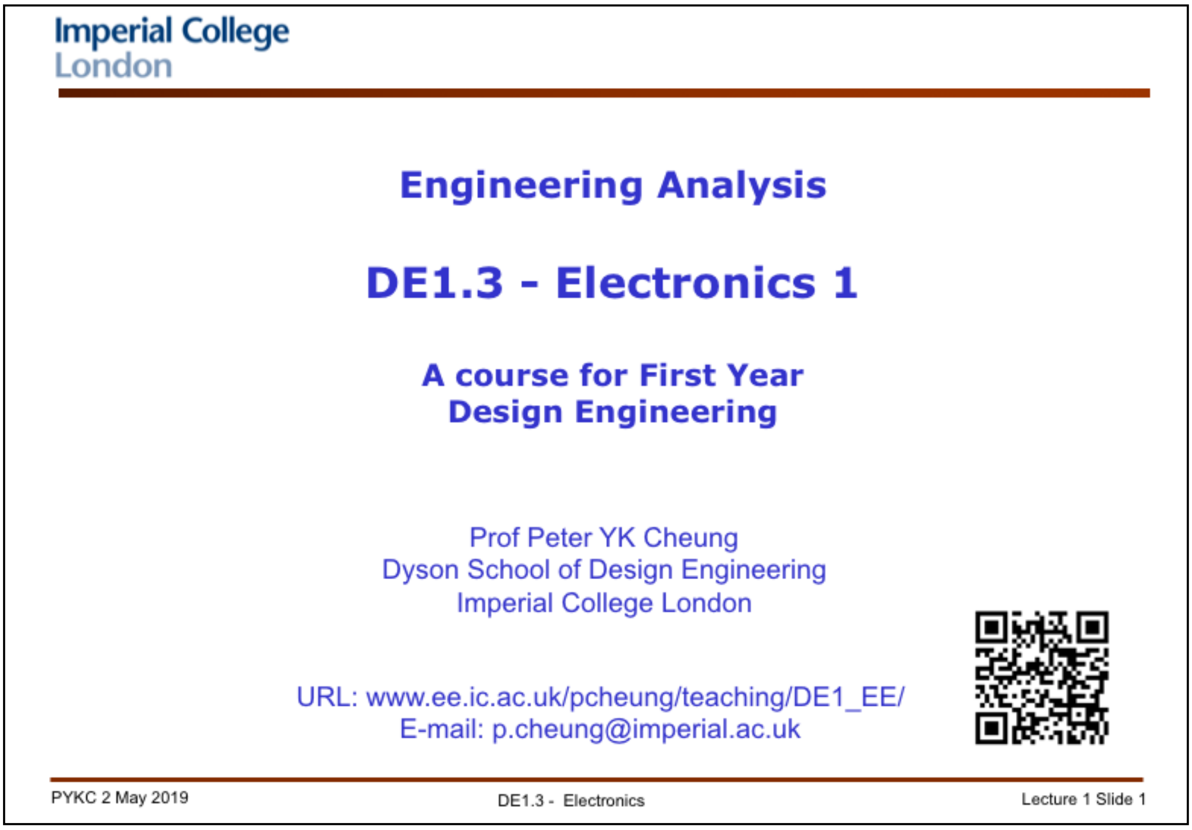

Welcome to this first course you will take on electronic engineering. This is my third time teaching this module. I had a great experience teaching this class last two years and hopefully I can repeat that or even improve upon it this year.

This course presents a personal challenge: how to select and teach from a vast amount of materials we normally teach to first year EE students, and cover all that with you in a quarter of the available time? Even more challenging is: how to ensure that you retain what you learn in electronics for years to come, while you only encounter this topic rarely during the entire degree programme?

All my teaching materials including lecture slides with notes, laboratory work and tutorial problem sheets, can be found on the course webpage shown here. Furthermore, all lectures will be recorded with Panopto.

