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ELECTRICITY MATTERS 3

CP7664

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Contents

WORKSHEETS

Worksheet 1 - Measuring Current

Electric current is one of the fundamental quantities of the SI system.

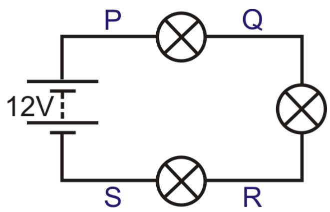
In simple circuits, we can use the brightness of bulbs as a measure of the size of the current. This is too crude for our present purposes for a number of reasons:

- Bulbs are mass-produced and so are not identical;
- Small changes in brightness, and so current, are difficult to judge;
- It doesn't work if the current is too small to light the bulb!

An ammeter is a much more reliable way of measuring current.

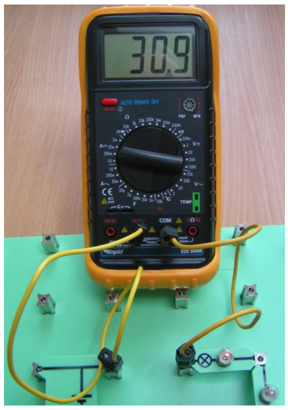
A multimeter, like that shown in the picture, offers a convenient and cheap way to measure a range of important electrical quantities such as current, voltage and resistance.

Over to you:



A. Series circuit:

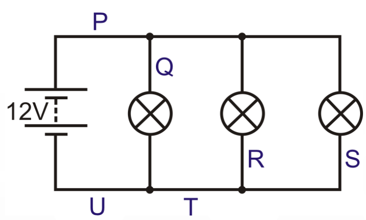
- Set up the arrangement shown, using 12V 0.1A bulbs.
- Make sure that the power supply is set to 12V.
- This is a series circuit - There is only one route for the electric current to flow around the circuit.
- Measure the current flowing at point **P**. To do this, plug the wires from the ammeter into the posts at the ends of the link at point **P**, and remove the link. This is shown in the picture.
- Record the result in the table.
- Now replace the link at **P.**
- Measure and record the current at point **Q** in the same way.
- Next, measure and record the current at points **R and S.**



Position	P	Q	R	S
Current				

B. Parallel circuit:

- Set up the second circuit, again using 12V 0.1A bulbs.
- The power supply is still set to 12V.
- This is a **parallel** circuit - there are 'branches' in the circuit, and a number of ways for current to flow around it.
- Measure the current at the points shown in the circuit diagram and record them in the table given below:



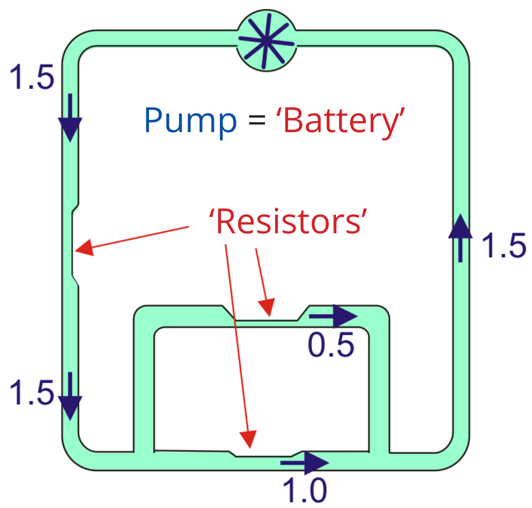
Position	P	Q	R	S	T	U
Current						

So What?

Can you spot patterns for the behaviour of electric currents in:
- Series circuits;
- Parallel circuits?

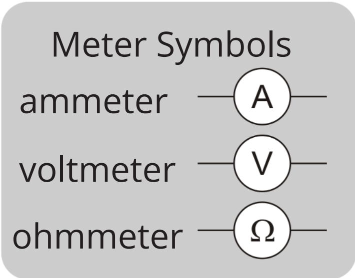
With some reasonable assumptions about the nature of electric current, your results make sense:
- An electric current is a flow of electrons, tiny particles found in all atoms.
- The current is a measure of how many electrons pass each second.
- Electrons lose energy as they flow around a circuit, but are not destroyed. The same number of electrons return to the power supply as left it.

It is worthwhile considering the flow of water around a closed system, like a central heating system. We need to insist that there are no leaks, as electricity does not leak from the circuits we have looked at. (It can do, when very high voltages are used!) For low voltages, the flow of water mirrors the flow of electricity.



The diagram shows a simple version of a water circuit. Here the battery is represented by the pump, and resistors (such as bulbs) by narrow sections of pipe. The flow-rates (currents) are shown in litres per minute.

For your records:
- In a series circuit, the same current flows in all parts.
- In a parallel circuit, the currents in all the parallel branches add up to the current leaving the power supply.



We can visualise electric current quite easily - it's the flow of tiny electrons around the circuit or, more precisely, the number of electrons per second passing a particular point in the circuit.

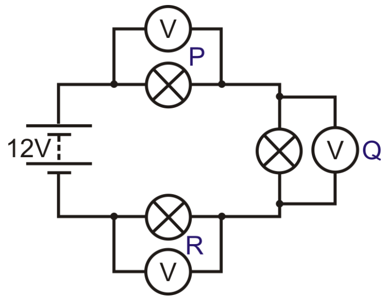
Voltage is more difficult to visualise . It is a measure of the force that pushes the electrons along the wires. It is a measure of the energy they transfer around the circuit. The bigger the power supply voltage, the more energy the electrons are given, and then give up, as they travel around the circuit.

However, voltage is easier to measure than current. No need to break the circuit - just add the voltmeter in parallel with the component you are interested in!

Over to you:

A. Series circuit:

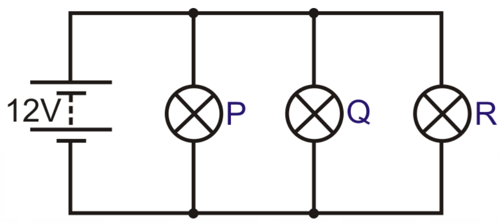
- Set up the arrangement shown, using 12V 0.1A bulbs, but without the voltmeters.
- Make sure that the power supply is set to 12V.
- This is a series circuit with only one route around it.
- Measure the voltage across the first bulb, shown as **P**. To do this, plug the wires from the voltmeter into the posts at either end of the bulb. Don't remove any connecting links!
- Record the result in the table.
- Next, measure and record the voltage across the second bulb, **Q**, in the same way.
- Then measure and record the voltage across the bulb, **R**.



Position	P	Q	R
Voltage			

B. Parallel circuit:

- Set up the second circuit, again using 12V 0.1A bulbs.
- The power supply is still set to 12V.
- This is a **parallel** circuit - notice the 'branches' in the circuit.
- Measure the voltage at the points **P, Q and R** and record them in the table given opposite:



Position	P	Q	R
Voltage			

So What?

Once again, look for patterns in your results for :
- Series circuits;
- Parallel circuits?

Hints:
- It will help to measure the power supply voltage in each circuit.
- Remember that 'voltage' is a measure of the energy each electron gains or loses.
- The most important idea is that the energy **gained** by each electron inside the battery or power supply (indicated by the **emf,** electromotive force) is equal to the energy **lost** (the **pd**, potential difference) in passing through resistive devices such as bulbs, as it goes round the circuit.
- Look at the routes the electrons can take. How many resistive devices does the electron pass through in each?
- In the series circuit, each electron passes through all three bulbs in going from one terminal of the power supply to the other.
- In the parallel circuit, each electron passes through only one bulb in going from one terminal of the power supply to the other.

For your records:
- In a series circuit, the voltages across the components add up to the voltage across the power supply .
- In a parallel circuit, the components all have the same voltage across them.

Worksheet 3 - Resistor Combinations

Resistors are basic components in electronic systems.

