locktronics™

simplifying electricity

Electricity matters 4

CP7773

MATRIX

Contents

Worksheet 1

Electrical energy and power

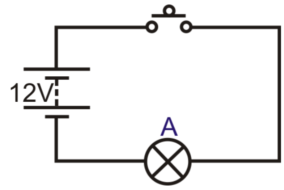
Electrical power is vital to the operation of many complex systems. An aircraft, for example, would not be able to fly without electrical power.

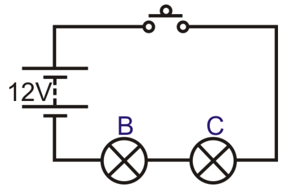
The ability to generate and make efficient use of electrical power is crucial in the modern world, and those working in it must understand electrical power and energy conversion.

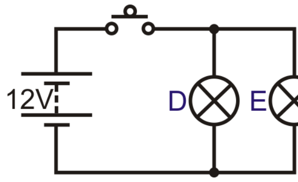
The activities below collect data which is then analysed in terms of energy and power on the following page.

Over to you:

Part A:



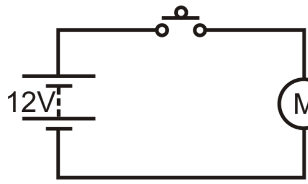




- Set up each the circuit in turn, using 6V 0.04A bulbs.
- Make sure that the DC power supply is set to 6V.
- **Before you switch on**, select the 200mA DC range on the ammeter, and the 20V DC range on the voltmeter.
- For each bulb, measure the current through it, and the voltage across it, when the switch is closed.
- Record your results in a table like that shown below:

Bulb	Current in mA	Voltage
A		
B		
C		
D		
E		

Part B:



- Now build the circuit shown opposite, using the 6V motor.
- Once again, make sure that the DC power supply is set to 6V.
- Close the switch.
- Measure the current through the motor, and voltage across it:
    - when it is running at full speed;
    - when you slow it down by resting your finger lightly on the cog.
- Record your results in a table like the one below:

Motor	Current in mA	Voltage
Full speed		
Under load		

Worksheet 1
Electrical energy and power

So what? - a few relationships that you need to know:

Electric current is a measure of how many electrons are passing per second.
Voltage is a measure of the energy the electrons gain or lose on passing through a component.

Fact 1: Number of coulombs Q = Current I x time t
(Common sense - current measures how many electrons pass per second, so to find out how may have passed in 10 seconds, for example, you simply multiply the current by 10!)

Fact 2: One volt means one joule of energy given to or lost by one coulomb of charge.
(A 12V battery gives each coulomb of charge that passes through it 12J of energy. If the voltage dropped across a resistor is 2V, every coulomb that passes through it loses 2J of energy (i.e. converts 2J to heat energy. It's the electrons struggling to squeeze past the atoms in the resistor - it makes them hot!)

Fact 3: Power is the rate at which energy is converted.
(So - a power rating of one watt of means that one joule of energy is converted from one form to another every second. Domestic filament lamps had power ratings of about 60W. Newer energy-saving types have a rating of 15W for the same brightness, because they convert less electrical energy into heat!)

Formula juggling - ignore all but the result if you wish:

$P = E / t$ *from fact 3* and $E = Q \times V$ *from fact 2* so $P = Q \times V / t$

but $Q = I \times t$ *from fact 1* so $P = I \times t \times V / t$

or, cancelling out the 't' **Result** $\mathbf{P = I \times V}$

The cast:
P = power in watts E = energy converted in joules Q = charge in coulombs
I = current in amps V = voltage dropped in volts! t = time energy conversion took in seconds

For your records:

- Power is the rate at which energy is being used.
- When a component has a voltage V across it, and a current I flowing through it, it is converting energy from one form to another at a rate given by the power formula

$$P = I \times V$$

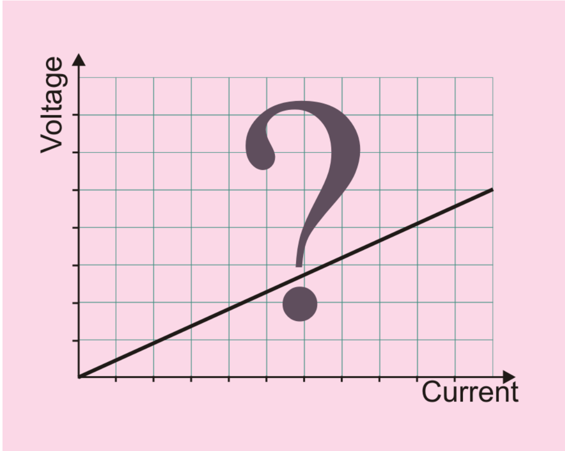
- **Use your results to answer the following:**
  - For bulbs **A** to **E**, calculate:
    - the power dissipated in each bulb, (using the formula P = I x V)
    - how long it takes each bulb to convert 1J of energy from the electrons;
    - how much energy (in joules) the power supply is losing each second.
  - For the motor, calculate:
    - the power dissipated when loaded and unloaded.
  - Each circuit transferred energy at different rates. The amount of energy transferred depended not only on the devices used, but also on the way they were connected.
  - Which battery will 'go flat' first? Explain your answer to a colleague or to your teacher.

Worksheet 2
Non-ohmic conductors

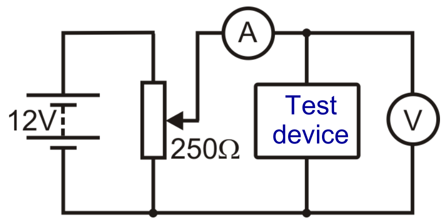
Ohm's law must be the most famous in electrical theory. It predicts that a graph of voltage against current will be a straight line. Yet it very rarely happens!

Any device that obeys it is called an ohmic conductor. Most are non-ohmic conductors, either because their temperature changes when current flows through them, or because changes take place in their structure at an atomic level.

This worksheet looks at two such devices.



Over to you:



- Build the circuit shown in the diagram, using a 6V 0.04A bulb as the test device. The variable resistor allows us to vary the voltage across it.
- **Make sure that the power supply is set to 6V!**
- **Before you switch on**, select the 200mA DC range on the ammeter, and the 20V DC range on the voltmeter.
- Turn the variable resistor knob to set the voltage supplied to a minimum.
- Then turn it slowly until the voltage across the resistor reaches 0.5V.
- Now read the current flowing through the resistor.
- Turn the voltage up to 1.0V, and take the current reading again.
- Keep doing this until the voltage reaches 5.0V.
- Write your results in a table like the one opposite.

6V 0.04A bulb	
Voltage	Current
0.5V	
1.0V	
⋮	⋮
5.0V	

- Now repeat the process using a thermistor as the test device.
- Write your results in a second table.

Thermistor	
Voltage	Current
0.5V	
1.0V	
	⋮
5.0V	

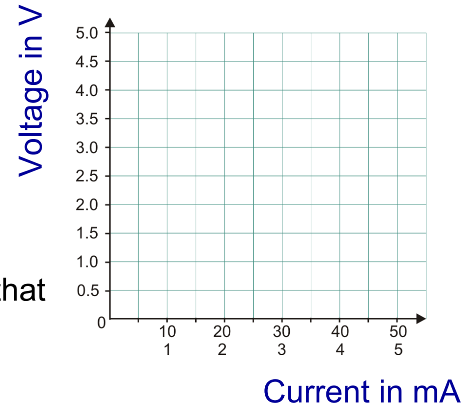
- Don't dismantle the circuit - it will be used in the next assignment!

Worksheet 2

Non-ohmic conductors

So what?

- Plot two curves on the same axes to show your results. The diagram suggests one way to do this. Although it is more usual to plot the independent variable, voltage in this case, on the horizontal axis, it makes the result clearer to plot it on the vertical axis. The current scales are different for the two devices. Label the curves 'Bulb' and 'Thermistor'.
- Ohm's law predicts a straight line. Your results should show that the devices do **not** obey Ohm's law. Draw smooth curves through your plotted points.



- The gradient of the graph at a particular point gives the value of **resistance** of the device at that point. Look at the way the resistance of the two devices changes as the current increases.
- In both cases, the device heated up as the current increased, and this heating effect caused the change in resistance. However, the underlying physical mechanisms were different.
  In the bulb, the ions that make up the bulk of the filament vibrate faster as the temperature increases. This makes it more difficult for the electrons to flow past.
  In the thermistor, which is made from a semiconducting material, the dominant effect is that the increased temperature liberates more electrons to flow through the material.

For your records:

- Ohm's law predicts that a graph of voltage against current will be a straight line.
- Nearly all conductors warm up when an electric current passes through them, and so do not obey Ohm's law.
- Explain to your colleague how, and why the resistance of the filament of the bulb changes as the current through it increases.
- Research sources such as the internet and then write a short explanation describing differences between (metallic) conductors and semiconductors.
- Find out about applications of ntc and ptc thermistors. Then write a brief summary of their uses.

Worksheet 3

Resistivity

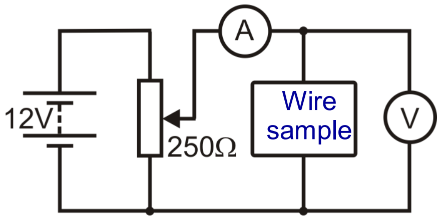
The resistors in the picture are similar in 'size' - physically - but very different in resistance - one is nearly a thousand times bigger than the other.

It is a bit like asking whether a ton of lead is heavier than a ton of feathers. They weigh the same but a ton of feathers takes up a lot more room. The important property is density - how tightly packed the material is.

In resistor terms, the equivalent is to ask whether a 1Ω resistor made out of gold wire has more resistance than a 1Ω resistor made out of graphite. The gold resistor takes up much more room than the graphite one. The relevant property, resistivity, measures how easily electrons flow through a particular material, and is the focus of this worksheet.

Over to you:

- The circuit is the same as in the previous investigation. As before, we use the variable resistor to vary the voltage across the test device. In this case, four samples of wire are tested. Three are made from nichrome, an alloy of nickel, chromium and iron, with different lengths or cross-sectional areas. The fourth is made from constantan, a copper-nickel alloy.



- **Make sure that the power supply is set to 6V!**
- Select the 200mA DC range on the ammeter, and the 2V DC range on the voltmeter .
- For each of the wire samples:
    - Reduce the voltage supplied to the wire to zero. Then increase it slowly to 0.5V. Now read the current flowing through the wire.
    - Record your results in a table like the one opposite.