Course Overview

- By the end of the course, you should have learned and understood:
  - Electrical signals in terms of **voltages** and **currents**
  - Measurements of electrical **signals** and their **accuracies**
  - Basic electrical circuit components: **resistors**, **capacitors** and **inductors**
  - Prediction of voltages and currents in electrical **circuits**
  - Electrical **energy** and **power**
  - **Amplification** of electrical signals
  - **Analogue** vs **digital** signals
  - Basic digital electronic building blocks including **logic gates** and **microprocessors**
  - Behaviour of circuits in **steady-state** or in **transient**
  - How to **sense** the environment and produce electrical signals
  - How to **drive** stuff externally from electronics
  - How to generate or store **energy**
  - How to add **flexibility** and **intelligence** to electronic circuits
  - How to communicate

Being an electronic engineering professor, my opinion is biased. However, I would argue that electronics is now ubiquitous in the modern world. There are now more electronic parts in a car than mechanical ones.

Shown here is a partial list of what you can expect to learn from this course. Even more importantly, before I started prepare for the contents of this course, I wrote a document stating the principle on which I will design this course. In it, I stated five basic principles:

1. Less is more – taking material out will result in students learning more.
2. Concept with rigour – focus on conceptual understanding instead of details, but at the same time not loosing rigour. Focus on fundamentals.
3. Top-down, not bottom-up – where possible go from system level view to component view where possible.
4. Confidence not ignorance – bring about student's confidence on electronics. Know what you know, but even more important, know what you don't know!
5. Formal teaching vs problem based learning – blending together practical laboratory and project work with the course materials taught formally in lectures.

A copy of this document is put on the course webpage.

Organization and Schedule

- All lectures are supported by:
  - Four lab experiments (compulsory) which will be assessed through an oral assessment session on 30th of May
  - A team project with three milestones, cumulating in a final penalty shootout competition on a date to be confirmed
- Recommended textbook
  - Practical Electronics for Inventors, Paul Scherz & Simon Monk (~£29 from Amazon, well worth the money!)
- Examination on a date to be confirmed
- Examination paper 60% of module
- Oral Assessment of Labs 20% of module
- Team Project (with webPA peer assessment) 20% of module
- The course is supported by 6 tutorial problem sheets

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Here is the current plan for my module. I will inform everyone if the schedule changes over the term.

Week	Date	Lecture	Tutorial	Lab
1	2 May	L1 Intro EEE L2 Digital basics		Lab 1 – Signal & Scope
2	7 May	L3 Signals & scope L4 Resistor networks		
	9 May	L5 Nodal analysis L6 Capacitors & Inductors		Lab 2 – Passive networks
3	14 May	L7 Linearity & superposition	Tutorial 1	
	16 May	L8 Amplification L9 OpAmps		Lab 3 - OpAmps
4	21 May	L10 Nodal analysis with impedance	Tutorial 2	
	23 May	L11 Digital Logic Circuits L12 CPU & Pyboard		Lab 4 – Sense, Drive, Link
5	28 May	L13 - Lab 4 explained & Team Project Specification	Tutorial 3	
	30 May	L14 Digital Logic Circuits L15 Sense		**Oral Examination** & Team Project Session 1
6	4 June	L16 Drive	Tutorial 4	
	6 June	L17 Link L18 Source		Team Project Session 2
7	11 June	Revision Lecture – past paper	Tutorial 5	
	13 June			Team Project Session 3
8	20 June	(Date to be confirmed)		**Written Exam**
	21 June	(Date to be confirmed)		**Team Project Oral & Demo**