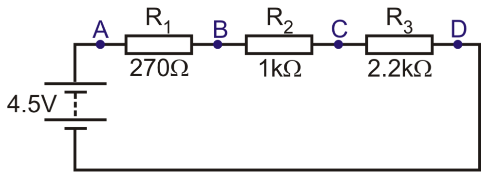
In a series connection, there are no alternative routes and no junctions. The electrons must pass through each resistor in turn.

Resistors connected in parallel offer different routes for the electric current. Easier routes pass greater current.

Over to you:

A. Series circuit:

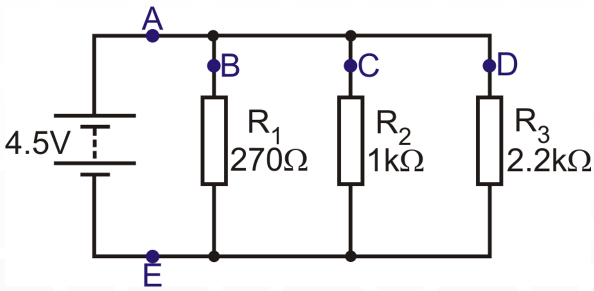
- Connect a 270Ω, a 1kΩ and a 2.2kΩ resistor in series with the power supply, as shown.
- Use extra connecting links so that the current can be measured at points **A, B, C and D.**
- Set the power supply to give a 4.5V output.
- Remove the link at **A**, and connect a multimeter to measure the current at that point. Record it in the table.
- Remove the multimeter and replace link **A.**
- Measure the current at **B,** then **C and D**, in the same way. Record these measurements.
- Connect the multimeter in parallel with resistor R_1 to measure the voltage across it, and record the result in the table.
- In the same way, measure and record the voltages across R_2 and R_3.



Power supply voltage	4.5V
Current at A in mA	
Current at B in mA	
Current at C in mA	
Current at D in mA	
Voltage across R_1	
Voltage across R_2	
Voltage across R_3	

B. Parallel circuit:

- Connect the 270Ω, 1kΩ and 2.2kΩ resistor in parallel, as shown below.
- Check that the power supply is still on the 4.5V setting.
- Measure the currents at **A, B, C, D and E.**
- Record them in the second table.
- Then, measure and record the voltages across R_1, R_2 and R_3.



Power supply voltage	4.5V
Current at A in mA	
Current at B in mA	
Current at C in mA	
Current at D in mA	
Current at E in mA	
Voltage across R_1	
Voltage across R_2	
Voltage across R_3	

So What?

Series combination

- Currents at **A, B, C and D** should be identical, as there is only one route around the circuit. Find the average of these measurements and record it in the table.
- Sum the voltages across the three resistors and write the result, V_S, in the table.
- There are two ways to calculate the total resistance:
  i. Use I and V_S in the formula R = V / I.
  ii. R_T equals the sum of the resistances.
- Calculate the total resistance, R_T, in both ways.
- Compare the two values for R_T. Think of reasons why these might be different.

Power supply voltage	4.5V
Average current I in mA	
Total voltage V_S across all resistors	
Total resistance $R_T = V_S / I$	
Total resistance $R_T = R_1 + R_2 + R_3$	

Parallel combination:

- Currents at **B, C and D** are different, as there are three different routes the current can take.
- R_1 is the smallest resistor, and so takes the biggest current. It is about four times smaller than R_2, and so the current at **B** should be about four times bigger than that at **C**.
- Similarly, the current at **C** should be about twice that at **D**.
- The power supply current divides up between the three possible routes, and then joins back up again. Adding the currents at **B, C and D**, the total should equal the current at **A, and E.**
- Do your results confirm these ideas?
- The voltages across the resistors should be the same as the power supply voltage.
- Calculate the total resistance RT using:
  i. I and VS in the formula R = V / I.
  ii. the formula:1/RT = 1/R1 + 1/R2 + 1/R3.

Again, why might these values for RT be different?

Power supply voltage	4.5V
Total of currents, I, at B, C and D in mA	
Average voltage across resistors V_S	
Total resistance $R_T = V_S / I$	
Total resistance from the $1/R_T$ formula	

For your records:

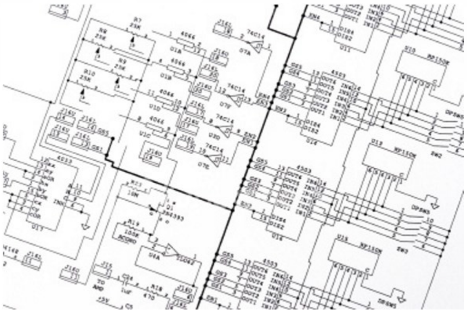
In a series circuit,

- The power supply voltage is shared between all components,
- The same current flows in all parts.
- The combined resistance equals the sum of individual resistances: $R_T = R_1 + R_2 + R_3 + \ldots$

In a parallel circuit,

- The current is shared between all components connected in parallel.
- Each component has the full supply voltage across it.
- The total resistance, RT of three resistors in parallel is: $1/R_T = 1/R_1 + 1/R_2 + 1/R_3$
- For two resistors in parallel, this reduces to: $R_T = \dfrac{R_1 \times R_2}{R_1 + R_2}$

Worksheet 4 - Current and Voltage in Complex Circuits

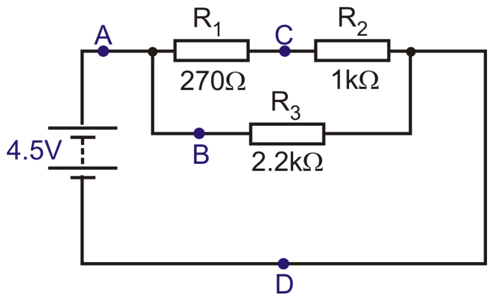


Most circuits are a combination of series and parallel connections.

The rules developed in the previous worksheets still apply, but only to the localised parts, instead of the whole circuit.

In a complex circuit, components in parallel have the same voltage across them but may carry different currents, while components in series have the same current flowing through them but may have different voltages across them.

Over to you:



- Connect a 270Ω resistor, a 1kΩ resistor and a 2.2kΩ resistor, as shown in the diagram.
- The 270Ω and 1kΩ resistor are in series, while the 2.2kΩ resistor is in parallel with that series combination.
- Use extra connecting links so that the current can be measured at **A, B, C and D.**
- Set the power supply to give a 4.5V output.
- Remove the connecting link at **A**, and connect a multimeter to read the current there.
- Record the measurement in the table.
- Remove the multimeter and replace link **A.**
- Remove the connecting link at **B**, and measure the current here.
- Record the current in the table.
- In the same way, measure and record the currents at points **C, and D.**
- Next, set up the multimeter to read the voltage across resistor R_1. Record it in the table.
- In turn, connect the multimeter to read the voltages across R_2 and R_3 and record them too.

Power supply voltage	4.5V
Current at A in mA	
Current at B in mA	
Current at C in mA	
Current at D in mA	
Voltage across R_1 (270Ω resistor)	
Voltage across R_2 (1kΩ resistor)	
Voltage across R_3 (2.2kΩ resistor)	

So What?

Let's analyse these results:

- The same current flows through R_1 and R_2, as they are in series. This is the current you measured at point **C**.
- The current readings at **A and D** should be the same, as these measure the total current leaving and returning to the power supply.
- The current from the power supply splits, with part going through R_1 (and then R_2), while the rest flows through R_3. In other words, adding together the readings at **B** and C should give a total equal to the reading at **A (and D).**
- The full power supply voltage appears across R_3, but is split between R_1 and R_2.
- Complete rows 2, 3 and 4 of the following table.

