



simplifying electricity

Electricity matters 3



LK7664

MATRIX

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Worksheet 1

Measuring current

Electricity Matters

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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.

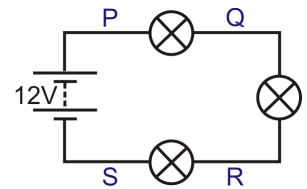


w1a

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**.



w1b

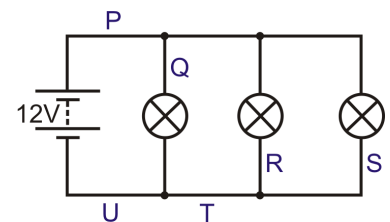


w1c

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 opposite:



w1d

Position	P	Q	R	S	T	U
Current						

Worksheet 1

Measuring current

Electricity Matters

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So what?

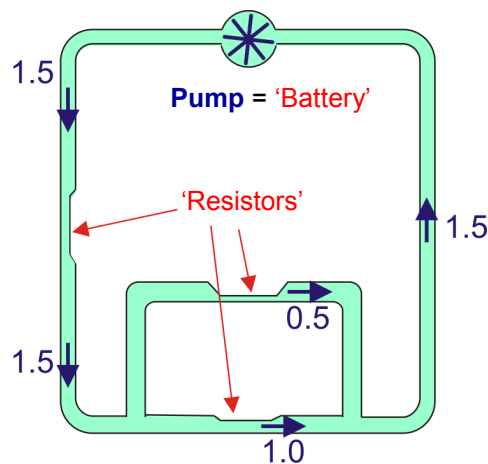
Can you spot patterns for the behaviour of electric currents in:

- 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.

Worksheet 2

Measuring voltage

Electricity Matters

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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!

Meter Symbols

ammeter — (A) —

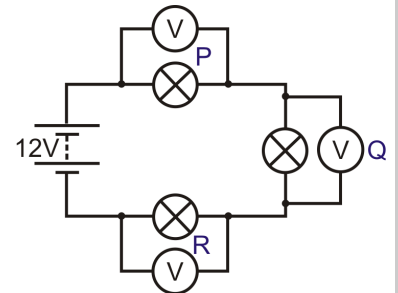
voltmeter — (V) —

ohmmeter — (Ω) —

Over to you:

A. Series circuit:

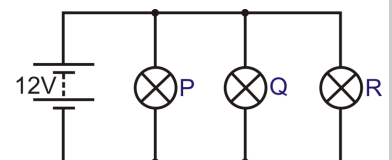
- Set up the arrangement shown, using 12V 0.1A bulbs, *but without the voltmeters*.
- Make sure that the power supply is set to 12V.
- This is a **series** circuit with only one route around it.
- Measure the voltage across the first bulb, shown as **P**.
To do this, plug the wires from the voltmeter 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			

Worksheet 2

Measuring voltage

Electricity Matters

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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

Electricity Matters

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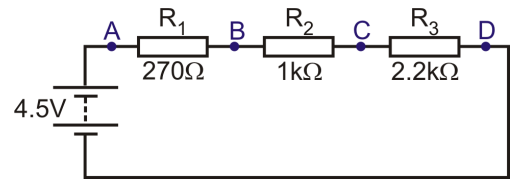
Resistors are basic components in electronic systems. In a series connection, there are no alternative routes and no junctions. The electrons must pass through each resistor in turn. Resistors connected in parallel offer different routes for the electric current. Easier routes pass greater current. Combining resistors in parallel reduces the total resistance, allowing more current to flow.



Over to you:

A. Series combination:

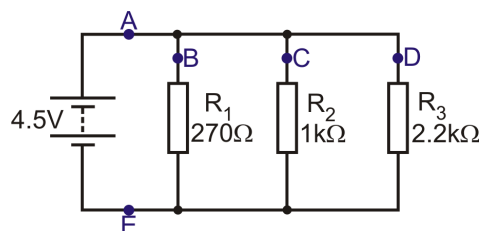
- Connect a 270Ω , a $1k\Omega$ and a $2.2k\Omega$ resistor in series with the power supply, as shown.
- Use extra connecting links so that the current can be measured at points **A**, **B**, **C** and **D**.
- Set the power supply to give a 4.5V output.
- Remove the link at **A**, and connect a multimeter 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 **R₁** to measure the voltage across it, and record the result in the table.
- In the same way, measure and record the voltages across **R₂** and **R₃**.