Imperial College London

Lecture 1

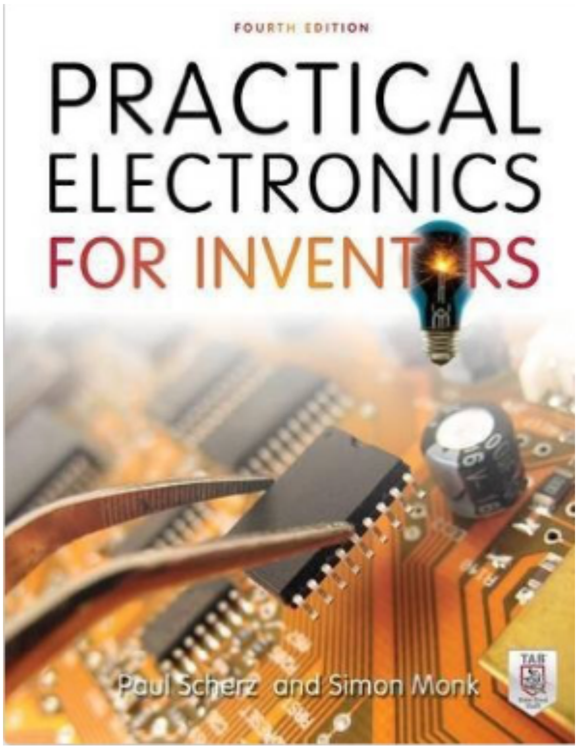
Basic electrical signals, circuits and systems

Prof Peter Cheung
Dyson School of Design Engineering
Imperial College London

URL: www.ee.ic.ac.uk/pcheung/teaching/DE1_EE/
E-mail: p.cheung@imperial.ac.uk

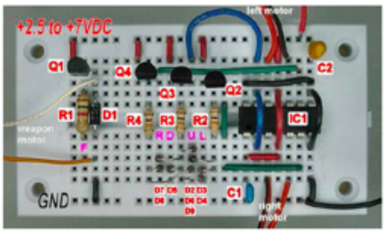
I recommend only one textbook – **Practical electronics for inventors**. This book is particularly suitable for Design Engineers because it has a good balance between theory and practice, it is relatively low cost in spite of size (>1000 pages) and it covers everything you need in electronics at sufficient depth.

In this introductory lecture, I will be laying the foundation for the rest of the module. I will focus on the basic ideas behind electrical signals and circuits.

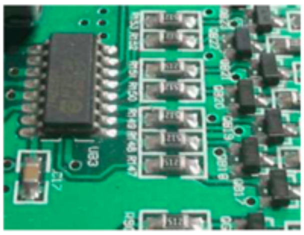


What are electrical circuits?

- 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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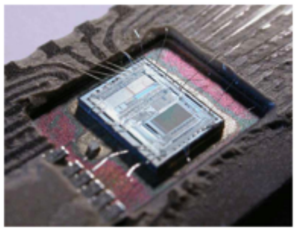

Integrated

- 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.

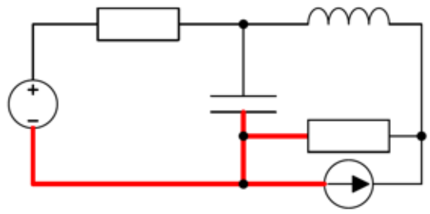
Finally, most electronics circuits are also integrated inside a chip. In fact is amazing how much you will find included in a single chip package nowadays.

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.

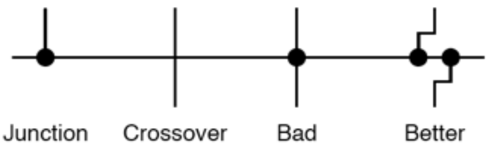
Circuit Diagrams

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.

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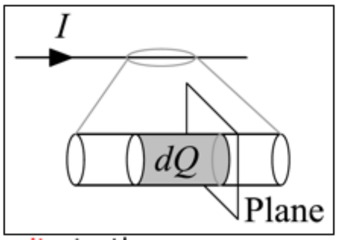
The foundation of electronics is of course the electrons you found inside atoms. Each electron has electrical charge, which is measured in Coulombs (C). An electron's charge is negative, and is measured as -1.6 x 10^{19} C, which is pretty small. This is balanced out by the proton in the atom, which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