Power supply voltage	4.5V
Average of currents at A and D in mA (= I)	
Sum of currents at B and C in mA	
Sum of voltages across R_1 and R_2 ($=V_S$)	
Total resistance $R_T = V_S / I$	
Combined resistance of R_1 and R_2 (in series) (=RC)	
Total resistance of all three resistors $R_T = R_C \times R_3 / R_C + R_3$	

- Complete the table by calculating the total resistance RT of the three resistors by:

i. using I and V_S in the formula R = V / I;
ii. adding together the resistance of R_1 and R_2, as these are in series, to give R_C, their combined resistance, and then using $R_T = R_C \times R_3 / R_C + R_3$.

- Think of reasons why these two approaches might give different values for R_T. Which, do you think, gives the more reliable result?

For your records:
Optional extension:

- Create a different circuit, using three different valued resistors.
- Calculate the currents through and voltages across each resistor.
- Set up the circuit, and measure these values. Compare them with your calculated values.

Worksheet 5 - Ohm's Law

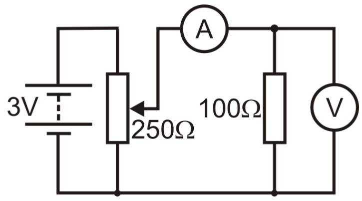
Current is a measure of how many electrons pass per second.

Voltage is a measure of how much energy the electrons gain or lose as they flow around a circuit. The term emf (electromotive force) applies when the electrons **gain** energy, as when they pass through a battery or power supply. Potential difference (pd) applies when the electrons **lose** energy, as when they pass through a resistor, bulb or motor.

Resistance shows how difficult it is for the electrons to pass through a material. In squeezing through, the electrons lose energy to the resistor, which warms up as a result.

The photograph shows Georg Simon Ohm—a significant figure in this study! Ohm's law leads to the important relationship we used in earlier worksheets: V = I x R

Over to you:



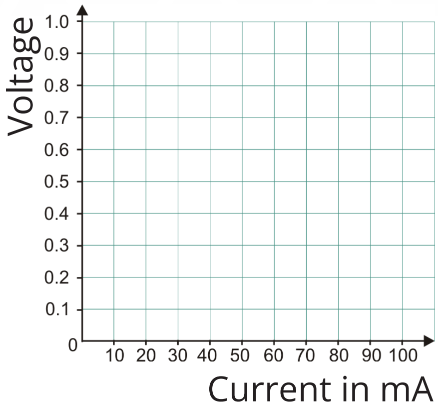
- Set up the arrangement shown in the diagram.
- Take care to use all three connections to make a 250Ω potentiometer! If in doubt, ask your teacher to check your circuit.
- The 250Ω 'pot' allows us to vary the voltage across the 100Ω resistor.
- Make sure that the power supply is set to 3V.
- Before you switch on, select the 200mA DC range on the ammeter, and 2V DC range on the voltmeter (or nearest values).
- Turn the knob on the 250Ω 'pot' fully anticlockwise, to set the voltage supplied to a minimum.
- Then turn it slowly clockwise until the voltage across the resistor reaches 0.1V and then read the current flowing through the resistor. Record it in the table.
- Turn the voltage up to 0.2V, and take the current reading again. Record it in the table.
- Keep doing this until the voltage reaches 1.0V.

Voltage across resistor	Current through resistor
0.1V	
0.2V	
0.3V	
0.4V	
0.5V	
0.6V	
0.7V	
0.8V	
0.9V	
1.0V	

(Don't go past this voltage or the resistor may overheat.)

So What?

- Plot your results on a graph, like that shown opposite.
- Ohm's law predicts a straight line, so draw the best straight line through your points.
- Calculate the gradient of your graph.
- If you have plotted it the same way round as the one shown, the gradient is the resistance of the resistor.
- Gradient = ...



For your records:

Ohm's law: states that the current through a conductor is directly proportional to the potential difference across it, providing the temperature remains constant. It leads to the formula:

$$V = I \times R$$

where V = pd across conductor, I = current flowing through it, and R = its resistance.

Resistor Colour Code:

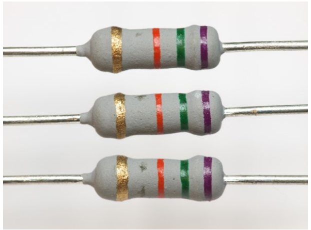
- Resistors often come with coloured bands across their body to show their resistance.

Black	Brown	Red	Orange	Yellow	Green	Blue	Purple	Grey	White
0	1	2	3	4	5	6	7	8	9

- Each colour represents a number, as shown in the table.
- To read the colour code, start from the opposite end to the gold or silver band:

Four-band resistors:

- Write down the number shown by the first colour band, and then the second colour band.
- Add the number of 0's shown in the next band (e.g. for red, add two 0's.)
- The final band (usually gold, (5%) or silver (10%)) shows you the tolerance - how accurately it is made.



For example, the resistors in the photograph have a resistance of:
7 (purple) 5 (green) 000 (orange)
= 75000Ω with a tolerance of 5%

Five-band resistors:

- Five colour bands are used for higher precision, i.e. lower tolerance resistors
- Write down the number shown by the first three colour bands.
- Add the number of 0's shown in the fourth band.
- The fifth band shows the tolerance. For example, brown = 1%, green = 0.5%.

WORKSHEETS

Worksheet 6 - Cells and Batteries

Individual cells are classed as either **primary or secondary.**

In primary cells, the active constituents are consumed in a one way chemical reaction. They are not rechargeable.

In secondary cells, the chemical reaction is reversible. They can be recharged, so that the cell can be re-used many times.

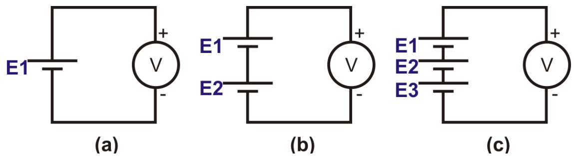
The table gives the emf of some popular types of cell.

Name	Type	Emf
Alkaine	Primary	1.5V
Lead-acid	Secondary	2.0V
Nickel-cadmium	Secondary	1.2V
Zinc-carbon	Primary	1.5V

A **battery** consists of a number of cells, connected either in series or in parallel.

Over to you:

Circuit (a) contains a single cell.
Circuits (b) and (c) are **batteries** of two and three cells respectively, connected in **series**.



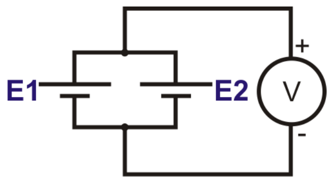
- Set up each arrangement in turn.
- Set a multimeter on the 20V DC range.
- Use it to measure the output voltage (emf) of each individual **cell.**
- Record your results in the first table.
- Next, measure the emf of **battery** (b), and then (c).
- Record the results in the second table.

Cell	Output voltage
E1	
E2	
E3	

Series-connected	Output voltage
(b) Two-cell battery	
(c) Three-cell battery	

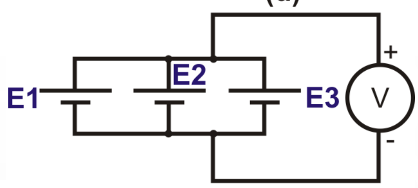
The next arrangements are batteries made using cells connected in **parallel.**

- Set up each in turn.
- As before, measure the output voltage of each **battery.**
- Record the results in the third table.



(d)

Parallel-connected	Output voltage
(d) Two-cell battery	
(e) Three-cell battery	



(e)

So What?

The predictions:

- For the two cell series-connected battery, the output voltage V should equal the sum of the emf's of the two cells, i.e.:

$$V = E1 + E2$$

- For the three cell series-connected battery, similarly,

$$V = E1 + E2 + E3$$

- In the case of the two cell parallel-connected battery, the output voltage V should equal the emf of each of the two cells, i.e.:

$$V = E1 = E2$$

- For the three cell series-connected battery,

$$V = E1 = E2 = E3$$

- Check that your measurements support these predictions.