Material	**Cross-sec area in mm^2**	**Length in mm**	**Voltage**	**Current**
Nichrome	0.075	250		
Nichrome	0.075	500		
Nichrome	0.21	500		
Constantan	0.075	500		

(Optional extension:)

- Replace the wire sample with a sampler carrier.
- Measure a suitable length of resistance wire - one metre would make the impending arithmetic easier!
- Measure the diameter of the wire in at least three places, and work out the average of these values.
- Clamp the two ends of the wire into the sampler.
- Apply 0.5V to the wire using the same procedure as before.
- Measure the current that flows as a result.
- Record your measurements in a table, like the one opposite, in the units shown.

Material	
Length 'l' in m	
Average diameter 'd' in m	
Voltage 'V' in V	
Current 'I' in A	

Worksheet 3
Resistivity

So what?

- Complete the 'Resistance' column of the table using the Ohm's law formula: $R = V / I$

Material	Cross-sec area in mm^2	Length in mm	Voltage	Current	Re-sistance
Nichrome	0.075	250			
Nichrome	0.075	500			
Nichrome	0.21	500			
Constantan	0.075	500			

- In the following analysis , remember that all measurements are necessarily approximate. Measuring instruments have calibration errors and sensitivity errors, as well as reading errors.
- Look at the results for the first and second samples.
  - The material is the same for both, as is the cross-sectional area.
  - Only the length is different - the second sample is twice as long as the first.
  - What do your results suggest about the resistance of a wire that is twice as long?
- Look at the results for the second and third samples.
  - The material and the length is the same.
  - The third has a cross-sectional area that is 2.8 times bigger than the second.
  - What do your results suggest about the resistance of a wire that is 2.8 times 'fatter'?
- Look at the second and fourth samples.
  - Their lengths and cross-sectional areas are the same.
  - They are made from different materials.
  - Here you can see the effect of resistivity.
- Use your results to calculate the resistivity ρ of nichrome and the resistivity ρ of constantan.

  The formula is: $\rho = \frac{R \times L}{A}$ where R = resistance, L = length, A = cross-sectional area of sample

If you carried out the optional investigation, use your results to calculate the resistivity of the material used in the sample of wire. First of all, work out the cross-sectional area of the wire, from your measurements of diameter, and then use the above formula to work out resistivity.

For your records:

- The **resistance** of a conductor is directly proportional to its length, and inversely proportional to its cross-sectional area.
- Putting all this together leads to the following formulae:

$$R = \frac{\rho \times L}{A} \quad \text{or} \quad \rho = \frac{R \times A}{L}$$

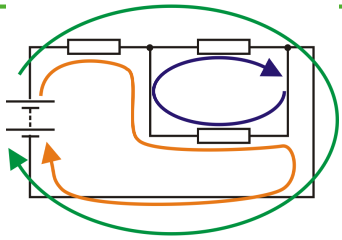
where R = resistance, ρ = resistivity, A = cross-sectional area, and L = length, of material.

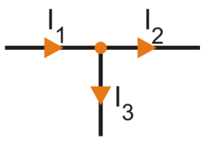
.

Worksheet 4

Using Kirchhoff’s laws

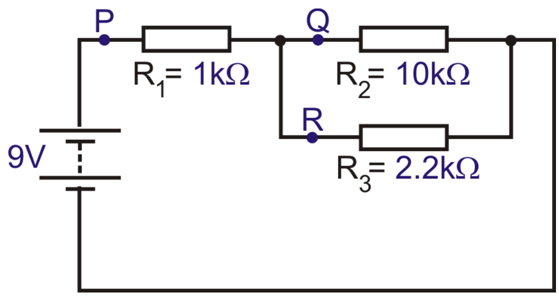
- **Kirchhoff’s Voltage Law** -
  Around any loop in the circuit, the (vector) sum of voltages is zero.
  There are three loops in the circuit you will investigate.
  These are shown in different colours in the diagram.





- **Kirchhoff’s Current Law** - ‘What flows in must flow out’
  The (vector) sum of all currents at any junction is zero.
  In other words, $I_1 = I_2 + I_3$

Over to you:



- Connect a 1kΩ, a 2.2kΩ and a 10kΩ resistor, to a DC power supply, as shown in the circuit diagram.
- Set the power supply to 9V.
- Remove the connecting link at **P**.
- Connect a multimeter, set on the 10mA DC range, to measure the current at **P**, (i.e. the total current leaving the power supply.)
- Record the value in a table like the one opposite.
- Remove the multimeter and replace link **P**.
- Measure the current at **Q** and then **R** in the same way, and record the results in the table.
- Set up the multimeter to read DC voltages of about 10V.
- Measure the voltages across the three resistors.
- Record these in the table.

Measurement	**Value**
Current at P in mA	
Current at Q in mA	
Current at R in mA	
Voltage across R_1	
Voltage across R_2	
Voltage across R_3	

On the next page, we are going to analyse these results using Kirchhoff’s Laws.

Worksheet 4
Using Kirchhoff's laws

So what?

- Kirchhoff's current law gives us the relationship:

  $$I_1 = I_2 + I_3$$

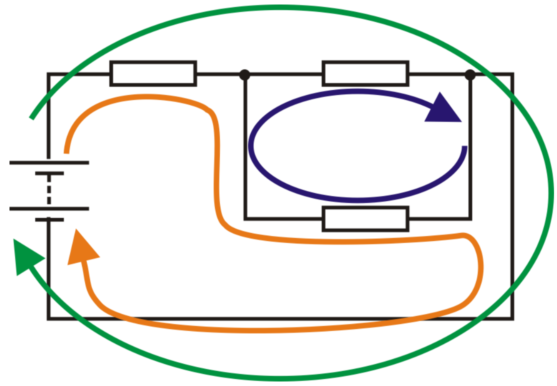
- Kirchhoff's voltage law applied to each loop gives.
  - The **green** loop: $9 = V_1 + V_2$ **equation 1**
  - The **orange** loop: $9 = V_1 + V_3$ **equation 2**

  The **blue** loop: $0 = V_2 + V_3$
- Ohm's law gives us the relationships:

  $$V_1 = I_1 \times R_1 = (I_2 + I_3) \times R_1$$
  $$V_2 = I_2 \times R_2$$
  $$V_3 = I_3 \times R_3$$

- Inserting the values of the resistors (in kΩ) gives:

  $$V_1 = (I_2 + I_3) \times 1 = (I_2 + I_3)$$
  $$V_2 = I_2 \times 10$$
  $$V_3 = I_3 \times 2.2$$



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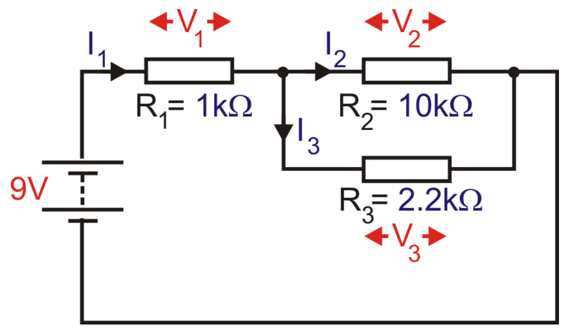


w4e

- Using these, **equation 1** becomes $9 = (I_2 + I_3) + (10 \times I_2)$

  or $9 = 11 I_2 + I_3$

  which means that $I_3 = 9 - 11 I_2$

  and **equation 2** becomes $9 = (I_2 + I_3) + (2.2 \times I_3)$

  or $9 = I_2 + 3.2 I_3$

  Inserting the value of I_3 gives $9 = I_2 + 3.2(9 - 11 I_2)$

  so $(35.2 - 1) I_2 = 28.8 - 9$

  which gives $I_2 =$ **0.58mA**

  Substituting this in earlier equations $I_3 = 9 - 11 I_2 = 9 - 11 \times 0.58 =$ **2.63mA**

  and so $I_1 = 0.58 + 2.63 =$ **3.21mA**

  In turn, these values give $V_1 = 3.21 \times 1 = 3.2V$

  $V_2 = 0.58 \times 10 = 5.8V$

  $V_3 = 2.63 \times 2.2 = 5.8V$ (not surprisingly!)

  Check your measured values against these results!

For your records:

- Kirchhoff's Current Law - 'What flows in must flow out'
  The (vector) sum of all currents at any junction is zero.
- Kirchhoff's Voltage Law -
  Around any loop in the circuit, the (vector) sum of voltages is zero.

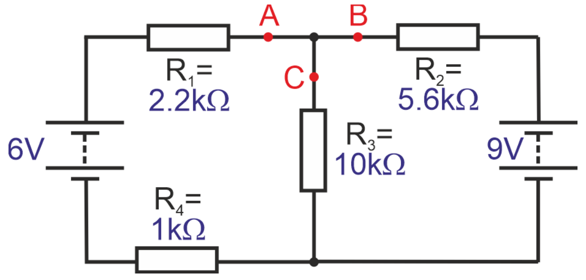
Worksheet 5

Kirchhoff’s laws and superposition

This investigation first looks at the effect on the circuit of each power source separately. Then the voltages and currents from the separate power supplies are “superimposed”.
In practice, the actual voltages and currents, in a circuit with multiple power sources would be calculated, but this investigation measures them to check that the approach works.

Over to you:

- Build the circuit shown opposite, but *do not switch on any power supplies yet!*



Step 1: Use only the 9V power supply

- Swap the 6V power supply carrier for a connecting link, and then switch on the 9V power supply.
- Measure the currents at **A**, at **B** and then at **C**. Record them in the table. The directions of current flow have been given for you.
- Measure the voltage across the power supply, and then across each resistor. Record these in the table. The voltage directions (opposite to current flow,) have been added for you.

Step 2: Use only the 6V power supply

- Swap the 9V power supply carrier for a connecting link, return the 6V power supply carrier, and switch on.
- Repeat the measurements and record them.
- Add arrows to show the directions of currents and voltages. (The way you connect the ammeter gives you a clue.)

Step 3: Use both power supplies

- Reconnect both power supplies, and switch on.
- Measure the currents and voltages once more, recording them in the table.
- Add arrows to show the directions of currents and voltages.