P7-9

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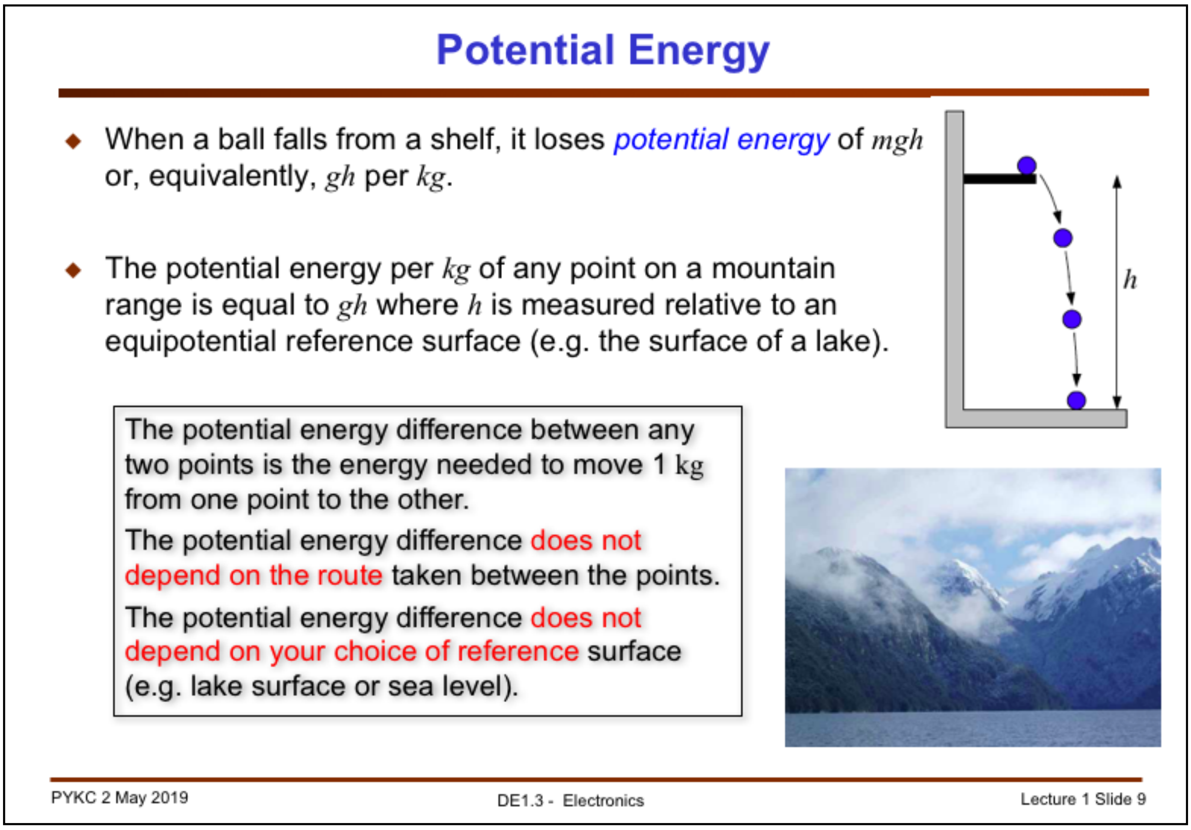
Electrical circuits would not be doing anything useful unless current flows in them. Electrical current is the flow of charge (electrons) as measure at a certain cross section. This is really similar to water molecules flowing through a pipe.

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.