Optional extension:

- Connecting cells in parallel does not increase the overall emf, so why do it?
- Investigate the effect on current by comparing the current delivered by the cell in circuit (a), with the current delivered by each cell in circuit (e). (Both circuits have the same overall emf!)

For your records:

Your investigation looked at the effect on **output voltage** of combining cells in series and then in parallel.

As far as the **current** delivered is concerned:

- With a series-connected battery, the same load current flows through each of the cells.
- With a parallel-connected battery, the load current is shared between the cells.

Combining cells in series increases the output voltage, but the cells all deliver the full load current and so will go 'flat' quicker.

Combining cells in parallel does not increase the output voltage. The cells take longer to discharge, and the available load current may be greater because the load current is shared.

WORKSHEETS

Worksheet 7 - Internal Resistance

Knowing the emf of a battery is not the full story!

A lead-acid battery like the one shown in the picture, has an emf of 12V, and costs around £60 (€70) whereas the same voltage in an alkaline battery costs a fraction of the price!

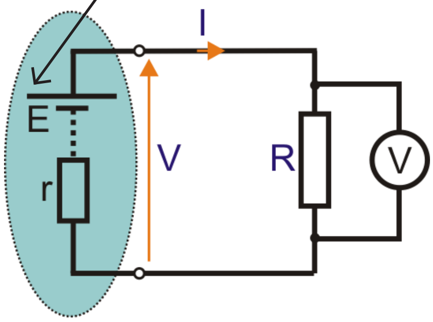
Why the difference? Internal resistance - the opposition to the flow of current within the battery itself!

An alkaline battery may have an internal resistance of only ~ 0.1Ω, but that of the car battery is typically one hundred times smaller than that. That is why it is expensive.

This worksheet shows how to measure internal resistance, and looks its importance.

Over to you:

The aim is to measure the internal resistance **r** of the cell.

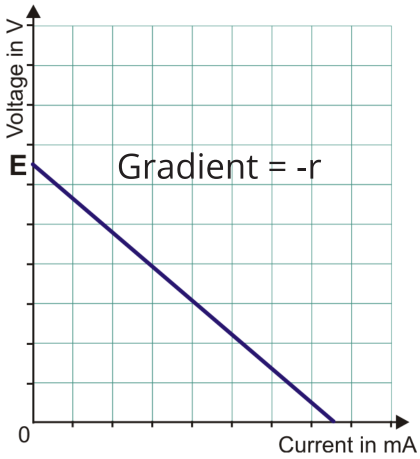


- Set up the arrangement shown opposite: It contains an AA zinc-carbon cell connected to a resistor **R**. To begin with, use a 100Ω resistor.
- With a multimeter set to the 20V DC range, measure the voltage, **V**, across the load resistor, **R**, and with a second multimeter, set to the 200mA DC range, measure the current **I** flowing through it.
- Record both in the table.
- Swap the 100Ω resistor for a 68Ω resistor, and repeat the measurements.
- Record the new measurements in the table.
- Repeat this process for the other resistor values listed in the table.
- The next page shows how to obtain the internal resistance of the cell from these readings.

Resistor R	Current I	Voltage V
100Ω		
68Ω		
47Ω		
10Ω		
3.9Ω		

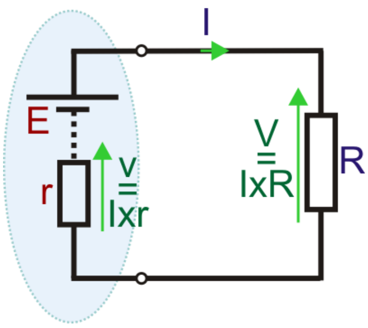
- **Optional extension:**
- Use the same procedure to measure the internal resistance of other cells, such as:
- A rechargeable cell,
- A new alkaline cell,
- A used alkaline cell.
- For each, record the results in a separate table, with an appropriate heading to identify the type of cell used.

So What?



- Use your results to plot a graph of voltage **V** against current **I.**
- Theory, given below, predicts a straight line relationship. Draw the best straight line through your points.
- The intercept on the 'Voltage' axis gives the emf of the cell. The gradient of the graph is '**-r**', from which the internal resistance r can be obtained.
- Use your graph to obtain:
- The emf, **E**, of the cell ....
- The internal resistance, r, of the cell ....

- **The theory:**



Looking at the circuit opposite:

E = V + v

= V + Ir

Re-arranging this:

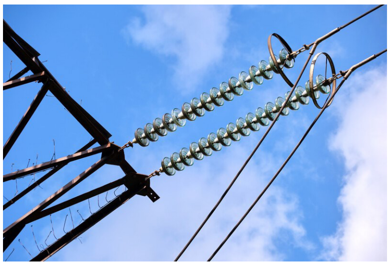
V = -Ir + E

This equation is in the form of the straight line equation 'y = mx + c', and so the graph of V against I has a 'y' intercept of **E** and a gradient of **-r**.

For your records:

Internal resistance:

- Limits the maximum current available from the cell. In some situations, this is a nuisance - the cheaper 12V alkaline battery unable to deliver enough current to start a car engine. In others it is an advantage - inadvertent short circuits do not lead to electrical fires resulting from overheated cables and components.
- Can be measured in a number of ways:
- DC load test (the one you used;)
- Flash testing - shorting the output with a 0.01Ω resistor for ~0.2s and measuring the terminal voltage;
- AC conductivity method - measuring the current resulting when a low frequency AC voltage is applied to the cell;
- Pulse testing - monitoring the terminal voltage when a series of pulses alternately charge and discharge the cell over a short period of time.
- All methods give similar results, though the internal resistance of a cell varies markedly with temperature (increasing at low temperatures.)



Resistors can be used to protect other components from excessive current. They can also be used in voltage dividers to carve up a voltage, from the power supply, for example, into smaller, predictable portions.

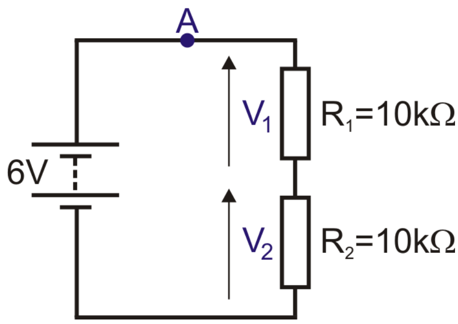
This is particularly useful when one of the resistors is a sensing component, such as an LDR, phototransistor or a thermistor, (temperature-dependent resistor.)

Voltage dividers form the basis of many sensing subsystems. The output voltage can represent temperature, light-level, pressure, humidity, strain or other physical quantities.

Over to you:

Part 1:

- Build the circuit shown opposite. It contains two 10kΩ resistors, connected in series.
- Set the power supply to give a 6V output.
- Remove the connecting link at **A**, and connect a multimeter, set on the 2mA DC range, to measure the current.
- Record it in the first table.
- Remove the multimeter and replace link **A.**
- Set the multimeter to read DC voltages of up to 5V.
- Connect it to read first, the voltage across resistor R_1, and then across R_2. Record these voltages in the table.



R_1 = 10kΩ, R_2 = 10kΩ		
Power supply voltage	6V	9V
Current at A in mA		
Voltage V_1 across R_1		
Voltage V_2 across R_2		

Part 2:

- Now, set the power supply to 9V.Repeat the measurements and record them in the same table.

R_1 = 1kΩ, R_2 = 10kΩ	
Power supply voltage	9V
Current at A in mA	
Voltage V_1 across R_1	
Voltage V_2 across R_2	

Part 3:

- Next, swap resistor R_1 for a 1kΩ resistor. Repeat the process and record the results in the second table.

Part 4:

- Finally, replace both resistors, with a 2.2kΩ resistor for R_1, and a 22kΩ resistor for R_2. Repeat the measurements and record them in the third table.

R_1 = 2.2kΩ, R_2 = 22kΩ	
Power supply voltage	9V
Current at A in mA	
Voltage V_1 across R_1	
Voltage V_2 across R_2	

So What?