9V supply only		
Current at A = I_A		←
Current at B = I_B		←
Current at C = I_C		↓
Voltage across power supply, V_S		↑
Voltage across 1kΩ resistor, V_1		←
Voltage across 2.2kΩ resistor, V_2		→
Voltage across 5.6kΩ resistor, V_5		→
Voltage across 10kΩ resistor, V_{10}		↑

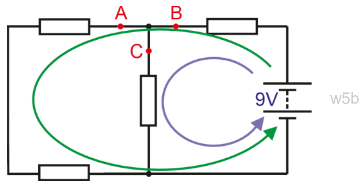
6V supply only		
Current at A = I_A		
Current at B = I_B		
Current at C = I_C		
Voltage across power supply, V_S		
Voltage across 1kΩ resistor, V_1		
Voltage across 2.2kΩ resistor, V_2		
Voltage across 5.6kΩ resistor, V_5		
Voltage across 10kΩ resistor, V_{10}		

Both power supplies		
Current at A = I_A		
Current at B = I_B		
Current at C = I_C		
Voltage across power supply, V_S		
Voltage across 1kΩ resistor, V_1		
Voltage across 2.2kΩ resistor, V_2		
Voltage across 5.6kΩ resistor, V_5		
Voltage across 10kΩ resistor, V_{10}		

Worksheet 5

Kirchhoff's laws and superposition

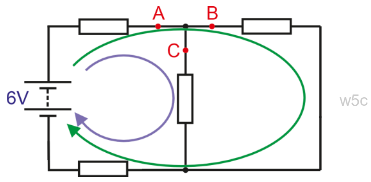
So what?



Step 1

- For steps 1 and 2, Kirchhoff's voltage rule applies, so
  $V_1 + V_2 + V_{10} = V_S$ and $V_1 + V_2 + V_5 = V_S$
  Kirchhoff's current rule still applies so $I_A = I_B + I_C$
- In step 3, the rules also apply but we have to take direction into account.

The diagrams show the directions of current flow for the first two stages.



Step 2

The current flows the same way through the 10kΩ resistor in both, so when both power supplies are used:

- current at **C** = sum of separate currents due to the two power supplies
- voltage across the 10kΩ resistor = sum of separate voltages from two power supplies

In all other resistors, the current direction reverses between step 1 and step 2, so

current at **A** = **difference** between separate currents at **A** due to each power supply.
current at **B** = **difference** between separate currents at **B** due to each power supply.
V_1 = **difference** between separate V_1 voltages due to each power supply.
V_2 = **difference** between separate V_2 voltages due to each power supply.
V_5 = **difference** between separate V_5 voltages due to each power supply.

The direction of the current or voltage is the direction of the bigger component in step 1 or 2.

For example, here are a set of typical results:

Step 1: I_A = 0.85mA ← I_B = 1.12mA ← V_2 = 1.87V → V_5 = 6.28V →
Step 2: I_A = 0.88mA → I_B = 0.57mA → V_2 = 1.94V ← V_5 = 3.17V ←

When both power supplies are used:

I_A = 0.03mA ← I_B = 0.56mA ← V_2 = 0.07V ← V_5 = 3.11V →

Look at the measurements you made. Check that the above treatment works for your results.

For your records:

To **calculate** the currents and voltages in a circuit that has more than one power source:

- replace all power sources but one with short-circuit links;
- calculate the currents and voltages caused by that remaining power source;
- do the same thing for each of the other power sources in turn;
- for each component, superimpose the currents and voltages from each separate power source (meaning that you must take into account the *direction* - add them when they are in the same direction - subtract smaller from bigger when they are in opposite directions.)

Worksheet 6

Electrostatics and capacitors

Static electricity can be produced by friction (for example, rubbing a balloon on a woollen sweater).

Bodies charged by this method have either positive or negative polarity, depending on whether a deficit or excess of charge-carrying electrons is present.

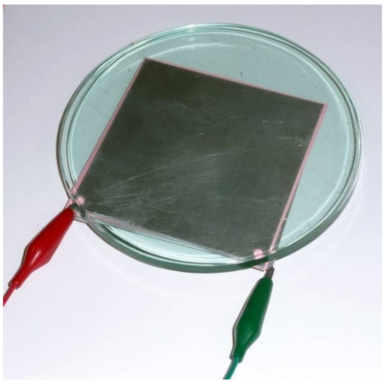
Bodies can remain in this state for some time. Stray static charge like this can cause electrical noise and interference to communications equipment, requiring special measures, to avoid the build-up of charge.

w6a

Capacitors provide us with a means of accumulating and storing electric charge. A simple capacitor consists of two metal plates separated by an insulating dielectric, such as polyester film. The charge present is the product of the capacitance of the capacitor (in Farad) and the applied voltage (in Volt). In other words $Q = C \times V$ coulomb.

Over to you (optional investigation):

- Make your own capacitor with a square of thin card between two square aluminium plates. Keep it clamped together by placing it between heavy glass plates with a heavy object on top.
- Measure the capacitance of your capacitor using a digital multimeter switched to the 2nF range.
- Increase the separation of the plates by adding extra pieces of card (up to six).
- Each time, measure and record the capacitance.



w6b

Thickness of card	**1**	**2**	**3**	**4**	**5**	**6**
C in nF						

- Next change the amount by which the plates overlap (whilst keeping the plates parallel). Mark lines on the capacitor at 75%, 50%, 37.5%, 25% and 12.5% of the surface and for each overlap, measure and record the capacitance in the table.

Overlap	**100%**	**75%**	**50%**	**37.5%**	**25%**	**12.5%**
C in nF						

Worksheet 6
Electrostatics and capacitors

So what?

Use your results to:

- Plot a graph showing how the capacitance changes with plate separation.
- Plot a graph showing how capacitance changes with the overlapping area of the plates.

Discuss the following with your colleague or teacher:

- What conclusions can you draw from the first graph?
- What conclusions can you draw from the second graph?

For your records:

- Increasing the separation of the plates reduces the capacitance.
  More precisely, capacitance is inversely proportional to the plate separation.
- Increasing the overlap of the plates increases the capacitance.
  More precisely, capacitance is directly proportional to the plate area.
- Combining these results we can arrive at the important relationship:

$$C \propto \frac{A}{d} = k\frac{A}{d} = \frac{\varepsilon_0 \varepsilon_r A}{d}$$

where:

C = capacitance;
A = plate area;
d = plate separation;
$\mathcal{E}_0$ = permittivity of free space;
$\mathcal{E}_r$ = relative permittivity of the dielectric material (insulator).

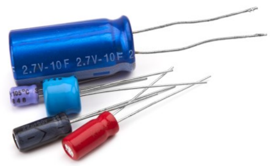
Worksheet 7

Capacitors - energy storage overview

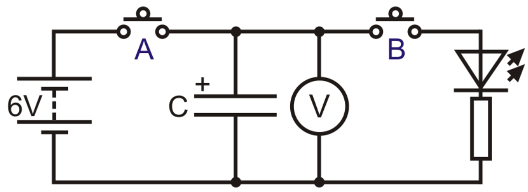
Electrical energy is notoriously difficult to store! Capacitors offer a small -scale storage solution and are currently used to preserve user data in computers, mobile phones and digital cameras.

Advances in ultracapacitors offer promising energy-storage benefits to electric vehicles. After all, capacitors charge up in a very short time, compared to batteries.

This worksheet looks at energy storage in capacitors.



Over to you:



- First, the effect of capacitance. Build the circuit shown, using a 1000µF capacitor for C.
  Make sure that it is connected to right way round!
- The power supply is set to deliver 6V DC.
- Switch on the power supply and press push switch **A**. Straightaway, the capacitor charges up to the supply voltage, as the voltmeter shows.
- Release switch **A** to disconnect the power supply.
- Close switch **B**, and immediately start the stopwatch.
- The light from the LED comes from the energy stored in the capacitor. Watch the voltmeter reading and time how long it takes for the capacitor voltage to drop to 1.70V.
- Record the result in a table like the one above.
- Now replace the 1000µF capacitor with a 2000µF capacitor, and repeat the process.
- Next, connect the 1000µF and 2000µF capacitors in parallel, to make a 3000µF capacitor. Repeat the process again.
- Finally, replace the two capacitors with a 22000µF capacitor, and repeat the process again.

Capacitor	**Discharge time**
1000µF	
2000µF	
3000µF	
22000µF	

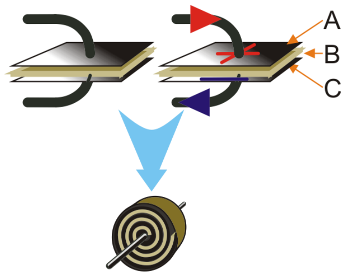
- Secondly, the effect of the capacitor voltage, (using the same circuit, with the 22000µF capacitor.)
- Initially, set the DC power supply to output 3V.
- Close switch **A**, to charge up the 22000µF capacitor to the supply voltage.
- Then close switch **B** and time how long it takes for the capacitor voltage to fall to 1.70V.
- Record the result.
- Set the power supply voltage to 6V, and repeat the process.
- Finally, set the power supply voltage to 9V, and repeat the process again.

Power supply	**Discharge time**
3V	
6V	
9V	

Worksheet 7

Capacitors - energy storage overview

So what?



A capacitor consists of three sheets, **A**, **B** and **C**. Two of them, **A** and **C**, are metal plates, usually aluminium. The third, **B**, a sheet of insulator, also called the dielectric, insulates the metal plates from each other.

These plates are usually rolled up into a 'Swiss roll', and covered in a protective casing, with wires connected to each, as shown in the lower diagram.

Normally, the metal sheets are uncharged. When an electric current flows, one plate becomes positively charged, and the other negatively charged. This storage of charge is how the capacitor stores energy.

Using capacitors for storing energy presents two problems:

- they are only practical for storing relatively small amounts of energy;
- they suffer from 'leakage,' which means that they store energy only for a limited time.

The investigations you carried out were based on timing how long it took the capacitors to discharge through the LED to a voltage of 1.70V. This value is relatively arbitrary, but is roughly the point at which appreciable conduction stops in the LED.

The results from your investigation show that:

- the bigger the capacitor, the greater the energy stored;
- the bigger the capacitor voltage, the greater the energy stored.

A more detailed study reveals that the energy stored:

- is directly proportional to the capacitance used;
- is directly proportional to the square of the capacitor voltage.

In fact, the energy stored $W = ½\, C\, V^2$

Alternative forms of this equation are:

$$W = ½\, Q\, V;$$

$$W = ½\, Q^2 / C.$$

For your records:

Use the internet to find out as much as you can about:

- ultracapacitors;
- the Dinorwig power station (and 'pump storage'.)

Present your results to the rest of the class in the form of a display.

Worksheet 8

Capacitors - energy storage in detail

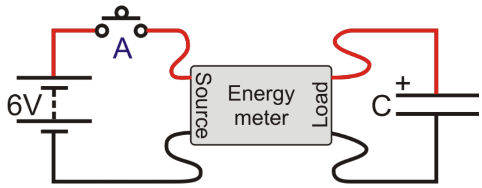
Electrical energy monitors (also called ‘smart meters’) are becoming commonplace, as consumers try to reduce energy costs.

The device shown on the right is a low-voltage version, able to measure energy transferred, power and average power delivered, as well as voltage and current.
More details are given on the next page.

Here, it is used to measure the energy stored in a capacitor.