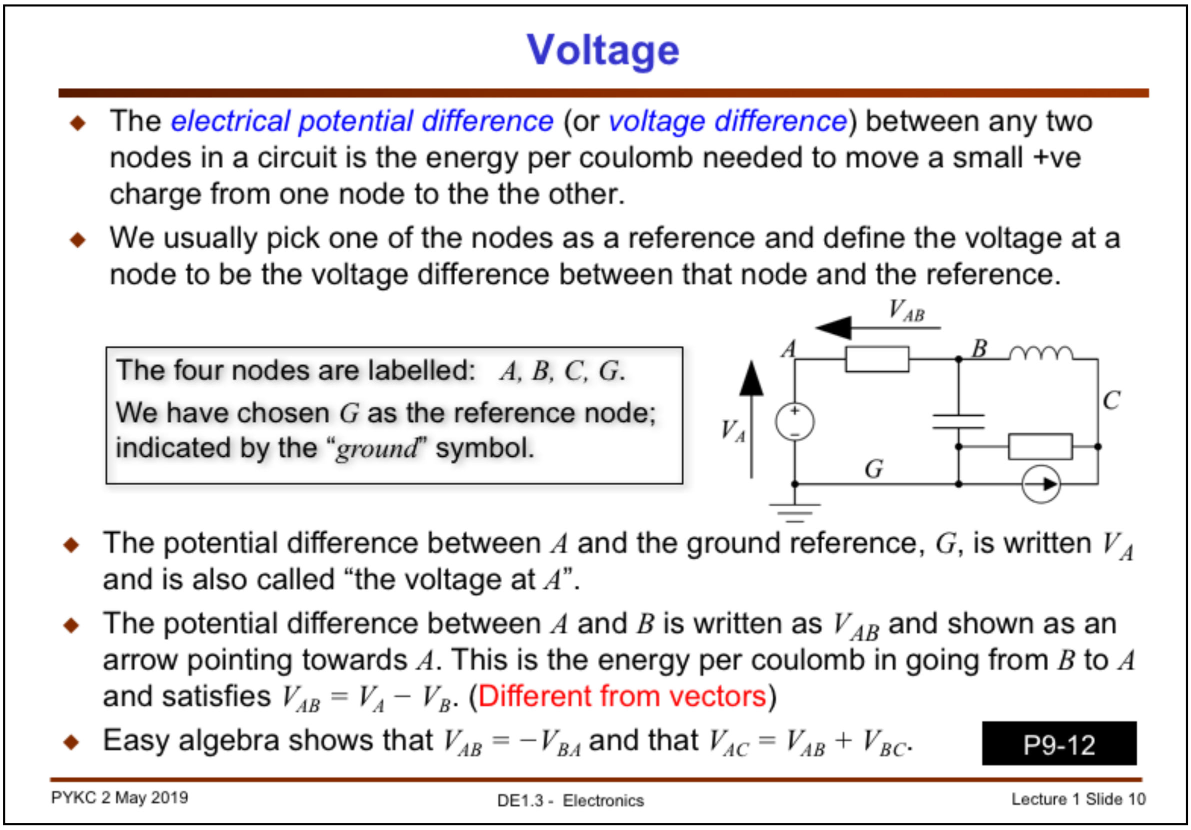


You are all familiar with gravity which relates to potential energy of objects. The lost of potential energy of an object of mass m, dropping a distance of h, is *mgh*.

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.

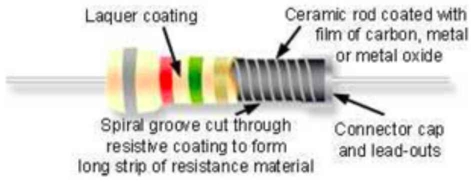
The voltage at node A is V_A, and it is assumed to be relative to the ground node G. We call this "the voltage at A".

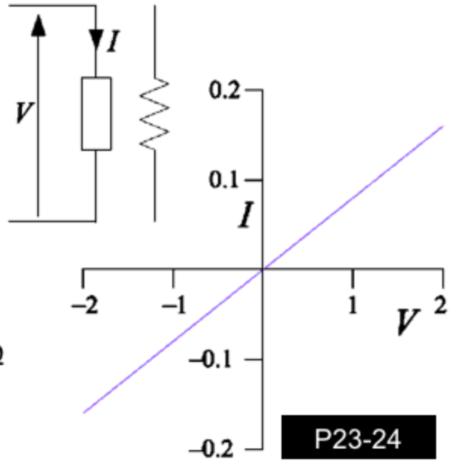
The potential difference between A and B (with B being the reference) is V_{AB}.