First of all, the theoretical behaviour of this circuit -

- Resistors R_1 and R_2 are connected in series, giving a total resistance of:
$$R_T = (R_1 + R_2)$$
- The full power supply voltage, V_S, appears across R_T, and so the resulting current I, through the two resistors is given by:
$$I = V_S / R_T$$
- The voltage across resistor R_1 is given by:
$$V_1 = I \times R_1$$
- The voltage across resistor R_2 is given by:
$$V_2 = I \times R_2$$

Now apply this to your results.

- Calculate R_T, I, R_1 and R_2 for each circuit, and complete the next table with your results:

Part	Circuit	R_T	I	V_1	V_2
1	R_1 = 10kΩ, R_2 = 10kΩ, Vs = 6V				
2	R_1 = 10kΩ, R_2 = 10kΩ, Vs = 9V				
3	R_1 = 1kΩ, R_2 = 10kΩ, Vs = 9V				
4	R_1 = 2.2kΩ, R_2 = 22kΩ, Vs = 9V				

- Compare the values of V_1 and V_2 with those you measured for each circuit.
- Why might you expect the experimental values to be different?

For your records:
There is a straightforward way to view these results:

- The voltage from the power supply is shared between the resistors, so that
$$V_1 + V_2 = V_S.$$

- The bigger the resistor, the bigger its share of the voltage.

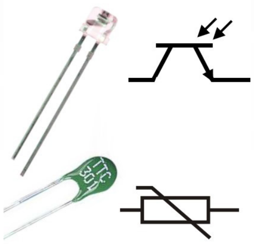
In the first circuit, $R_1 = R_2$ = 10kΩ so $V_1 = V_2 = ½V_S$.

In the second and third circuits, $R_2 = 10 \times R_1$, and so $V_2 = 10 \times V_1$.

The second and third circuits seem to perform in the same way, except for current. In some cases, it is best to use big resistor values, to reduce battery drain and power dissipation.

However, using lower resistor values allows us to draw more current from the voltage divider circuit without really affecting voltage V_1 and V_2.

Worksheet 9 - Phototransitor and thermistor



This investigation focuses on two very useful types of resistor, the light-sensitive phototransistor and the thermistor, which could be called a temperature-dependent resistor.

We will use them as the basis for light-sensing and temperature-sensing units, by combining them into voltage divider circuits.

Over to you:

The first aim is to measure the resistance of a thermistor at different temperatures.

- Half-fill a beaker with hot water.

Take care when handling hot water!
Use heat-resistant gloves to hold the beaker.

- Connect a thermistor carrier to the multimeter, set to the 20kΩ range. The diagram shows one way to do this using croc. clips. (Alternatively, use a separate thermistor connected directly to the multimeter.)

- Lower the thermistor carrier into a beaker of hot water.
- Lower a thermometer, or temperature probe to the same depth as the thermistor.
- Stir the water gently to make sure that the thermistor and thermometer / temperature probe are at the same temperature.
- Measure and record the resistance of the thermistor.
- Measure and record the temperature of the water.
- Add enough cold water to lower the water temperature by about 10^{0}C.
- Repeat the measurements until you have a set of at least six readings

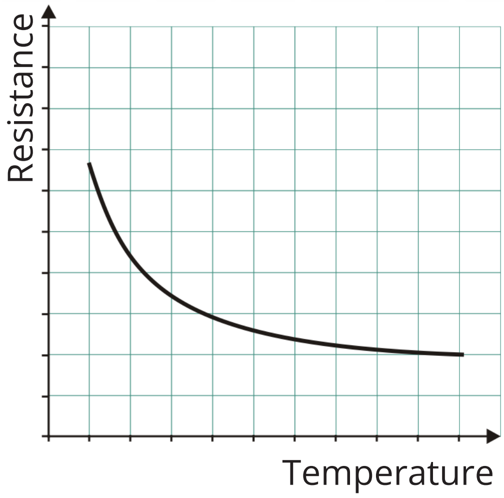
Temp in ^{0}C	Resistance in kΩ

A challenge!

- Design an experiment to investigate how the resistance of a phototransistor changes when the intensity of the light falling on it changes.
- You will need a way to produce different intensities of light, and a way to measure that. The phototransistor must be shielded from other sources of light.
- Discuss your ideas with your partner and then with your teacher.

So What?

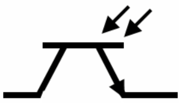
- Plot a graph to show your results. Choose suitable scales to match your readings.
- Draw a smooth curve, using your plotted points as a guide.



You should find that the resistance of the thermistor increases as the temperature drops. This kind of thermistor is called NTC (negative temperature coefficient.)

You can buy PTC (positive temperature coefficient.) thermistors. In these, the resistance drops when the temperature drops, and rises as the temperature rises.

For your records:
- The diagram shows the circuit symbols for the new components:

Phototransistor   Thermistor

- A NTC thermistor has a resistance which falls as the temperature rises.
- A PTC thermistor has a resistance which increases as the temperature rises.
- The resistance of a phototransistor falls as the light intensity increases.

Thermistor applications:
- NTC thermistors are used in temperature-sensing systems to monitor the temperature inside an incubator, or in motor vehicle cooling systems.
- NTC thermistors can be used to protect components from surges of current. Initially, they are cold, and so have a high resistance and so prevent large currents from flowing. As they subsequently heat up, their resistance falls, allowing higher currents to flow during normal operation.
- PTC thermistors can also be used to protect sensitive components. When a current flows through the thermistor, it heats up, and so its resistance increases. As a result, it heats up still more, increasing its resistance still further. The effect of this is to reduce the current flowing through the sensitive device, thus protecting it.

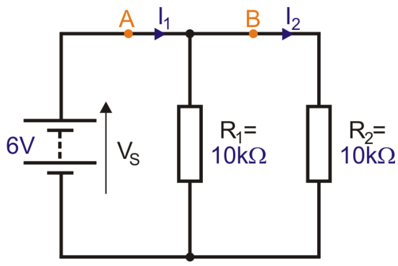
Worksheet 10 - Current Dividers

Voltage dividers use resistors connected in **series** to divide up a voltage into calculable fractions.

Current dividers use resistors connected in **parallel** to set up known fractions of current.

One application is in ammeters, where a known fraction of the total current passes through the meter and is measured. From that the total current is calculated.

Over to you:



- Connect two 10kΩ resistors in parallel, as shown opposite.
- Set the power supply to 6V.
- Remove the connecting link at A. Connect a multimeter, on the 2mA DC range, to measure the current, I_1, at **A** (i.e. the total current leaving the power supply.)
- **Record the value in the first table.**
- Remove the multimeter and replace link **A**.
- Measure the current at **B**, I_2, in the same way, and record it in the table.
- Set the multimeter to read DC voltages of about 10V, and connect it across the power supply to read V_S. **Record it in the table.**

R_1 = 10kΩ, R_2 = 10kΩ	
Power supply voltage, V_S	6V
Current at A, I_1, in mA	
Current at B, I_2, in mA	

- Set the multimeter to read DC voltages of about 10V, and connect it across the power supply to read V_S. **Record them in the second table.**

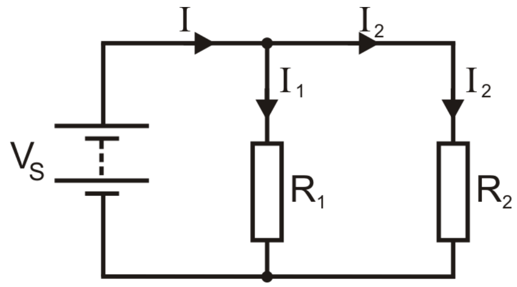
R_1 = 10kΩ, R_2 = 10kΩ	
Power supply voltage, V_S	9V
Current at A, I_1, in mA	
Current at B, I_2, in mA	

- Lastly, swap resistor R_1 for a 1kΩ resistor.
- Use the 10mA range when measuring currents.
- Leave the power supply set to 9V.
- Repeat the process.
- **Record the results in the third table.**

R_1 = 1kΩ, R_2 = 10kΩ	
Power supply voltage, V_S	9V
Current at A, I_1, in mA	
Current at B, I_2, in mA	

So What?

