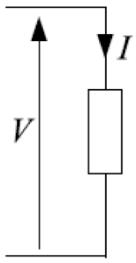
There are many types of resistors, mostly dependent on the specification required. The cheapest and most common type of resistor is made of a thin strip of metalic film on a ceramic substrate. Some resistors are made from a resistive wire wound round the substrate. These are more expensive and usually of a higher accuracy.

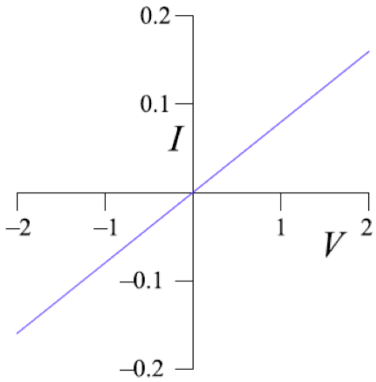
All of you should have come across Ohm's Law in physics at high school. R = V/I. Electrical engineers sometimes use the reciprocal of resistance G = 1/R, which is called the conductance (measured in Siemens S).

Note that the voltage across a resistor and the current flowing through the resistor is in the positive direction. In our convention, we assume that current flows from the more positive node to the more negative node.

Cause and Effect

Ohm's law relates the voltage drop across a resistor to the current flowing in it.





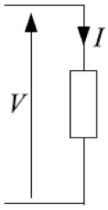
- If the voltage, V , is fixed elsewhere in the circuit, it is convenient to think that V ***causes*** the current I to flow.
- If the current, I, is fixed elsewhere in the circuit, it is more convenient to think that V is ***caused by*** the current I flowing through the resistor.
- Neither statement is "more true" than the other. It is perhaps truer to say that I and V are ***constrained to satisfy*** $V = I \times R$.

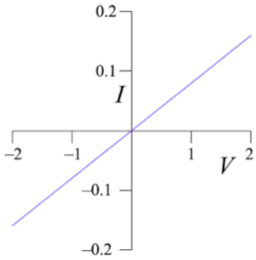
Resistor is said to be a "linear" component, because the current vs voltage characteristic is a linear function (i.e. straight line). The gradient of the line is the conductance.

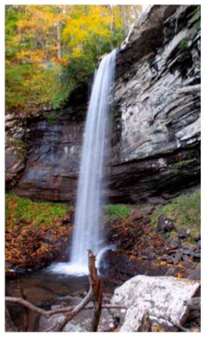
Resistor Power Dissipation

- Gravitational potential energy, mgh, lost by a falling object is transformed into kinetic energy or heat.

> Current in a resistor always flows from a high voltage (more positive) to a low voltage (more negative).







- When current flows through a resistor, the electrical potential energy that is lost is transformed into heat.
- The power dissipated as heat in a resistor is equal to $V \times I$ Watts (W). 1 Watt equals one Joule of energy per second. Since V and I always have the same sign (see graph) the **power dissipation is always positive**.
- **Any component**: P = V I gives the power absorbed by any component.
- **For a resistor only** $\frac{V}{I} = R \quad \Rightarrow \quad P = VI = \frac{V^2}{R} = I^2 R.$

P31-33

Whenever current flows through a resistor, energy is dissipated as heat. This is analogous to falling by a distance and converting the lost potential energy into kinetic energy.

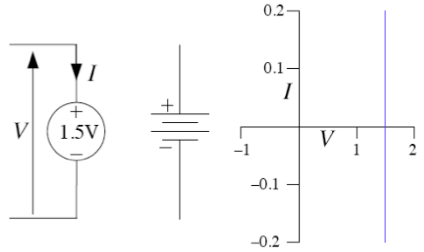
The power dissipated in a resistor is V x I and this is measure in watt. Which is one Joule of energy per second. (Power = Energy/time)

Power is always positive. (Otherwise, we will be generating and not dissipating energy.)

Voltage and Current Sources

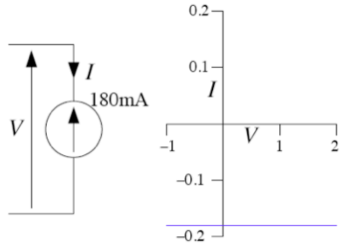
- Energy in an electrical circuit is supplied by voltage and current sources

An ***ideal voltage source*** maintains the same value of V for all currents. Its characteristic is a vertical line with infinite gradient. There are two common symbols:



An ***ideal current source*** maintains the same value of I for all voltages. Its characteristic is a horizontal line with zero gradient.

Notice that I is negative.



- If the source is ***supplying*** electrical energy to a circuit, then $VI < 0$.
- However, when a rechargeable battery is charging, $VI > 0$.

P31-33

There are two other common components: 1) an ideal voltage source that has a constant voltage value no matter how much current are flowing from it; 2) an ideal current source that can provide the fixed amount of current no matter what the voltage is across the source.

A battery approximates the characteristics of an ideal voltage source, although in reality it is far from ideal. We will be using batteries a lot on our course.

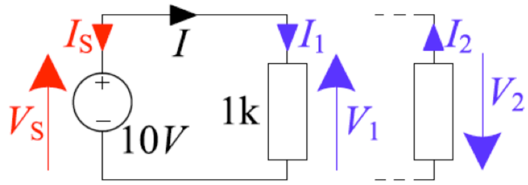
We won't be using current source in our practical work, but you will be using them in analysis of electronic circuits.

Note the direction of current flow. In a battery acting as a source, current is flowing OUT from the battery. Therefore I is negative. Therefore a battery supplying current I at a voltage V is providing power V x I, and the power is negative.

When you charge a battery, current is flowing into the voltage source and power is positive.

Power Conservation

- In any circuit some circuit elements will be supplying energy and others absorbing it. At all times, the power absorbed by all the elements will sum to zero.



- The circuit has two nodes whose potential difference is 10 V.
- Ohm's Law: $I = \frac{V}{R} = 0.01 \text{ A}$
- **Power absorbed by resistor**:

$$P_R = V_1 \times I_1 = (+10) \times (+0.01) = +0.1 \text{ W}$$

  - For Ohm's law or power dissipation, V and I can be measured either way round but must be in opposite directions.

$$P_R = V_2 \times I_2 = (-10) \times (-0.01) = +0.1 \text{ W}$$

- **Power absorbed by voltage source**:

$$P_S = V_S \times I_S = (+10) \times (-0.01) = -0.1 \text{ W}$$

- **Total power absorbed by circuit elements**:

$$P_S + P_R = 0$$

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The law of conservation of energy (hence power) applies in electronic circuits. Consider the simple circuit above. Power absorbed by the 1k resistor connected to a 10v battery is 0.1W. If you reverse the voltage (V_2) the current (I_2) must flow from high voltage to low voltage, and therefore is reversed (i.e. pointing up). Using this second convention, the power is still 0.1W.

Power absorbed by the 10v battery (source) is -0.1W because the current I_S is flowing in the opposite direction and is therefore negative.

Total power in the circuit is 0.

Summary

- Circuits and Nodes
- Charge, Current and Voltage
- Resistors, Voltage Source and Current Sources
- Power Dissipation and Power Conservation