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 $\mathrm{G} = 80\ \mathrm{mS}$. Alternative zigzag symbol.





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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.

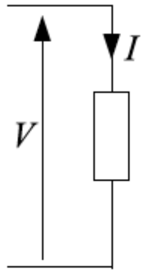
There are many types of resistors, mostly dependent on the specification required. The cheapest and most common type of resistor is made of a thin strip of metalic film on a ceramic substrate. Some resistors are made from a resistive wire wound round the substrate. These are more expensive and usually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

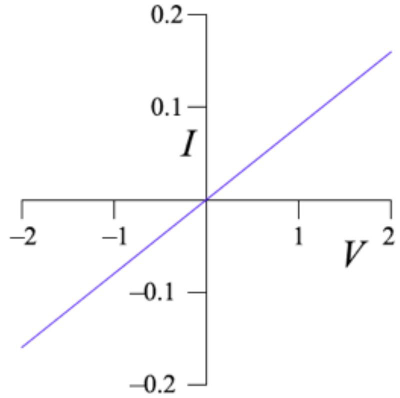
All of you should have come across Ohm's Law in physics at high school. R = V/I. Electrical engineers sometimes use the reciprocal of resistance G = 1/R, which is called the conductance (measured in Siemens S).

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.





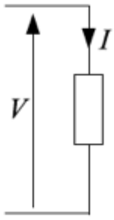
- If the voltage, V, is fixed elsewhere in the circuit, it is convenient to think that V *causes* the current I to flow.
- If the current, I, is fixed elsewhere in the circuit, it is more convenient to think that V is *caused by* the current I flowing through the resistor.
- Neither statement is "more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

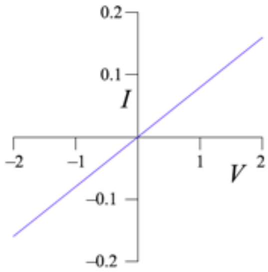
Resistor is said to be a "linear" component, because the current vs voltage characteristic is a linear function (i.e. straight line). The gradient of the line is the conductance.

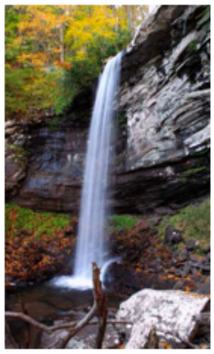
Resistor Power Dissipation

- 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

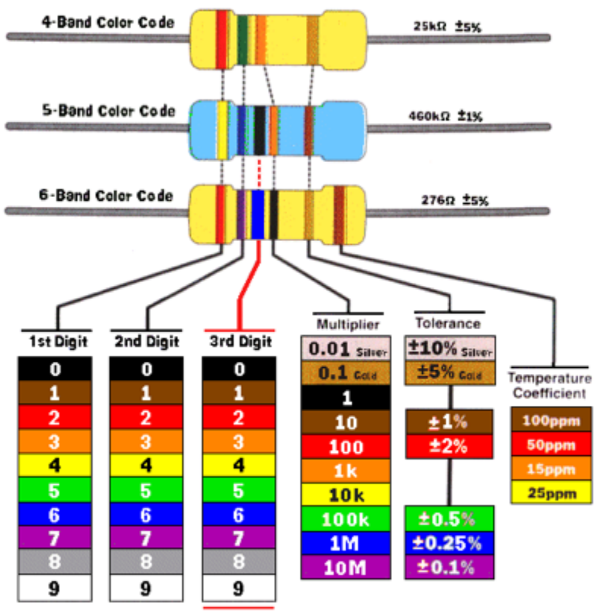
Whenever current flows through a resistor, energy is dissipated as heat. This is analogous to falling by a distance and converting the lost potential energy into kinetic energy.

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.)