First of all, the theoretical behaviour:



- The voltage across resistor $R_1 = V_S$, and so:

  $V_S = I_1 \times R_1$
- Similarly, $V_S = I_2 \times R_2$

  which means that: $I_1 \times R_1 = I_2 \times R_2$

  or: $I_1 = I_2 \times (R_2 / R_1)$

The current I from the power supply splits into I_1 and I_2 at the junction.

In other words: $I = I_1 + I_2$

Using the equation for I1 given above: $I = I_2 \times (R_2 / R_1) + I_2$

$= I_2 (1 + R_2 / R_1)$

Re-arranging this gives $I_2 = I \times \dfrac{(R_1)}{R_1 + R_2}$

This can be used to calculate the current I_2 flowing in the branch of the circuit.

- Use this formula to calculate I_2 in the three cases you looked at in your investigation. Write your results in the following table:

Circuit	I_2 in mA
R_1 = 10kΩ, R_2 = 10kΩ. Power supply set to 6V	
R_1 = 10kΩ, R_2 = 10kΩ. Power supply set to 9V	
R_1 = 1kΩ, R_2 = 10kΩ. Power supply set to 9V	

- Compare the calculated values of I_2 with those you measured for each circuit. Why might you expect the experimental values to be different?

For your records:
As with voltage dividers, there is a straightforward way to view these results:

- The current from the power supply is shared between the resistors, so that:

  $I = I_1 + I_2$
- The bigger the resistor, the smaller its share of the current.

  In the first and second circuits: $R_1 = R_2 = 10k\Omega$

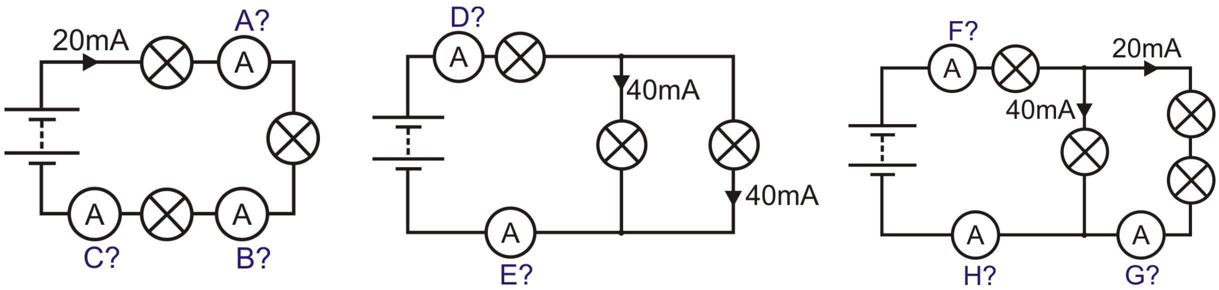
  so $I_1 = I_2 = ½ I$.

  In the third circuit: $R_2 = 10 \times R_1$

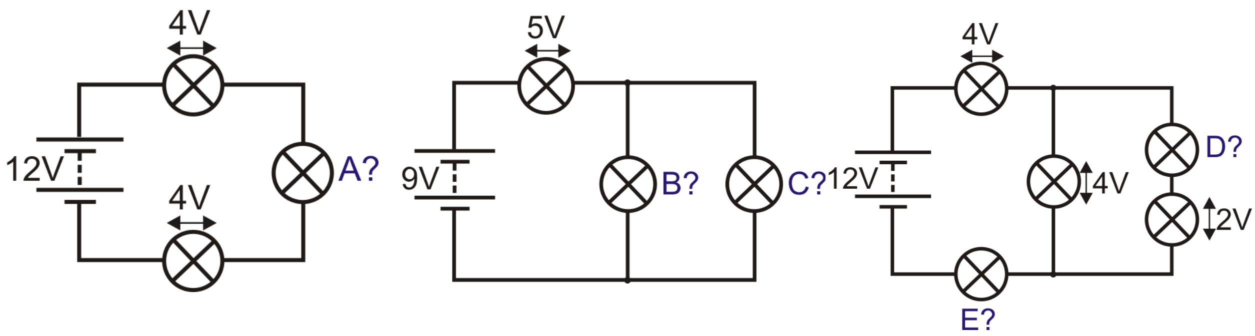
  and so $I_1 = 10 \times I_2$.

Revision Questions

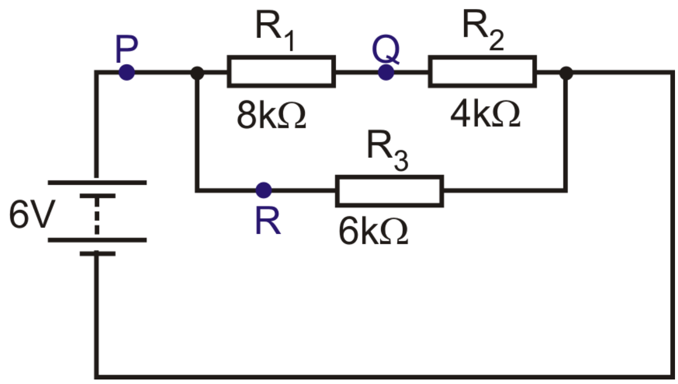
Worksheet 1:
Copy the following circuit diagrams, and add the readings on ammeters **A to H**.



Worksheet 2:
Copy the circuit diagrams, and add the voltages across bulbs **A to E**.



Worksheet 4:
For the circuit shown opposite, calculate:
a. total resistance;
b. current at **P**;
c. voltage across R₃, the 6kΩ resistor;
d. current at **R**;
e. current at **Q**;
f. voltage across R₁, the 8kΩ resistor.



Worksheet 6:
Answer the following questions:

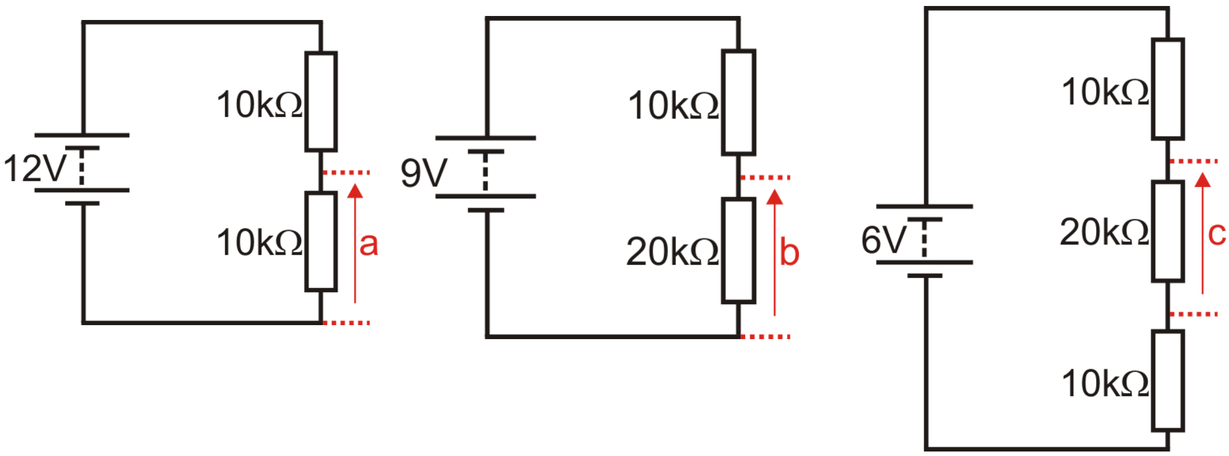
1. How many nickel-cadmium cells are required in a series-connected 24V battery?
2. Two batteries are connected in parallel in order to supply the 180A load current demanded by an aircraft main engine starter. How much current is supplied by each ?
3. An emergency lamp uses eight conventional 1.5V dry-cells connected in series. What voltage is produced to supply the lamp?
4. A 24 V battery supplies 18 parallel-connected lights. Each light consumes 150mA. What current is supplied by the battery?