Over to you (optional investigations):

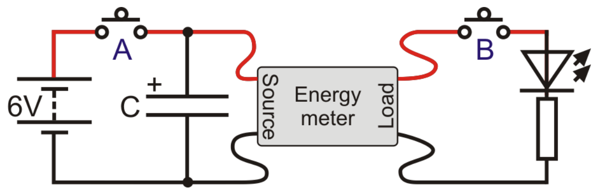
A. The energy needed to charge a capacitor -



- Build the circuit, using a 1000μF capacitor for C.
  Make sure that it is connected to right way round!
- The power supply is set to 6V DC. Switch it on.
- Select the energy meter function, and press the ‘Start / Pause’ button.
- Press and hold down push switch **A**.
- The capacitor charges up to the supply voltage, and the Energy Meter shows how much energy was transferred from the power supply in doing so. Record this in a table like that opposite.
- Release switch **A** to disconnect the power supply.
- Now replace the 1000μF capacitor with a 2000μF capacitor, and repeat the process.
- Next, connect the 1000μF and 2000μF capacitors in parallel, to make a 3000μF capacitor. Repeat the process again.
- Finally, replace the two capacitors with a 22000μF capacitor, and repeat the process again.

Capaci-tor	Energy needed
1000μF	
2000μF	
3000μF	
22000μF	

B. The energy stored in a capacitor -



- Build the modified circuit, initially using a 1000μF capacitor for C.
  Be sure to connect it the right way round!
- Check that the power supply is still set to 6V DC, and switch it on.
- Press and hold down switch **A** for a few seconds to allow the capacitor to charge fully.
- Select the energy meter function, and press ‘Start / Pause’.
- Press and hold down switch **B**. The capacitor discharges through the LED. The Energy Meter shows the energy transferred from the capacitor in doing so. Record this in a table like that opposite.
- Now replace the 1000μF capacitor with the other values, as before, and repeat the process.

Capaci-tor	Energy needed
1000μF	
2000μF	
3000μF	
22000μF	

Worksheet 8

Capacitors - energy storage in detail

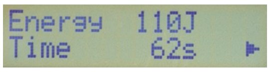
So what?

Energy meter functions:

The Energy Meter can measure a range of quantities, by selecting the appropriate mode.
This is done by pressing the function button until the required screen display is obtained.

Measuring energy

In this mode the meter shows the energy that has been transferred through the device in the time shown. You can use the start/stop and reset buttons to control the display.



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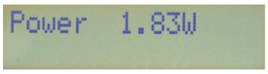
Measuring power

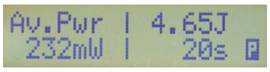
Here, the meter shows the instantaneous power delivered through the meter.



w8f

Measuring average power

In this mode the meter shows the average power over the time shown, and gives the values used to calculate it .



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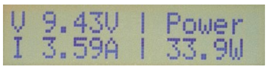
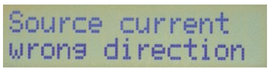
Measuring voltage, current and power

Here, the meter shows the voltage, current and power at each instant.



w8h

The message shown opposite means that the cables connected to the Energy Meter have the wrong polarity, and need to be swapped round.



w8j

For your records:

- The energy values you obtained in part A of the investigation were much bigger then the corresponding ones in part B. Think of a reason for this.
  Would it have made a difference if a resistor had been included in series with switch **A** in the charging circuit? (Try it!)
  Discuss your ideas with a colleague.

- Devise an experiment using the Energy Meter, to find out how the energy stored in a capacitor depends on the capacitor voltage.
  Write a detailed set of instructions for the investigation, and then show it to your teacher. If it is good enough, you may get the chance to try it out.

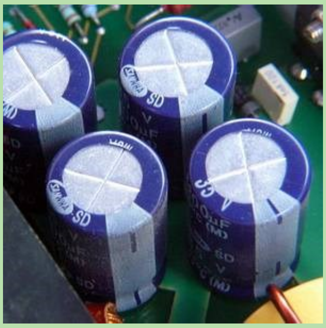
Worksheet 9

Capacitor charge and discharge

Capacitors provide a means of storing electric charge, acting as a reservoir for electrical energy. Charge can be transferred to a capacitor by connecting it to a power supply or a battery.

When it discharges, the stored energy is released, usually as heat. Later, the capacitor can be recharged. The stored energy is then replenished.

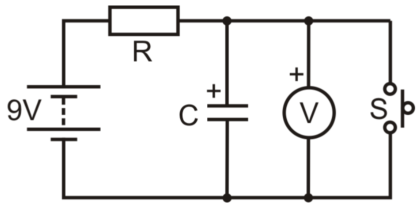
In this worksheet, you investigate capacitor charge and discharge.



Over to you:

Charging a capacitor:

- Build the circuit shown opposite, using values R = 10kΩ and C = 1,000μF.
- Make sure that the DC power supply is set to 9V.
- Use a multimeter, on the 20V DC scale to measure the voltage across the capacitor.
- Press and hold down switch S to discharge the capacitor fully.



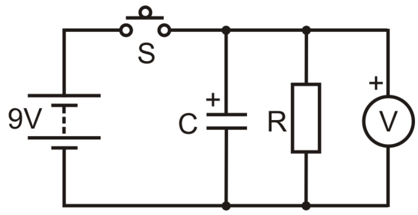
- Release S so that the capacitor begins to charge, and measure and record the capacitor voltage every 10 seconds.

R = kΩ, C = μF													
Time in s	0	10	20	30	40	50	60	70	80	90	100	110	120
Capacitor voltage in V													

- Repeat this process using values of C = 2,200μF and R = 10kΩ , and then C = 1,000μF with R = 22kΩ. You now have three sets of readings, set out in three tables like the one above:

Discharging a capacitor:

- Build the circuit shown opposite, with R = 10kΩ and C = 1,000μF.
- Again, make sure that the power supply is set to 9V DC and that the multimeter is on the 20V DC range.
- Press and hold down switch S to charge the capacitor fully. The charge will build up rapidly as there is no resistance to limit the charging current.

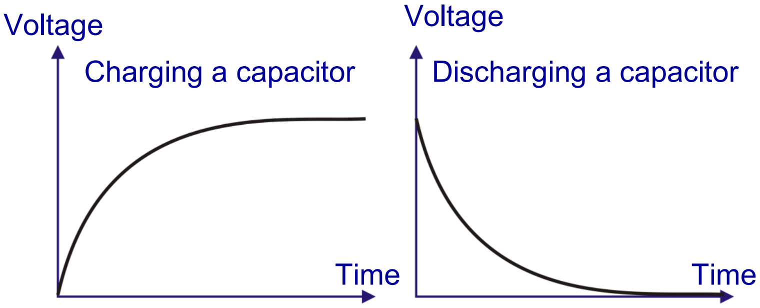


- Release S so that the capacitor begins to discharge and record the voltage every 10 seconds in a table like the one above.
- Repeat the same process for values of C = 2,200μF and R = 10kΩ , and then C = 1,000μF with R = 22kΩ. You should once again have three sets of readings set out in three tables.

Worksheet 9
Capacitor charge and discharge

So what?

- Use your results to:
  - plot three graphs showing how the capacitors charge, when connected to series resistors, (over the period from 0 to 120s.)
  - plot three graphs showing the discharge of capacitors through 'shunt' resistors, (again over the period from 0 to 120s.)
- The diagrams show typical shapes for these graphs. Guided by your experimental points, draw smooth curves for each graph.



- Take a close look at your graphs. Does the capacitor ever completely charge or discharge?
- What effect do the values chosen for C and R have on the rate at which the capacitor charges or discharges?
- For each charging graph, find the time it takes for the capacitor voltage to reach 63% of its final value. Compare this with the corresponding time constant (= R x C, where R is in MΩ and C in μF.)
- For each discharging graph, find the time it takes for the capacitor voltage to fall to 37% of its final value. Once again, compare this time value with the corresponding time constant).
- The charge and discharge curves show **exponential growth** and **exponential decay** respectively. Find out as much as you can about the exponential constant, *e*.

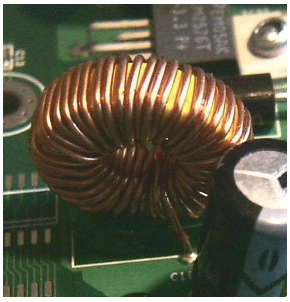
For your records:

- A capacitor charges faster initially, as a larger charging current flows, and then the rate of charging slows down. The shape of the charging curve is an example of exponential growth.
- When a capacitor discharges, the voltage across it falls rapidly to begin with, and then falls more slowly. This is an example of exponential decay.
- The rate of change of voltage for both charge and discharge is governed by the time constant for the R-C network. The time constant **T** is calculated using the formula:

  $$\mathbf{T} = \mathbf{R} \times \mathbf{C}$$

  and it has units of seconds if **R** is in Ω and **C** in F,
  or if **R** is in MΩ when **C** is in μF.

Worksheet 10
Inductors and back emf

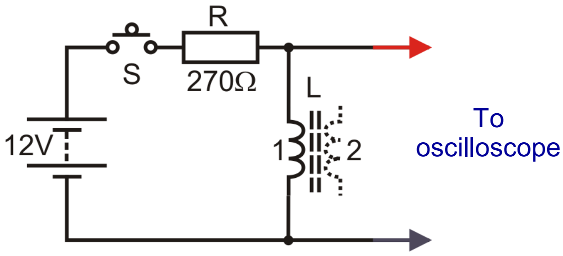


A current flowing in a conductor creates a magnetic field in the space around it. This can be intensified by winding the conductor into a coil and then inserting a core of a material such as iron, steel or ferrite, a ceramic material containing iron oxide.

When a changing current passes through an inductor, an induced emf appears across its terminals. This opposes the change that created it, which explains why larger inductors are often referred to as **chokes**.

Inductors are used in many applications, from filters to florescent lighting and ignition units.

Over to you:



- Build the circuit shown.
  Switch **S** is connected in series with resistor **R**, which limits the current through the inductor.
  The inductor, **L** is the primary of the 2:1 transformer, (the secondary winding is not used.)
- Set the power supply to 12V DC.
- Connect an oscilloscope to display the voltage drop across the inductor. Make sure the leads are connected with the polarity shown on the diagram. Typical settings for the oscilloscope are given in the next section.
- Switch on the DC power supply and then press, and hold the switch closed so that current flows through the inductor.
- Keep the switch closed for a few seconds then release it and observe the result on the oscilloscope . You should see a sudden, very large negative voltage spike.
- You may have to repeat this step several times to obtain a satisfactory display.

(Optional extension:)

- Repeat the investigation with the other inductors to see how inductance affects the size of the induced emf.