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 R₁	
Voltage across R₂	
Voltage across R₃	

B. Parallel combination:

- Connect the 270Ω , $1k\Omega$ and $2.2k\Omega$ 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 **R₁**, **R₂** and **R₃**.



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 R₁	
Voltage across R₂	
Voltage across R₃	

Worksheet 3

Resistor combinations

Electricity Matters

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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:
 - Use I and V_S in the formula $R = V/I$.
 - R_T equals the sum of the resistances.
- Calculate the total resistance, R_T , in both ways.
- Compare the two values for R_T .

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 $R_T = R_1 + R_2 + R_3$	

Think of reasons why these might be different.

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 R_T using:
 - I and V_S in the formula $R = V/I$.
 - the formula: $1/R_T = 1/R_1 + 1/R_2 + 1/R_3$.

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	

Again, why might these values for R_T be different?

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: $R_T = R_1 + R_2 + R_3 + \dots$

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, R_T 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:

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

Worksheet 4

Current and voltage in complex circuits

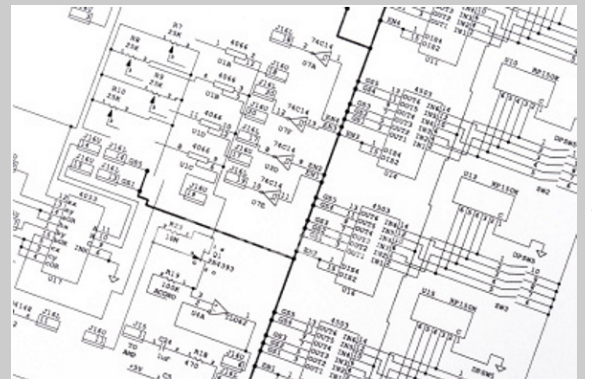
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Most circuits are a combination of series and parallel connections.

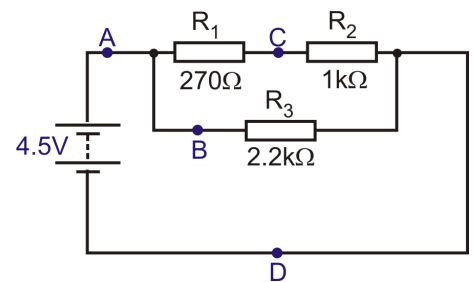
The rules developed in the previous worksheets still apply, but only to the localised parts, instead of the whole circuit.

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 **R₁**. Record it in the table.
- In turn, connect the multimeter to read the voltages across **R₂** and **R₃** and record them too.



Power supply voltage	4.5V
Current at point A in mA	
Current at point B in mA	
Current at point C in mA	
Current at point D in mA	
Voltage across R₁ (270Ω resistor)	
Voltage across R₂ (1kΩ resistor)	
Voltage across R₃ (2.2kΩ resistor)	

Worksheet 4

Current and voltage in complex circuits

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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) (= R_C)	
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 R_T of the three resistors by:
 - using I and V_S in the formula $R = V/I$;
 - 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

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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.

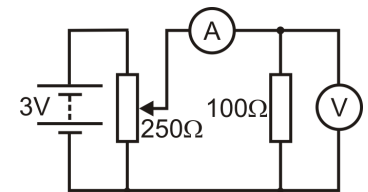
Resistance shows how difficult it is for the electrons to pass through a material. In squeezing through, the electrons lose energy to the resistor, which warms up as a result.

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: $V = I \times R$



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.)

Worksheet 5

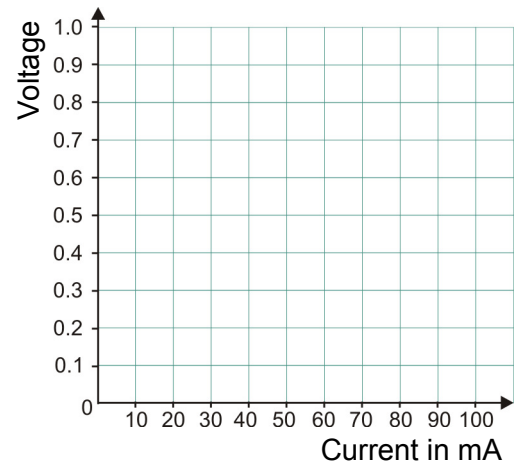
Ohm's law

Electricity Matters

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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