Revision Questions

Worksheet 7:
A cell has an emf of 1.5V and an internal resistance of 0.5Ω.

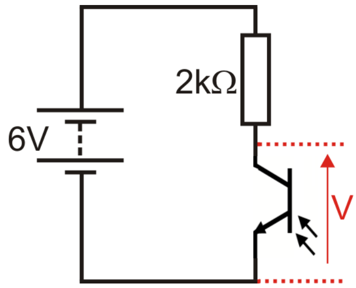
a. What is the output voltage of the cell when it is delivering a current of 1A?
b. What is the maximum current that can be drawn from the cell?
c. What will be the pd across a 2.5Ω resistor connected across the terminals of the cell?

Worksheet 8:
Calculate the output voltages, **a, b and c,** of each voltage divider.

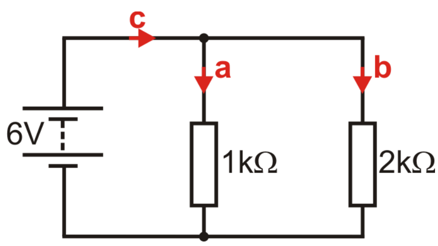


Worksheet 9:
In bright light (1000 lux) the phototransistor in the circuit diagram has a resistance of 1kΩ.

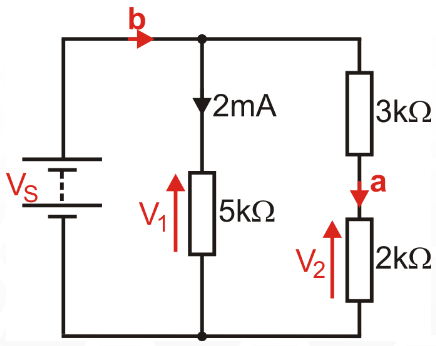
Calculate the voltage V when the light intensity is 1000 lux.



Worksheet 10:
Calculate the currents at a, b and c.



Worksheets 8 and 10:
For the circuit shown opposite, calculate:
a. voltage V_1;
b. supply voltage V_S;
c. current at a;
d. current at b;
e. voltage V_2.



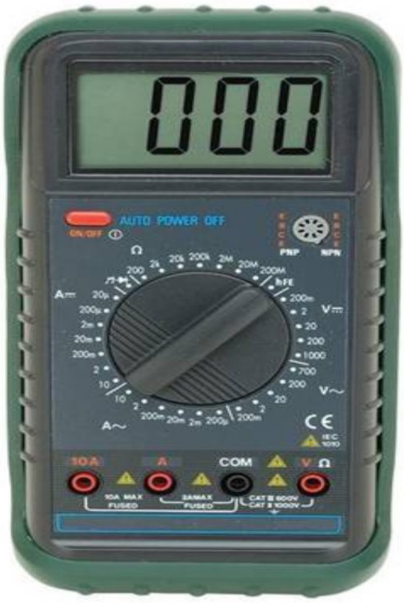
Multimeter Help

A multimeter, like the one shown, can measure either AC or DC quantities.

The following symbols are used to distinguish between the two:

AC ∿

DC ⎓



Using a multimeter to measure voltage:

- Plug one wire into the black COM socket.
- Plug another into the red V socket.
- Select the 20V DC range by turning the dial to the '20' mark next to the 'V⎓' symbol. (It is good practice to set the meter on a range that is much higher than the reading you are expecting. Then you can refine the measurement by choosing a lower range that suits the voltage you find.)
- Plug the two wires into the sockets at the ends of the component under investigation.
- Press the red ON/OFF switch when you are ready to take a reading.
- If you see a '-' sign in front of the reading, it means that the wires from the voltmeter are connected the wrong way round. Swap them over to get rid of it!

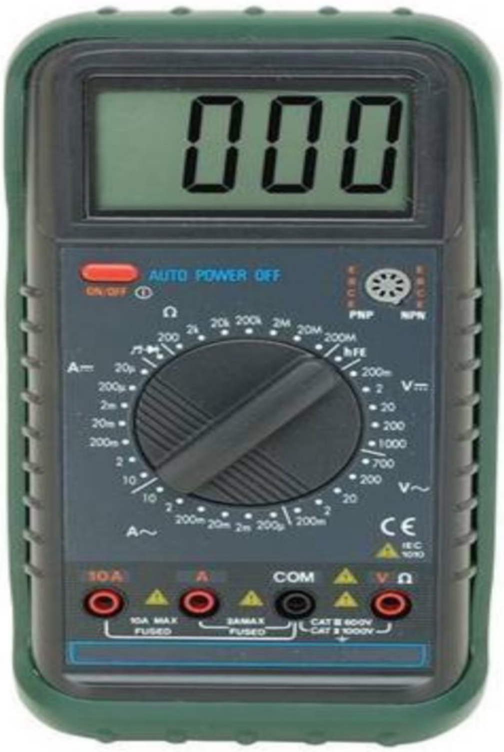
Using a multimeter to measure current:

- Plug one wire into the black COM socket.
- Plug another into the red mA socket.
- Select the 200mA DC range by turning the dial to the '200m' mark next to the 'A⎓' symbol.
- Break the circuit where you want to measure the current, by removing a link, and then plug the two wires in its place.
- Press the red ON/OFF switch when you are ready to take a reading.

A possible problem!

The ammeter range is protected by a fuse located inside the body of the multimeter. This fuse may have 'blown', in which case the ammeter range will not work. Report any problems to your teacher so that the fuse can be checked .

Multimeter Help



Using a multimeter to measure resistance:
You cannot measure the resistance of a component while it is in the circuit.
It must be removed first.

- Plug one wire into the black COM socket, and the other into the V Ω socket.
- Select the 200kΩ range, (or a range which is much higher than the reading you expect.)
- Plug the two wires into the sockets at the ends of the component under investigation.
- Press the red ON/OFF switch when you are ready to take a reading.
- Turn the dial to choose a lower range, until you find the reading.

STUDENT HANDOUT

Worksheet 1

A.

Position	P	Q	R	S
Current				

B.

Position	P	Q	R	S	T	U
Current						

Worksheet 2

A.

Position	P	Q	R
Voltage			

B.

Position	P	Q	R
Voltage			

Worksheet 3

A.

Power supply voltage	4.5V
Current at A in mA	
Current at B in mA	
Current at C in mA	
Current at D in mA	
Voltage across R_1	
Voltage across R_2	
Voltage across R_3	

B.