Typical oscilloscope settings:

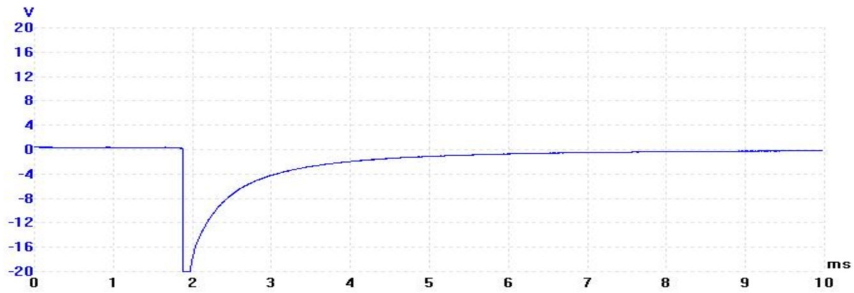
Timebase	1 ms/div (X multiplier x1)		
Voltage range	Input A ±20 V DC (Y multiplier x1)		
	Input B Off		
Trigger mode	Repeat	**Trigger channel**	Ch.A
Trigger direction	Falling	**Trigger threshold**	1000 mV

Worksheet 10
Inductors and back emf

So what?

The trace shows a typical display, produced when the switch is released.

It shows the large negative spike generated as the magnetic field in the inductor suddenly collapses, when the current is interrupted.



w10c

Here's the physics:

- When the switch is closed, a steady current flows in the inductor and produces a steady magnetic field in its core.
- When the current is interrupted by opening the switch, the magnetic field collapses rapidly because there's nothing to maintain it.
- When the field collapses through the turns of the inductor coil, a voltage is generated across the terminals of the inductor. This can be many times greater than the supply voltage.
- The induced voltage is negative. In other words it opposes the original direction of current flow, and as a result it is called a *back emf.*
- A large 'back emf' can cause considerable damage such as arcing at switch or relay contacts and destruction of low-voltage electronic components.

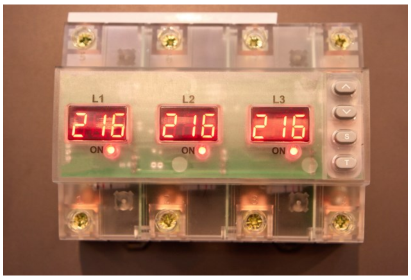
For your records:

Back emf:

- appears whenever current is suddenly removed from an inductor.
- opposes the original current flow.
- can be very large and many times greater than the supply voltage.

- We often take precautions to limit the back emf generated when an inductive component (such as a relay coil) is switched on and off, using a diode, connected with reverse bias, in parallel with the inductive component.

Worksheet 11
AC measurements



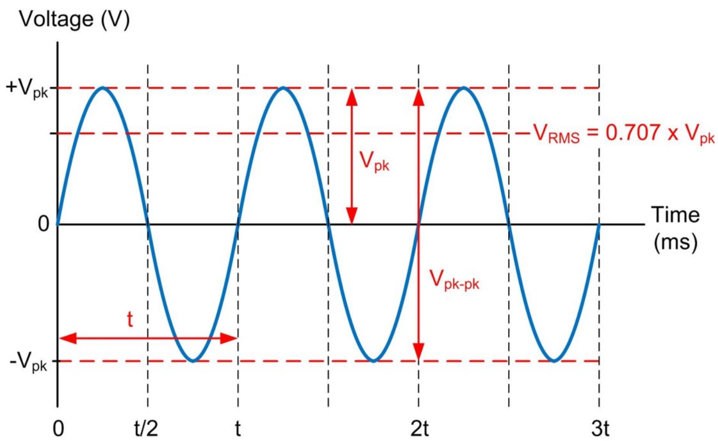
The ability to make accurate measurements of alternating current and voltage is an important skill. In reality, AC measurements are not quite so easy to make as DC.

Here's a brief introduction to some of the vocabulary that you will need to get to grips with:

AC voltage and current

When measuring alternating voltage and current, we usually use *root-mean-square* (rms) values. These are the effective value of an alternating current - the DC equivalents that would produce the same heating effect if applied to a resistor.

It is sometimes useful to use the *peak* or *peak-to-peak* value of an AC waveform as they are easy to measure using an oscilloscope (see the picture).



Frequency

The frequency of a repetitive waveform is the number of cycles of the waveform which occur in one second. Frequency is expressed in hertz, (Hz), - a frequency of 1Hz means one cycle per second - 400Hz means that 400 cycles of it occur every second.

Periodic time

The periodic time (or period) of a signal is the time taken for one complete cycle of the wave. The relationship between periodic time, t, (in s) and frequency, f, (in Hz) is:

$$t = 1 / f \quad \text{or} \quad f = 1 / t$$

For example, the periodic time of a 400Hz AC signal is 2.5ms.

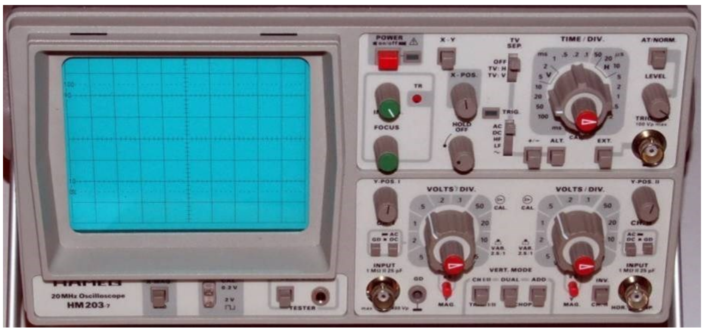
Waveforms

Waveforms describe how voltage or current signals vary with time.

Common types include sine (or sinusoidal), square, triangle, ramp and pulse.

In this module we look at the most basic of these, the sine wave.

Waveforms are viewed and measured using an oscilloscope, either a conventional type or a virtual instrument (like a Picoscope).



Worksheet 11

AC measurements

Over to you:

- Connect an oscilloscope to display the output of an audio frequency signal generator. (Typical oscilloscope settings are given at the bottom of the page.)
- Adjust the signal generator to produce a sine wave output at 100Hz. and set the amplitude of the signal to 2V peak-peak.
- Sketch the oscilloscope display on graph paper, and make sure that you label the voltage and time axes.
- Use the X-axis (time scale) on the oscilloscope to measure accurately the time for one complete cycle (i.e. the periodic time). Record this in a table like the one shown opposite.
- Set the signal generator to 200Hz, then 400Hz, 600Hz, 800Hz and finally 1,000Hz and at each frequency measure and record the time period in the table.

Frequency in Hz	**Periodic time in ms**
100	
200	
400	
600	
800	
1000	

- Use the data in the table to plot a graph of periodic time against frequency. Use this to verify the relationship f = 1/t.

For your records:

- Write a short description of the following AC terms:
  - amplitude;
  - frequency;
  - period.
- The rms (root-mean-square) value of a sinusoidal AC signal gives the equivalent DC voltage which has the same effect. To replace an AC power source, which has a rms voltage of 12V, you could use a 12V DC source instead.
- The rms and peak values of a sinusoidal AC signal are related by the relationship:

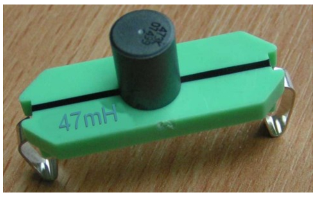
$$\text{Peak value} = \text{rms value} \times \sqrt{2}$$

Typical oscilloscope settings:

Timebase - 1ms/div (X multiplier x1)
Voltage range - Input A - ±5V DC (Y multiplier x1) Input B - Off
Trigger Mode - Auto **Trigger Channel** - Ch.A
Trigger Direction - Rising **Trigger Threshold** - 10mV

Worksheet 12

Inductors and AC

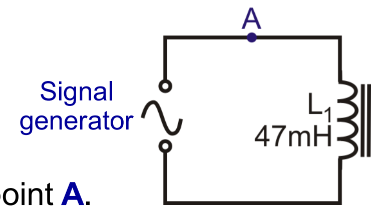


Resistors oppose electric currents. Inductors oppose *changes* to electric currents, but the mechanism is different.

An electric current flowing in the inductor, sets up a magnetic field. Increasing the current means increasing the magnetic field, and that takes energy from the current, opposing the increase. Reducing the current means reducing the magnetic field, and that releases energy which tries to maintain the current.

Inductors behave rather like flywheels on a rotating shaft. Their angular momentum tries to keep the shaft rotating at the same speed. When the shaft starts to slow down, the stored energy in the flywheel tries to keep it going. When the shaft tries to speed up, the flywheel requires energy to speed it up, and so the flywheel seems to resist the change.

Over to you:



- Connect a 47mH inductor in series with a signal generator, as shown in the circuit diagram.
- Use extra connecting links so that the current can be measured at point **A**.
- Remove the connecting link at **A**, and connect a multimeter, set to read up to 20mA **AC**, in its place.
- Set the signal generator to output a frequency of 50Hz, with an amplitude sufficient to produce a measurable current.
- Record the current flowing at point **A** in a table like the one below.
- Remove the multimeter and replace link **A**.
- Set up the multimeter to read **AC** voltages of up to 20V and connect it in parallel with the inductor.
- Record the voltage in the table.
- Now change the power supply frequency to 100Hz and repeat the measurements. Record them in the table.

- Do the same for frequencies of 1kHz (1 000Hz) and 10kHz (10 000Hz). Again, record these measurements in the table.

Frequency	Current I	Voltage V
50Hz		
100Hz		
1kHz		
10kHz		

Worksheet 12

Inductors and AC

So what?

- Resistors behave in a straightforward way, spelled out by Ohm's Law. If you double the current through the resistor, you double the voltage dropped across it, and so on. The ratio of voltage to current is called resistance.
- Inductors are more complicated. If you double the *rate of change* of current through it, you double the voltage dropped across the inductor, and so on. The ratio of voltage to rate of change of current is called ***inductance L***.
- The higher the frequency of the AC, the faster the current changes, and so the greater the voltage drop across the inductor. In other words, the voltage dropped depends on the frequency of the AC supply. This is **not** the case with pure resistors, where the frequency has no effect.
- We describe this behaviour in terms of the **(inductive) reactance**, $\mathbf{X_L}$, defined, in the same way as resistance, as $\mathbf{X_L = V / I}$. As a result, the units of reactance are ohms.
- The inductive reactance measures the opposition of the inductor to changing current. The higher the frequency ,**f**, the greater the change in current. In fact, the formula for inductive reactance is: $\mathbf{X_L = 2 \pi f L}$
- Using your measurements, calculate the X_L, from the formula: $X_L = V / I$ and compare that with the value calculated using $X_L = 2 \pi f L$ where L = 47mH.
- Carry out those calculations and fill in a table like the one following with your results:

Frequency	**Inductive reactance $X_L = V / I$**	**Inductive reactance $X_L = 2 \pi f L$**
50Hz		
100Hz		
1kHz		
10kHz		

For your records:

- The opposition of an inductor to changing currents is called inductive reactance, X_L, given by the formula: $X_L = 2 \pi f L$ where f is the frequency of the AC signal, and L is the inductance of the inductor.
- It can also be obtained from the formula $X_L = V / I$, where V and I are rms voltage and current respectively.
- Inductance is measured in a unit called the henry, (H) and reactance in ohms.
- Complete the following:
    - When the AC frequency is doubled, the inductive reactance is …………… .