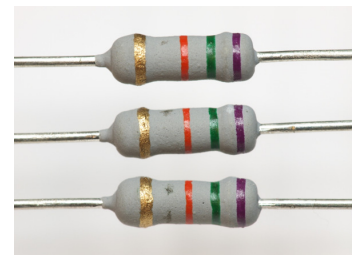
- Each colour represents a number, as shown in the table.
- To read the colour code, start from the opposite end to the gold or silver band:

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:

$$7 \text{ (purple)} \ 5 \text{ (green)} \ 000 \text{ (orange)} \\ = 75000\Omega \text{ with a tolerance of } 5\%$$



Five-band resistors:

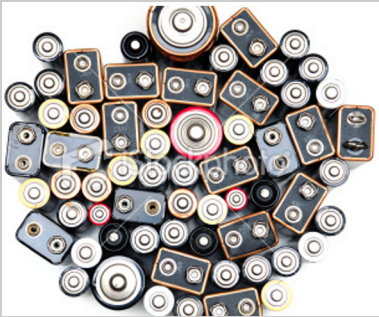
- Five colour bands are used for higher precision, i.e. lower tolerance resistors
- Write down the number shown by the first three colour bands.
- Add the number of 0's shown in the fourth band.
- The fifth band shows the tolerance. For example, brown = 1%, green = 0.5%.

Worksheet 6

Cells and batteries

Electricity Matters

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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.

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

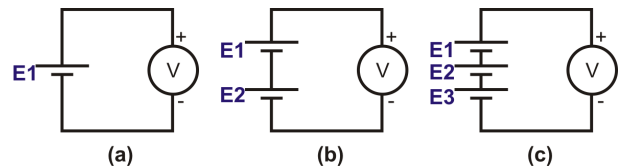
The table gives the emf of some popular types of cell.

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.

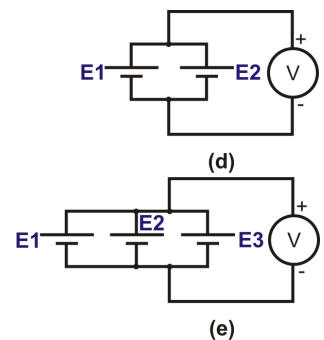
Cell	Output voltage
E1	
E2	
E3	

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.

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



Worksheet 6

Cells and batteries

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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.

Worksheet 7

Internal resistance

Electricity Matters

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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!

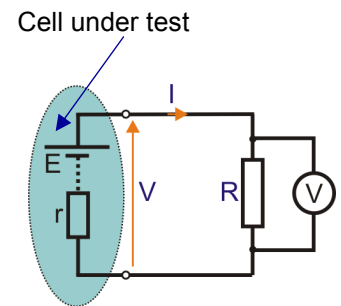
An alkaline battery may have an internal resistance of only $\sim 0.1\Omega$, but that of the car battery is typically one hundred times smaller than that. That is why it is expensive.

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.



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

- The next page shows how to obtain the internal resistance of the cell from these readings.

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.

Worksheet 7

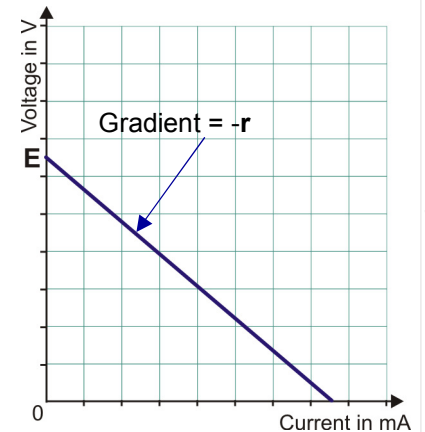
Internal resistance

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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:

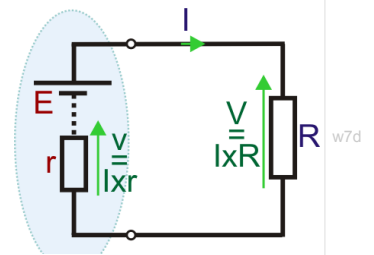
Looking at the circuit opposite:

$$\begin{aligned} E &= V + v \\ &= V + Ir \end{aligned}$$

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 $\sim 0.2s$ 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.)

Worksheet 8

Voltage dividers

Electricity Matters

3

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.)