Power supply voltage	4.5V
Current at A in mA	
Current at B in mA	
Current at C in mA	
Current at D in mA	
Current at E in mA	
Voltage across R_1	
Voltage across R_2	
Voltage across R_3	

Power supply voltage	4.5V
Average current I in mA	
Total voltage V_S across all resistors	
Total resistance $R_T = V_S / I$	
Total resistance $R_T = R_1 + R_2 + R_3$	

Power supply voltage	4.5V
Average current I in mA	
Total voltage V_S across all resistors	
Total resistance $R_T = V_S / I$	
Total resistance $R_T = R_1 + R_2 + R_3$	

Worksheet 4

Power supply voltage	4.5V
Current at A in mA	
Current at B in mA	
Current at C in mA	
Current at D in mA	
Voltage across R_1 (270Ω resistor)	
Voltage across R_2 (1kΩ resistor)	
Voltage across R_3 (2.2kΩ resistor)	

Student Handout

Worksheet 4

Power supply voltage	4.5V
Average of currents at A and D in mA (= I)	
Sum of currents at B and C in mA	
Sum of voltages across R_1 and R_2 ($=V_S$)	
Total resistance $R_T = V_S / I$	
Combined resistance of R_1 and R_2 (in series) (=RC)	
Total resistance of all three resistors $R_T = R_C \times R_3 / R_C + R_3$	

Worksheet 5

Voltage across resistor	Current through resistor
0.1V	
0.2V	
0.3V	
0.4V	
0.5V	
0.6V	
0.7V	
0.8V	
0.9V	
1.0V	

Worksheet 6

Cell	Output voltage
E1	
E2	
E3	

Parallel-connected	Output voltage
(d) Two-cell battery	
(e) Three-cell battery	

Series-connected	Output voltage
(b) Two-cell battery	
(c) Three-cell battery	

Worksheet 7

Resistor R	Current I	Voltage V
120Ω		
68Ω		
47Ω		
15Ω		
10Ω		
3.9Ω		

Worksheet 8

R_1 = 10kΩ, R_2 = 10kΩ		
Power supply voltage	6V	9V
Current at A in mA		
Voltage V_1 across R_1		
Voltage V_2 across R_2		

R_1 = 1kΩ, R_2 = 10kΩ	
Power supply voltage	9V
Current at A in mA	
Voltage V_1 across R_1	
Voltage V_2 across R_2	

R_1 = 2.2kΩ, R_2 = 22kΩ	
Power supply voltage	9V
Current at A in mA	
Voltage V_1 across R_1	
Voltage V_2 across R_2	

Part	Circuit	R_T	I	V_1	V_2
1	R_1 = 10kΩ, R_2 = 10kΩ, Vs = 6V				
2	R_1 = 10kΩ, R_2 = 10kΩ, Vs = 9V				
3	R_1 = 1kΩ, R_2 = 10kΩ, Vs = 9V				
4	R_1 = 2.2kΩ, R_2 = 22kΩ, Vs = 9V				

Worksheet 9

Temp in ^{0}C	Resistance in kΩ

Worksheet 10

R_1 = 10kΩ, R_2 = 10kΩ	
Power supply	6V
Current at A, I_1, in mA	
Current at B, I_2, in mA	

R_1 = 1kΩ, R_2 = 10kΩ	
Power supply	9V
Current at A, I_1, in mA	
Current at B, I_2, in mA	

R_1 = 10kΩ, R_2 = 10kΩ	
Power supply	9V
Current at A, I_1, in mA	
Current at B, I_2, in mA	

Circuit	I_2 in mA
R_1 = 10kΩ, R_2 = 10kΩ. Vs = 6V	
R_1 = 10kΩ, R_2 = 10kΩ. Vs = 9V	
R_1 = 1kΩ, R_2 = 10kΩ. Vs = 9V	

Student Handout

Summary:
- In a series circuit, the same current flows in all parts.
- In a parallel circuit, the currents in all the parallel branches add up to the current leaving the power supply.
- In a series circuit, the voltages across the components add up to the voltage across the power supply .
- In a parallel circuit, the components all have the same voltage across them.

In a series circuit,
- The power supply voltage is shared between all components,
- The same current flows in all parts.
- The combined resistance equals the sum of individual resistances: $R_T = R_1 + R_2 + R_3 + ...$

In a parallel circuit,
- The current is shared between all components connected in parallel.
- Each component has the full supply voltage across it.
- The total resistance, RT of three resistors in parallel is: $1/R_T = 1/R_1 + 1/R_2 + 1/R_3$
- For two resistors in parallel, this reduces to: $$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

Ohm's law: states that the current through a conductor is directly proportional to the potential difference across it, providing the temperature remains constant. It leads to the formula:

$$V = I \times R$$

Where V = pd across conductor, I = current flowing through it, and R = its resistance.

Resistor colour code:
- Resistors often come with coloured bands across their body to show their resistance.

Black	Brown	Red	Orange	Yellow	Green	Blue	Purple	Grey	White
0	1	2	3	4	5	6	7	8	9

- Each colour represents a number, as shown in the table.
- To read the colour code, start from the opposite end to the gold or silver band:

Four-band resistors:
- Write down the number shown by the first colour band, and then the second colour band.
- Add the number of 0's shown in the next band (e.g. for red, add two 0's.)
- The final band (usually gold, (5%) or silver (10%)) shows you the tolerance - how accurately it is made.

Five-band resistors:
- Five colour bands are used for higher precision, i.e. lower tolerance resistors.
- Write down the number shown by the first three colour bands.
- Add the number of 0's shown in the fourth band.
- The fifth band shows the tolerance. For example, brown = 1%, green = 0.5%.

Cells
- In a series-connected battery, the same load current flows through each of the cells.
- In a parallel-connected battery, the load current is shared between the cells.

Combining cells in series increases the output voltage, but the cells all deliver the full load current and so will go 'flat' quicker.

Combining cells in parallel does not increase the output voltage. The cells take longer to discharge, and the available load current may be greater because the load current is shared.

Internal resistance:
- Limits the maximum current available from the cell. In some situations, this is a nuisance - the cheaper 12V alkaline battery unable to deliver enough current to start a car engine. In others it is an advantage - inadvertent short circuits do not lead to electrical fires resulting from overheated cables and components.
- Can be measured in a number of ways:
- DC load test;
- Flash testing - shorting the output with a 0.01Ω resistor for ~0.2s and measuring the terminal voltage;
- AC conductivity method - measuring the current resulting when a low frequency AC voltage is applied to the cell;
- Pulse testing - monitoring the terminal voltage when a series of pulses alternately charge and discharge the cell over a short period of time.
- All methods give similar results, though the internal resistance of a cell varies markedly with temperature (increasing at low temperatures.)

Student Handout

For a voltage divider made from two resistors, R_1 and R_2:

- The voltage from the power supply is shared between the resistors, so that
$$V_1 + V_2 = V_S.$$
- The bigger the resistor, the bigger its share of the voltage.

When $R_1 = R_2$ — $V_1 = V_2 = ½V_S$.

When $R_2 = 10 \times R_1$, — $V_2 = 10 \times V_1$.

In some cases, it is best to use big resistor values, to reduce battery drain and power dissipation.

However, using lower resistor values allows us to draw more current from the voltage divider circuit without really affecting voltage V_1 and V_2.

For a current divider made from two resistors, R_1 and R_2:

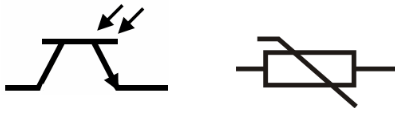
- The current from the power supply is shared between the resistors, so that:
$$I = I_1 + I_2$$
- The bigger the resistor, the smaller its share of the current.

When $R_1 = R_2 = 10k\Omega$: — $I_1 = I_2 = ½ I$

When $R_2 = 10 \times R_1$ — $I_1 = 10 \times I_2$.

LDR and thermistor:

- The diagram shows the circuit symbols for the phototransistor and thermistor:



Phototransistor Thermistor

- A NTC thermistor has a resistance which falls as the temperature rises.
- A PTC thermistor has a resistance which increases as the temperature rises.
- The resistance of a phototransistor falls as the light intensity increases.

Thermistor applications:

- NTC thermistors are used in temperature-sensing systems to monitor the temperature inside an incubator, or in motor vehicle cooling systems.
- NTC thermistors can be used to protect components from surges of current. Initially, they are cold, and so have a high resistance and so prevent large currents from flowing. As they subsequently heat up, their resistance falls, allowing higher currents to flow during normal operation.
- PTC thermistors can also be used to protect sensitive components. When a current flows through the thermistor, it heats up, and so its resistance increases. As a result, it heats up still more, increasing its resistance still further. The effect of this is to reduce the current flowing through the sensitive device, thus protecting it.

Notes

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