Worksheet 13

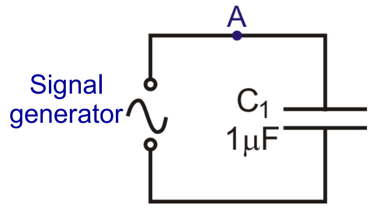
Capacitors and AC

An electric current sets up a *magnetic* field inside an inductor. This then oppose changes to electric *currents*.

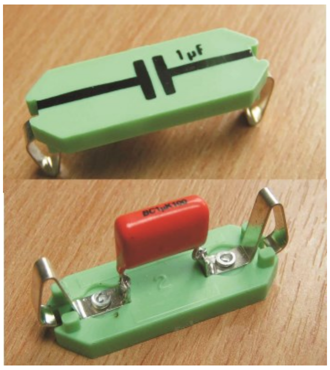
An electric current sets up an *electric* field across the plates of a capacitor. This opposes changes to the *voltage* applied to the capacitor. Before the voltage can increase, electrons must flow onto the plates of the capacitor, increasing the electric field. This requires energy. When the voltage tries to decrease, electrons flow off the plates, reducing the electric field. These electrons try to maintain the voltage across the capacitor.

Capacitors behave rather like buckets in a water circuit. They must fill up before any water flows anywhere else in the circuit. When the flow of water starts to fall, excess water flows from the bucket, trying to maintain the flow.

Over to you:



- Connect a 1µF capacitor in series with a signal generator, as shown in the circuit diagram.
- Use extra connecting links so that the current can be measured at point **A**.
- Remove the connecting link at **A**, and connect a multimeter, set to read up to 20mA **AC**, in its place.



- Set the signal generator to output a frequency of 50Hz, with an amplitude sufficient to produce a measurable current.
- Record the current flowing at point **A** in a table like the one below.
- Remove the multimeter and replace link **A**.
- Set up the multimeter to read **AC** voltages of up to 20V and connect it in parallel with the capacitor.
- Record the voltage in the table.
- Now change the signal generator frequency to 100Hz and repeat the measurements. Record them in the table.
- Do the same for frequencies of 1kHz (1 000Hz) and 10kHz (10 000Hz). Again, record these measurements in the table.

Frequen-cy	Current I	Voltage V
50Hz		
100Hz		
1kHz		
10kHz		

Worksheet 13

Capacitors and AC

So what?

- With resistors, when you double the *current* through the resistor, you double the voltage dropped across it, and so on. With inductors, when you double the *rate of change* of current through the inductor, you double the voltage dropped across it, and so on.
- Capacitors oppose a changing *voltage*. The faster the *rate of change of voltage*, the greater the current that must flow to charge or discharge the capacitor. The higher the frequency of the AC, the faster the *voltage* changes, and so the greater the current flowing in the circuit. In other words, the current depends on the frequency of the AC supply.
- We describe this behaviour in terms of the **capacitive reactance**, $\mathbf{X_C}$, defined, in the same way as resistance, as $\mathbf{X_C = V / I}$. As before, the units of reactance are ohms.
- The capacitive reactance measures the opposition of the capacitor to changing current. The higher the frequency ,**f**, the greater the change in voltage, and the greater the current flow. The formula for capacitive reactance is: $\mathbf{X_C = 1/(2 \pi f C)}$
- Capacitors are very much a mirror image of inductors. As the frequency of the AC supply increases, an inductor offers more opposition, (i.e. the inductive reactance increases, and the current decreases) whereas a capacitor offers less opposition, (i.e. the capacitive reactance decreases, and the current increases).
- Using your measurements, calculate the X_C, using both :

  $X_C = V / I$ and $X_C = 1 / (2 \pi f C)$ where $C = 1\mu F$.
- Carry out those calculations and fill in a table like the one following with your results:

Frequency	**Capacitive reactance $X_L = V / I$**	**Capacitive reactance $X_L = 2 \pi f L$**
50Hz		
100Hz		
1kHz		
10kHz		

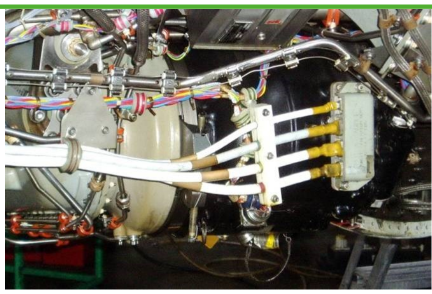
For your records:

- The opposition of a capacitor to changing voltage is called capacitive reactance, X_C, given by the formula: $X_C = 1 / (2 \pi f C)$ where f is the AC signal frequency, and C is capacitance.
- It can also be obtained from the formula $X_C = V / I$, where V and I are rms voltage and current respectively.
- Capacitance is measured in farads (F), though, in practice, this unit is too large - most have values given in microfarads (μF).
- Complete the following:
  - When the AC frequency is doubled, the capacitive reactance is …………… .

Worksheet 14
Generating electricity

Many electrical components, such as the generator shown here, are based on the application of electromagnetism.

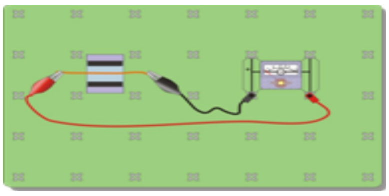
To generate an emf, you need a magnetic field, a wire conductor and relative movement as you will see from this investigation.



w14a

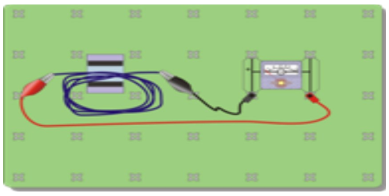
Over to you (optional investigations):

- Set up the arrangement shown in the diagram. The amount of electricity generated will be tiny. We can observe it (just) using the Locktronics milliammeter module! Alternatively, use a multi-meter, set to its most sensitive DC current scale. (However, this *samples* the input signal periodically. If you move the wire in between samples, the meter may miss the event ,so you may need several attempts to produce convincing results.)



w14b

- Move the wire into the magnetic field between the magnets as fast as you can. The movement must be at right-angles to the magnetic field and at right-angles to the length of wire. Watch the meter reading, as you do so.
- Next reverse the direction of motion, again watching the meter to see the effect.
- Now replace the single strand of wire with a coil of about fifty turns. You can use sticky tape, or a paper clip to hold the turns together. The diagram shows one way to set this up.



w14c

- Move the coil up and down, into and out of the magnetic field. Watch the meter reading as you do so.
- Notice the effect of speed of movement on the amount of electricity produced.
- To see the effects more clearly, set up an oscilloscope to monitor the emf. generated. Connect the single strand of wire and then the coil to the oscilloscope input. (Suitable settings are given in the next section.)

Typical oscilloscope settings:

Timebase 5s/div (X multiplier x1)

Voltage range Input A ±100mV DC (Y multiplier x1)
Input B Off

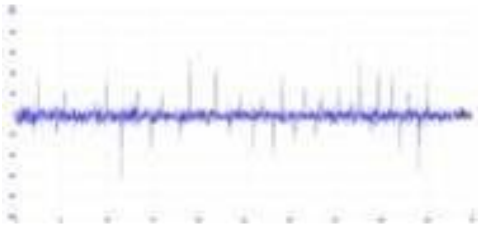
Trigger mode Auto **Trigger channel** Ch.A

Trigger direction Rising **Trigger threshold** 10mV

Worksheet 14

Generating electricity

So what?



From the results, the generated current and voltage have:

- a **magnitude** that depends on:
    - the speed of movement;
    - the number of wires present.
- a **polarity** that depends on the direction of motion.

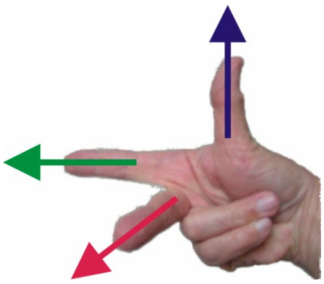
Typical results can be seen in oscilloscope traces like that shown above. The sharp peaks indicate pulses of current generated by moving the coil inside the magnetic field. The lower band is electrical noise. Again, sampling has an effect. The system can miss some peaks because they occur between samples. (Experiment with other time base settings to try to get more reliable results.)

Here's the underlying physics:

- When the wire moves at right-angles to the magnetic field, the electrons move with it.
- Whenever electrons move, they generate a magnetic field.
- This interacts with the field of the ceramic magnets, exerting a force on the electrons at right-angles to the direction of motion and to the magnetic field.
- This force pushes electrons from one end of the wire to the other, generating a voltage and a current if there is an electrical circuit.
- Using a coil of wire increases the size of voltage and current generated because each turn in it is moving inside the magnetic field, and so has electricity generated in it. The effects of all these turns adds together, increasing the amount of electricity generated.

Fleming's Right-hand Rule:

Fleming devised a painful way of predicting the direction of the generated current .



Use your **right**-hand to produce the gesture shown in the picture. When the **F**ore finger points in the direction of the magnetic **F**ield (from North pole to South pole,) and the thu**M**b points in the direction of the **M**otion, the **C**entre finger points in the direction of the resulting **C**urrent. This is also known as the *dynamo rule*.

For your records:

Use the results of the investigation to answer the following questions:

- What factors determine the emf generated?
- How can you predict the polarity of the emf generated?

Worksheet 15

Generating electricity - a closer look

locktronics

The last worksheet focussed on the physics of electricity generation. This one looks at how to generate more electricity and at an important application.

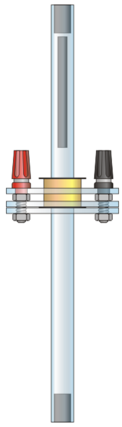
In a car, the electrical system obtains its energy from a combination of battery and alternator. The alternator output is rectified and regulated. It delivers
electrical energy to peripheral units, like headlamps, and also keeps the lead-acid battery charged.

In some vehicles, eddy current braking uses the same principles to slow down vehicles without relying on friction braking.