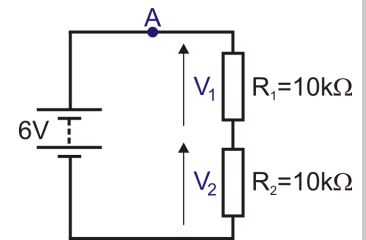
Voltage dividers form the basis of many sensing subsystems. The output voltage can represent temperature, light-level, pressure, humidity, strain or other physical quantities.



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 **R₁**, and then across **R₂**. Record these voltages in the table.



R ₁ = 10kΩ, R ₂ = 10kΩ		
Power supply voltage	6V	9V
Current at A in mA		
Voltage V₁ across R ₁		
Voltage V₂ across R ₂		

Part 2:

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

Part 3:

- Next, swap resistor **R₁** for a 1kΩ resistor. Repeat the process and record the results in the second table.

R ₁ = 1kΩ, R ₂ = 10kΩ	
Power supply voltage	9V
Current at A in mA	
Voltage V₁ across R ₁	
Voltage V₂ across R ₂	

Part 4:

- Finally, replace both resistors, with a 2.2kΩ resistor for **R₁**, and a 22kΩ resistor for **R₂**. 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 V₁ across R ₁	
Voltage V₂ across R ₂	

Worksheet 8

Voltage dividers

Electricity Matters

3

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	$R_1 = 10k\Omega$, $R_2 = 10k\Omega$, $V_S = 6V$				
2	$R_1 = 10k\Omega$, $R_2 = 10k\Omega$, $V_S = 9V$				
3	$R_1 = 1k\Omega$, $R_2 = 10k\Omega$, $V_S = 9V$				
4	$R_1 = 2.2k\Omega$, $R_2 = 22k\Omega$, $V_S = 9V$				

- 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, $R_1 = R_2 = 10k\Omega$ so $V_1 = V_2 = \frac{1}{2}V_S$.

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

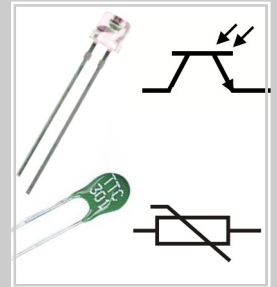
Phototransistor and thermistor

Electricity Matters

3

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.



W9a_rchs

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 20k Ω 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 $^{\circ}$ C.
- Repeat the measurements until you have a set of at least six readings.



w9b

Temp in $^{\circ}$ C	Resistance in k Ω

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.

Worksheet 9

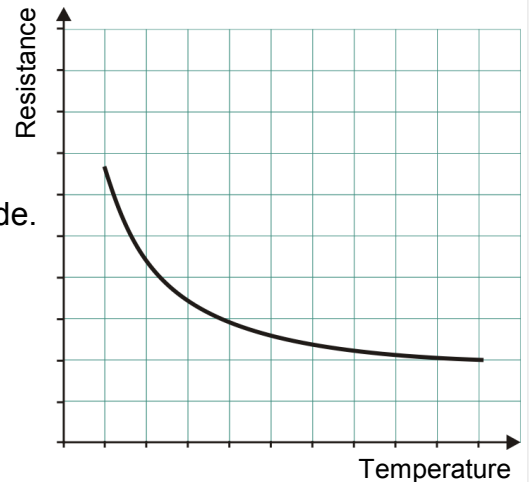
Phototransistor and thermistor

Electricity Matters

3

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:



- 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

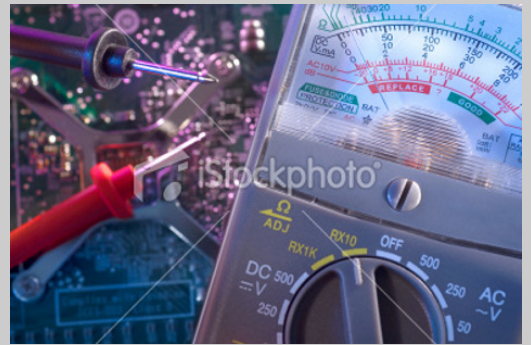
Electricity Matters

3

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

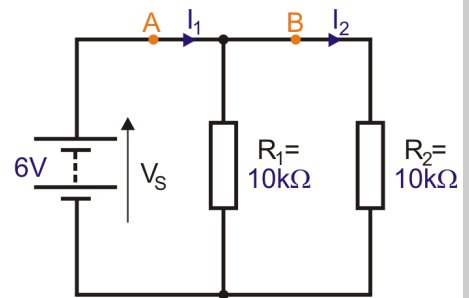
Current dividers use resistors connected in **parallel** to set up known fractions of current.