Resistor parameters and identification

- Resistors are usually colour coded with their values and other characteristics as shown here.
- They also come in different tolerances (e.g. ±0.1% to ±10%).
- Other important parameters are:
  - Power rating (in Watts)
  - Temperature coefficient in parts per million (ppm) per degree C
  - Stability over time (also in ppm)
  - Inductance (don't worry about this for now)
- Resistors can be made of different materials: carbon composite (most common), enamel, ceramic etc.



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A resistor is characterised by a number of parameters:

1. Its nominal value;
2. Its tolerance or accuracy (e.g. ±5%);
3. Its power rating (i.e. maximum power that it can dissipate);
4. Its temperature coefficient (how much the resistance vary with temperature);
5. Its stability (i.e. how much it changes over time);
6. Its self inductance (something we don't worry about unless you are using resistors at very very high frequencies).

These characteristics are often shown on the resistor itself as a colour code.

The colour code is as shown above. (The printed notes are not in colour. You can download the PDF file from the course webpage, which will be shown in full glorious colours.)

Consider the top resistor. It has four bands, and the band colours are:

RED, GREEN, ORANGE, a gap, BROWN

The first two colour bands are the first two digits of the resistance, i.e. RED = 2, GREEN = 5. The third band in this case is the multiplier. ORANGE = 10^3 or 1k. The gap is always there to separate value bands from tolerance band. BROWN =±5%.

Resistor – Preferred values

- In theory, resistor values is a continuous quantity with infinite different values.
- In reality, resistor as a component exists within some tolerance (say, ±5% is common)
- Therefore there is NO reason to provide more than selected number of different resistor values for a given tolerance.
- The standard "preferred values" for resistors are given in this table for ±5% (most common), ±10% and ±20%, respectively designated as the E24, E12, E6 series.
- For example, if you need a 31.3kΩ resistor with tolerance of ±10%, you could use a 30kΩ E24 resistor (±5%) instead and still stay within the allowable tolerance.
- Therefore, when computing solutions resistor values for electronic circuits, it is silly to use precision with many digits.

Resistor Values

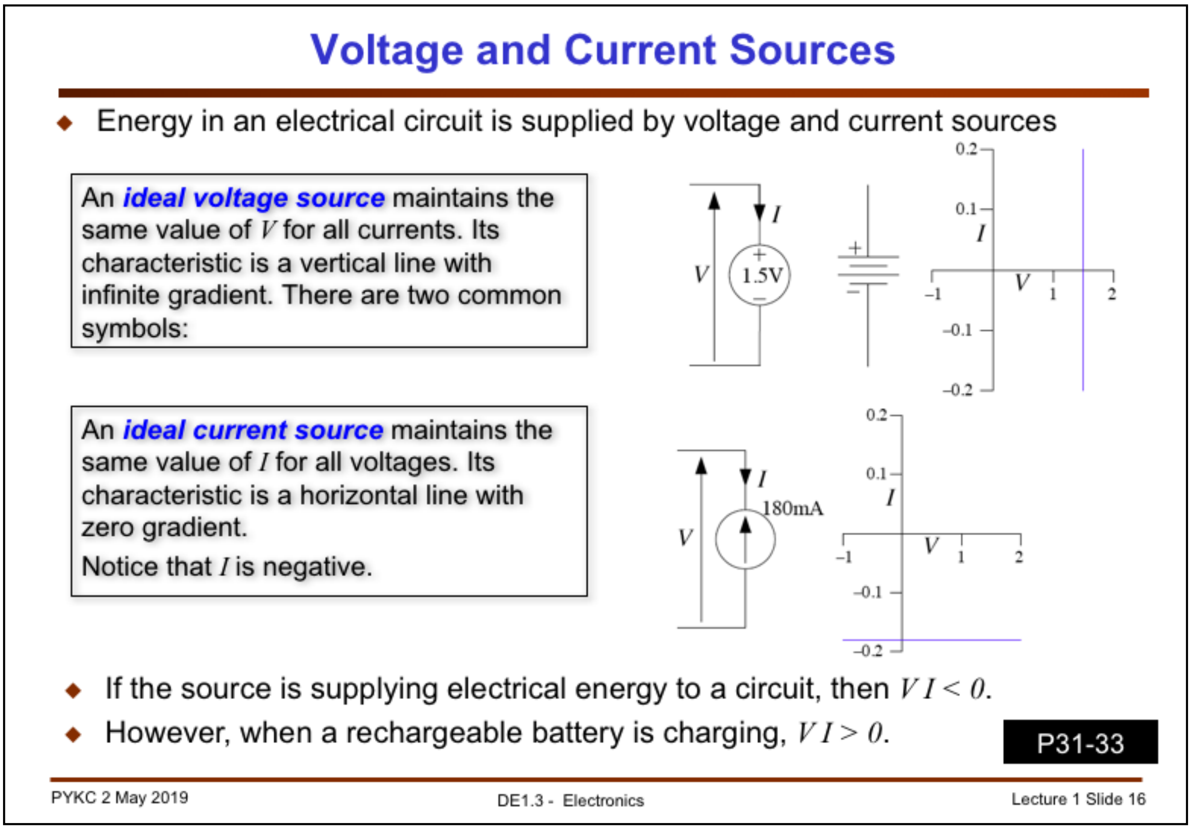
E6 (20%)	E12 (10%)	E24 (5%)
10	10	10
		11
	12	12
		13
15	15	15
		16
	18	18
		20
22	22	22
		24
	27	27
		30
33	33	33
		36
	39	39
		43
47	47	47
		51
	56	56
		62
68	68	68
		75
	82	82
		91