Over to you (optional investigations):

1. Generating more electricity:

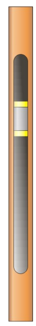
The amount of electricity generated depends on factors like the number of turns of wire, and the speed of motion of a magnetic field through it. This investigation looks at the electricity generated when a magnet is dropped through a 400 turn coil, mounted on a clear plastic tube



- Connect the Faraday's law apparatus, shown opposite, to an oscilloscope. This is used to monitor any electricity generation.
  Typical settings are given in the section at the bottom of the page.
- Drop the magnet through the coil, and record the result on the oscilloscope.
- Reverse the magnet and do the same thing again.

2. Eddy current magic:

The Lenz's law kit consists of a copper tube and two identical-looking projectiles.



- Hold the copper tube in a vertical position.
- Drop the first projectile down the tube.
- Now drop the second projectile. What is the difference?
- Look at the two projectiles. One is a magnet, the other is not. Find out which is which - you might need an object like a paper clip to help you decide.
- Which fell faster? Why?

Typical oscilloscope settings:

Timebase 1s/div (X multiplier x1)

Voltage range Input A ±500mV DC (Y multiplier x1)
Input B Off

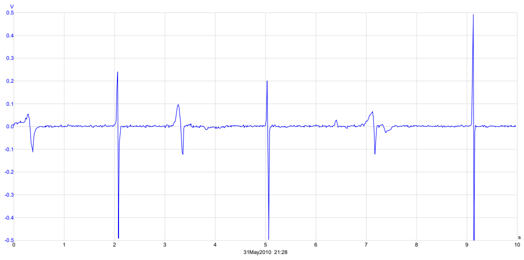
Trigger mode Auto **Trigger channel** Ch.A

Trigger direction Rising **Trigger threshold** 10mV

Worksheet 15

Generating electricity - a closer look

So what?


w15d

A typical trace for the first investigation is shown opposite.

The spikes are produced by pulses of current generated when the magnet falls through the coil. These are around ten times bigger than in the previous investigation.

The bipolar nature of the pulses (above and below the centre axis,) is the result of the magnet first approaching and then retreating from the coil, generating a current first in one direction and then in the other.

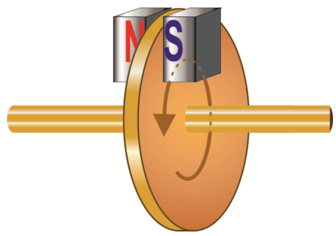
This is a demonstration of Faraday’s law of electromagnetic induction.

Eddy current magic -

The unmagnetised projectile did exactly what was expected - it fell under gravity.

The magnet fell much more slowly. Its moving magnetic field interacted with the conductor, the copper pipe, and random currents were generated as a result. These produced a magnetic field that opposed the motion, slowing it down, just as Lenz’s law predicts.

This effect is used in braking systems, for some buses and trains. A disc attached to the rotating wheels of the vehicle sits in between the poles of an electromagnet. Normally, there is no effect on the spinning disc. However, when the electromagnet is energised, the resulting magnetic field induces eddy currents in the spinning disc. In turn, these produce a magnetic field that opposes the motion, slowing down the disc and converting its rotational energy to heat.



w15e

The braking effect is varied by adjusting the current to the electromagnet. As the spinning disc slows, the induced eddy currents decrease, reducing the braking effect. In this way, the vehicle is braked smoothly.

For your records:

- Investigate the connection between the speed of movement and the amount of electricity produced using Faraday’s law kit.
- Write an account, in less than fifty words, to **explain** to a colleague what happened in the Lenz’s law demonstration.
- Use the internet to find out as much as you can about:
    - applications of Faraday’s law of electromagnetic induction, (such as induction heaters;)
    - applications of Lenz’s law (such as magnetic levitation for transport.)
- Present your results to the rest of the class in the form of a display.

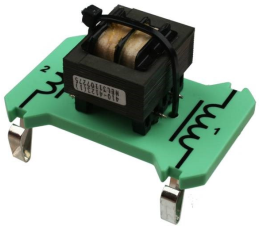
Worksheet 16

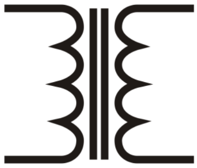
Transformers

A huge advantage of generating electricity as AC is that it allows us to use transformers, which allow us to step-up or step-down and AC voltage to any desired value.

Our treatment of the transformer links it, in four steps, to the principles we met earlier. We saw that an electric current is generated when a magnetic field moves across a conductor. In the transformer, the moving magnetic field is produced by an electro-magnet supplied with AC.

Next, you investigate a simple transformer made from two coils with a 'core' linking the magnetic field of one coil to the other.





Over to you:

Step 1 - Moving the magnet:

- Connect a coil of wire to an oscilloscope. Typical settings are given on the next page.
- Plunge a magnet into the coil, and then pull it out, watching the oscilloscope as you do so.

Step 2 - Moving the coil:

- Using the same arrangement, move the coil over the magnet, while watching the trace.

Step 3 - Electromagnet, not magnet:

- Now, replace the magnet with an electromagnet, made from a second coil connected to the DC power supply, set to 3V.
- Move the first coil over the electromagnet, as in step 2, observing the effect.
- Sit the second coil on top of the first. Switch the electromagnet on and off, watching the trace as you do so.

Step 4 - AC not DC:

- This time, the moving magnetic field is produced not by physical movement of the magnet, or the coil, but by using an alternating magnetic field.
- Disconnect the DC power supply from the electromagnet, and instead connect a signal generator, set to an amplitude of 3V and a frequency of 300Hz.
- Again, sit the electromagnet on top of the first coil.
- Switch on the signal generator, and watch the trace.
- Lower a ferrite core down the middle of the two coils, and notice the effect this has. We now have a simple but very inefficient transformer!
- Notice the effect of doubling the amplitude of the supply from the signal generator.
- Explore what happens if you separate the two coils or link them with a material like steel instead of ferrite for the core.

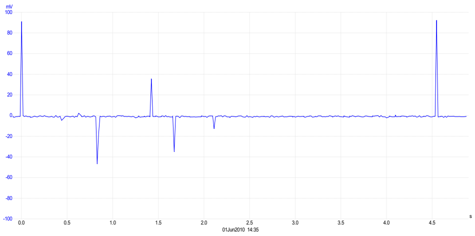
Worksheet 16

Transformers

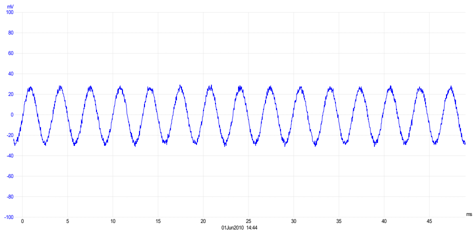
So what?

The pictures show typical traces:

- the upper one shows current spikes generated when the DC supply to the second coil is switched on and off.
- the lower one shows current generated when the second coil is connected to the AC supply .



w16e



w16d

It was pointed out earlier that the essential ingredients to generate electricity are a magnet, a piece of wire and movement. The only difference here is that we have replaced the magnet with an electromagnet (second coil), and produced movement by using an alternating magnetic field.

One coil, called the **primary**, is supplied with AC current, and generates an alternating magnetic field. This links with the other coil, called the **secondary**. As a result, an alternating voltage is generated in the secondary. This is the principle of the transformer.

Some refinements:

- The *strength* of the magnetic field in the primary depends on factors like:
  - the number of turns of wire in the primary coil
  - the current flowing through it, which, in turn, depends on the voltage applied to it.
- The *voltage* generated in the secondary coil depends on factors like:
  - the strength of the magnetic field generated by the primary
  - the number of turns of wire in the secondary coil
  - how effectively the magnetic field of the primary links with it.

In other words, the voltage generated in the secondary depends on the number of turns in the primary, and the number of turns in the secondary. The next worksheet explores this link.

For your records:

- Copy the circuit symbol for the transformer.
- Describe the role played by each of the three components in the transformer:
  - the primary coil,
  - the secondary coil,
  - the core.

Typical oscilloscope settings:

Timebase		1s/div (X multiplier x1)
Voltage range		Input A - ±500mV DC (Y multiplier x1)
		Input B - Off
Trigger Mode	Auto	**Trigger Channel** - Ch.A
Trigger Direction	Rising	**Trigger Threshold** - 10mV

Worksheet 17

Practical transformers

Transformers play an important role in many electrical and electronic applications by allowing AC voltages to be stepped up or down to any desired value.

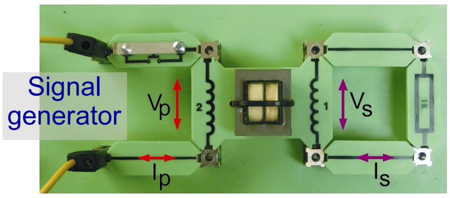
In this worksheet you investigate the operation of a small transformer, which has a laminated steel core, when used for step-down and then step-up operation.

Over to you:

Step-down transformer:

In a step-down transformer, the primary coil, the one supplied with AC power, has more turns of wire than the secondary, the one that generates the transformer output voltage.

Here we use a commercial transformer with a turns ratio of 2:1, meaning that one coil has twice as many turns as the other. The primary will be the ‘2’ coil, and the secondary the ‘1’ coil.



- Build the system shown, which delivers power to a 1kΩ load.
- Connect a signal generator to the ‘2’ coil (primary). Use the low impedance output (typically 50Ω.) Set it to output a sine wave with frequency 300Hz, and amplitude 6.0V. (If in doubt, check these with your instructor.)
- Connect a digital multimeter, set on the 20V AC voltage range, to measure voltage V_P across the primary (the ‘2’) coil, and then V_S across the secondary (the ‘1’ coil.)
- Set the multimeter to the 20mA AC current range, and connect it to replace the link below the ‘2’ coil, to read the primary current, I_P.
- Replace the connecting link.
- In the same way, measure the current, I_S, in the secondary coil.
- Record all measurements in the table.

Step-up transformer:

In a step-up transformer, the primary coil has fewer turns than the secondary. In this case, the primary will be the ‘1’ coil, and the secondary the ‘2’ coil.

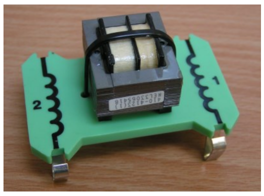
- The system is the same as above, except that the transformer carrier is now upside down.
- Connect the multimeter to measure the secondary voltage V_S. Adjust the amplitude of the signal from the signal generator until V_S is the same as in the previous investigation.
- Now measure and record V_P, I_P and I_S.