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.
- Next, set the power supply to 9V, and repeat the measurements. Record them in the second table.
- 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.



$R_1 = 10k\Omega, R_2 = 10k\Omega$	
Power supply voltage, V_S	6V
Current at A , I_1 , in mA	
Current at B , I_2 , in mA	

$R_1 = 10k\Omega, R_2 = 10k\Omega$	
Power supply voltage, V_S	9V
Current at A , I_1 , in mA	
Current at B , I_2 , in mA	

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

Worksheet 10

Current dividers

Electricity Matters

3

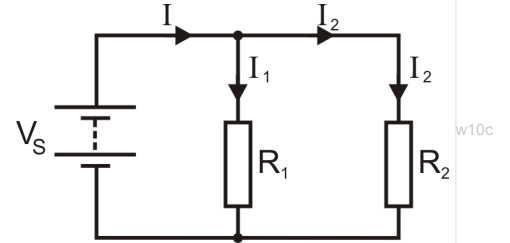
So what?

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 I_1 given above: $I = I_2 \times (R_2 / R_1) + I_2$
 $= I_2 (1 + R_2 / R_1)$

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

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
$R_1 = 10k\Omega, R_2 = 10k\Omega$. Power supply set to 6V	
$R_1 = 10k\Omega, R_2 = 10k\Omega$. Power supply set to 9V	
$R_1 = 1k\Omega, R_2 = 10k\Omega$. 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 $I_1 = I_2 = \frac{1}{2} I$.

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

and so $I_1 = 10 \times I_2$.

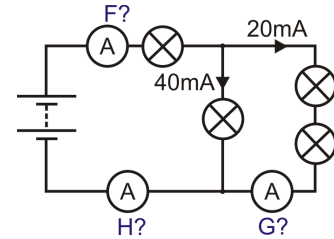
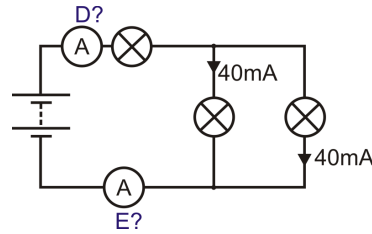
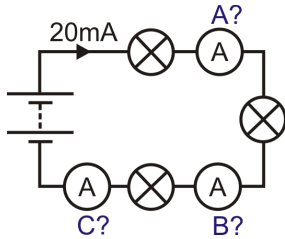
Revision questions

Electricity Matters

3

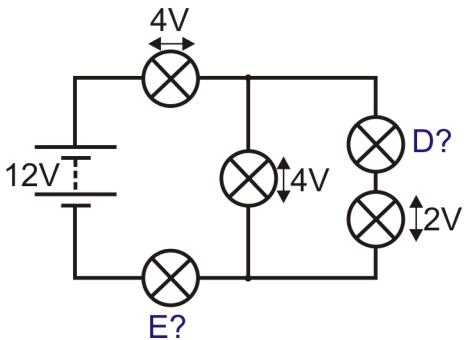
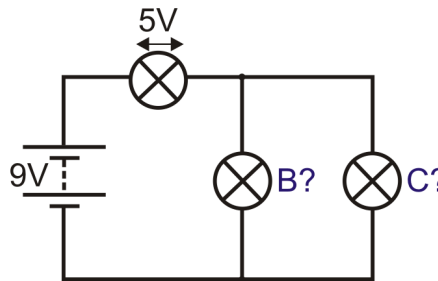
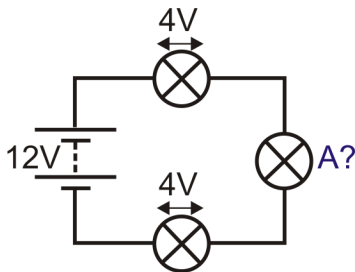
Worksheet 1:

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



Worksheet 2:

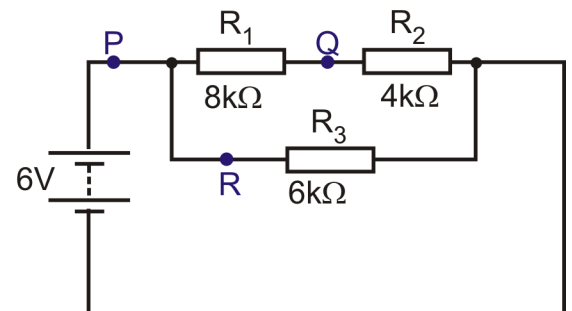
Copy the circuit diagrams, and add the voltages across bulbs **A** to **E**.