Since resistors have tolerances, it is not necessary normal even sensible to provide resistors of ALL values. Let us suppose you have a 1kΩ resistor with a tolerance of 10%. This resistor could vary from 900Ω to 1.1kΩ in value. You want to guarantee that another resistor with lower nominal value is always lower in resistance. Therefore it does not make sense to provide any resistance with a value above 820Ω, say 850Ω. This is because 850Ω at 10% would give you a range of 765Ω to 935Ω, which would be higher than the lowest value of the 1k resistor!

Therefore in industry, only selected values (known as Preferred Values) of resistors are made, dependent on the tolerance. Shown here are the ±20%, ±10% and ±5% resistors values in a decade range. They are called E6, E12 and E24 respectively because there are 6, 12 and 24 values in each decade (similar to musical nodes).

GOOD ENGINNERING PRACTICE: you can see that since in engineering design, we always have to consider tolerance, and even the humble resistor only exists in defined values, it does not make sense to use precision in your solutions having many digits.

In our laboratory, we will be mostly using the E24 series of resistors at ±5% tolerance.



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.

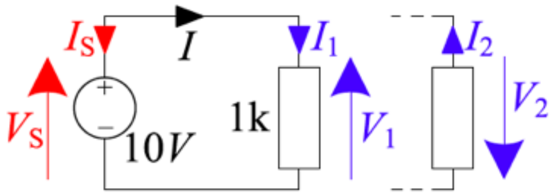
We won’t be using current source in our practical work, but you will be using them in analysis of electronic circuits.

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: $I = \frac{V}{R} = 0.01\ \mathrm{A}$
- Power absorbed by resistor:



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

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

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

- Power absorbed by voltage source:

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

- 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.

Units and Multipliers

Quantity	Letter	Unit	Symbol
Charge	Q	Coulomb	C
Conductance	G	Siemens	S
Current	I	Amp	A
Energy	W	Joule	J
Potential	V	Volt	V
Power	P	Watt	W
Resistance	R	Ohm	Ω

Value	Prefix	Symbol
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f

Value	Prefix	Symbol
10^{3}	kilo	k
10^{6}	mega	M
10^{9}	giga	G
10^{12}	tera	T
10^{15}	peta	P

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Here are the common quantities used in electrical engineering, their units and symbolic representations for the units.

Furthermore, we do not generally use all decades for multipliers (say of resistors), but the multipliers are in steps of THREE decade.

Summary

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