Reading	Step-down	Step-up
V_P		
V_S		
I_P		
I_S		

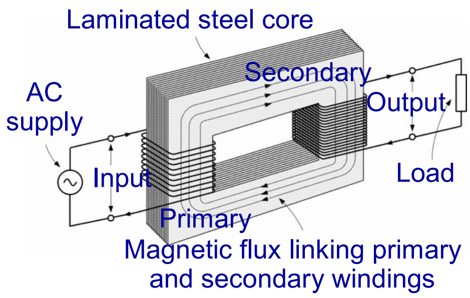
Worksheet 17
Practical transformers

So what?

The last worksheet looked at transformer principles, but the final device was very inefficient. The picture shows an improved version - two coils, side by side, as before, but now linked by a much more elaborate core, which threads through the centre of the coils, and wraps around the outside too. The result is a much more effective linkage between the secondary coil, and the magnetic field generated in the primary.



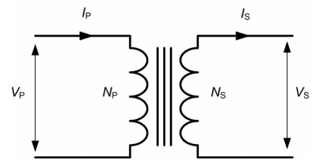
What the results show:



- Look at the ratio $V_P:V_S$ for both step-up and step-down transformers. The transformer equation says that, for an ideal transformer:

  $$V_P / V_S = N_P / N_S$$

  where N_P and N_S are the number of turns on the primary and secondary coils respectively.
- Next look at the ratio $I_P:I_S$ for both transformers.
  In general terms:



  - the step-up transformer ‘steps up’ the voltage (virtually doubles it) but ‘steps down’ the current - I_P, is much greater than I_S.
  - the step-down transformer ‘steps down’ the voltage, but delivers the same secondary current for a much smaller primary current.
  - Both transformers delivered the same voltage, V_S, for the 1kΩ load, and so I_S, the secondary current, should have been very similar.

The acid test:

What about the power delivered to the primary compared to the power obtained from the secondary?

Using the formula: Power = Current x Voltage:

Power delivered to the primary coil, $P_P = I_P \times V_P =$ ....mW

Power delivered from the secondary, $P_s = I_S \times V_S =$ ....mW

For an ideal transformer (100% efficient): $P_P = P_S$

and $I_S / I_P = N_P / N_S$

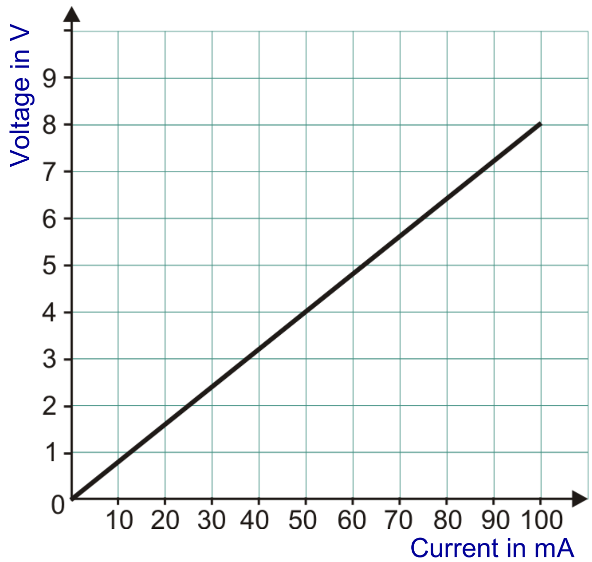
For your records:

- Copy the transformer equation, and explain what it means, in words.
- Explain what is meant by ‘*step-up*’ and ‘*step-down*’ when applied to transformers.
  Include the role of the number of turns of wire, and specify exactly what is stepped up, and what is stepped down in each case.

Revision Questions

1. In a car, a bulb is rated at 12V 48W.
Calculate:
- (a) the energy released in the bulb each second;
- (b) the current that normally flows in the bulb when it is fully lit;
- (c) the number of coulombs that pass through the bulb in 10s;
- (d) the energy that is lost by each coulomb.

2. The graph shows how the voltage across a component varies when the current through it changes.
Use it to answer the following questions:
- (a) does it obey Ohm's law – how do you know?
- (b) calculate the resistance of the device under test.



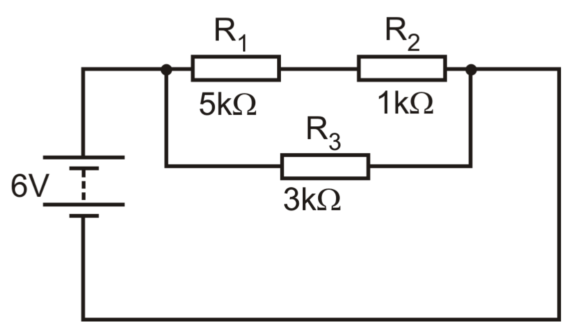
rq1

3. Four resistors, A, B, C and D, are made by winding wire around an insulating core. The same material is used for each.
The details of each resistor are shown below.
Which one has the greatest resistance?

Resistor A. Length of wire = 500mm; cross-sectional area = $0.005mm^2$
Resistor B. Length of wire = 750mm; cross-sectional area = $0.01mm^2$
Resistor C. Length of wire = 1000mm; cross-sectional area = $0.01mm^2$
Resistor D. Length of wire = 1250mm; cross-sectional area = $0.005mm^2$

4. Calculate the resistivity of a material given that a sample 2.0m long, with a cross-sectional area of $0.1mm^2$ has a resistance of 2.0Ω .

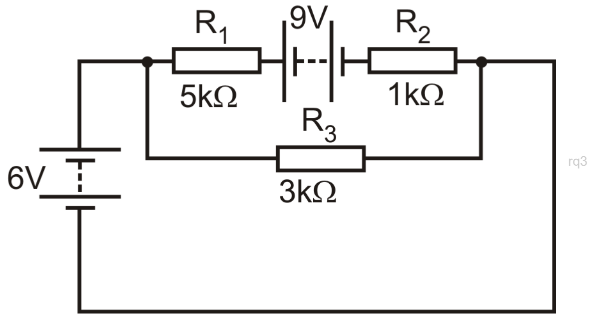
5. Use Ohm's law and Kirchhoff's laws to calculate:
- (a) voltage across R_3;
- (b) current through R_3;
- (c) voltage across R_1;
- (d) current through R_1;
- (e) voltage across R_2;
- (f) current supplied by 6V power supply.



rq2

6. Use Ohm's law and Kirchhoff's laws to calculate the following quantities in the circuit shown opposite:

(a) voltage across R_3;
(b) current through R_3;
(c) voltage across R_1;
(d) current through R_1;
(e) voltage across R_2;
(f) current supplied by 6V power supply.



7. Which of the following parallel-plate capacitors, A, B, C or D, has the biggest capacitance?

Capacitor A. Plate area = 0.5m^2 plate separation = 1mm dielectric = polystyrene;
Capacitor B. Plate area = 0.8m^2 plate separation = 2mm dielectric = polystyrene;
Capacitor C. Plate area = 1.0m^2 plate separation = 4mm dielectric = polystyrene;
Capacitor D. Plate area = 1.2m^2 plate separation = 6mm dielectric = polystyrene;

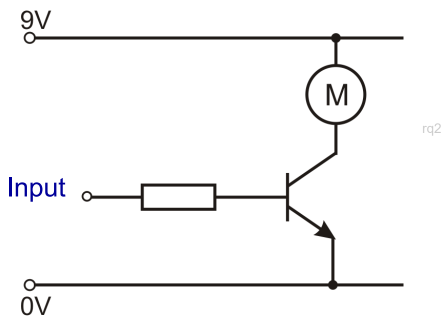
8. The following table gives some data about energy storage in capacitors.
Complete the blank cells.

Capacitor	Energy stored in J	Voltage across plates	Charge stored in C	Capacitance in F
W	0.24		0.08	
X		12		0.0001
Y			0.2	0.01
Z	0.01	2		

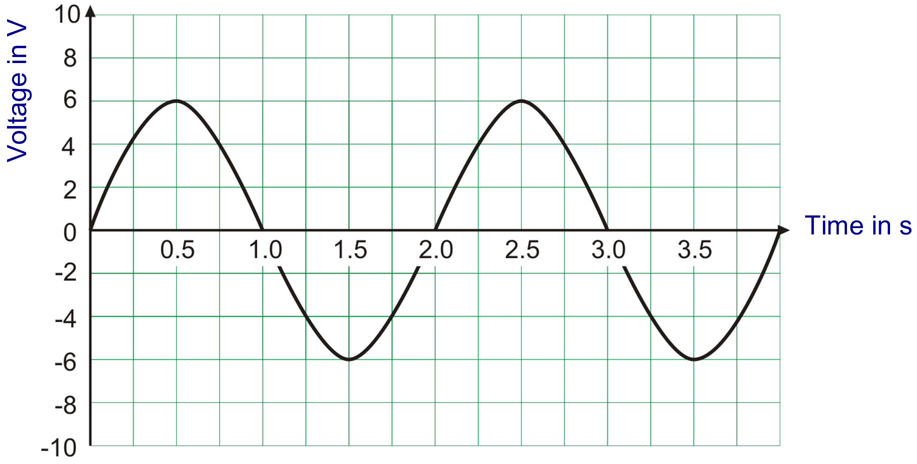
9. Which one of the following capacitors, **C**, will charge up the quickest when connected through resistor, **R**, to a 12V DC power supply?

Network	C in μF	R in kΩ
A	10	10
B	100	10
C	10	100
D	100	100

10. The circuit diagram shows a transistor switch controlling a motor. Add a diode to protect the transistor against back emf when it switches off.



11.



For the signal shown,

(a) measure:

(i) the amplitude;

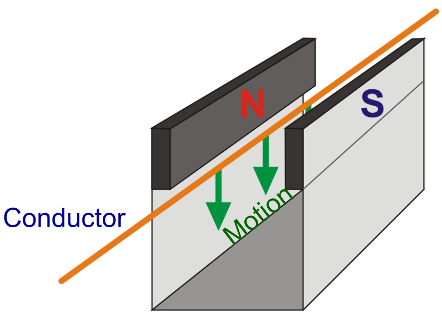
(ii) the period,

(b) Hence calculate the frequency.

12. (a) Calculate the inductive reactance of a 10mH inductor at a frequency of 300Hz.
(b) **Estimate** its reactance at a frequency of 600Hz.

13. (a) Calculate the capacitive reactance of a 10µF capacitor at a frequency of 300Hz.
(b) **Estimate** its reactance at a frequency of 600Hz.

14. When the conductor shown in the diagram moves down into the magnetic field of the magnets, in which direction will the current flow?



15. A transformer has 300 turns on its primary coil and 6000 turns on its secondary.
An AC signal of amplitude 12V and frequency 50Hz is applied to the primary.
What is the amplitude of the signal at the secondary?