Worksheet 4:

For the circuit shown opposite, calculate:

- total resistance;
- current at **P**;
- voltage across **R**₃, the 6kΩ resistor;
- current at **R**;
- current at **Q**;
- voltage across **R**₁, the 8kΩ resistor.



Worksheet 6: Answer the following questions:

- How many nickel-cadmium cells are required in a series-connected 24V battery?
- 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?
- An emergency lamp uses eight conventional 1.5V dry-cells connected in series. What voltage is produced to supply the lamp?
- A 24 V battery supplies 18 parallel-connected lights. Each light consumes 150mA. What current is supplied by the battery?

(See answers on pages 34 and 35.)

Revision questions

Electricity Matters 3

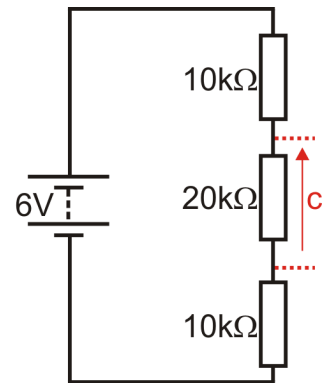
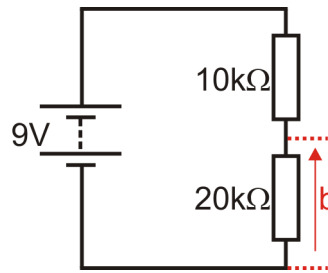
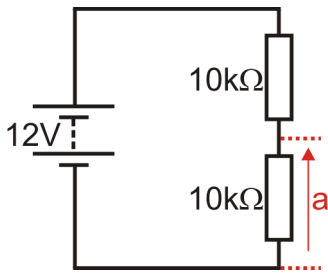
Worksheet 7:

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

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

Worksheet 8:

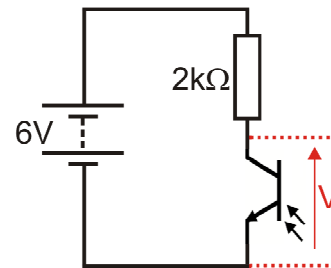
Calculate the output voltages, **a**, **b** and **c**, of each voltage divider.



Worksheet 9:

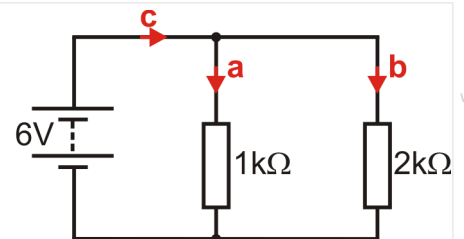
In bright light (1000 lux) the phototransistor in the circuit diagram has a resistance of 1kΩ.

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



Worksheet 10:

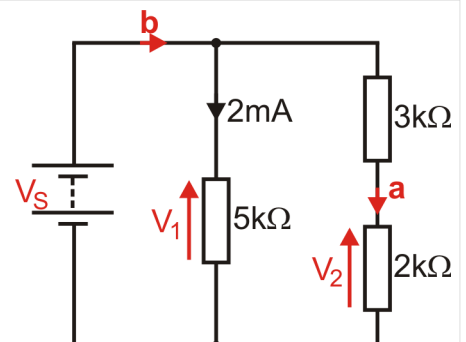
Calculate the currents at **a**, **b** and **c**.



Worksheets 8 and 10:

For the circuit shown opposite, calculate:

- voltage **V₁**;
- supply voltage **V_S**;
- current at **a**;
- current at **b**;
- voltage **V₂**.



(See answers on pages 34 and 35.)

Tutor's notes

Electricity Matters 3

About this course

Introduction

This workbook is intended to reinforce the learning that takes place in the classroom or lecture room. It provides a series of practical activities and investigations that complement syllabus specifications in Advanced Level Physics

Locktronics equipment makes circuit construction simple and quick. The end result can look exactly like the circuit diagram, thanks to the symbols printed on each component carrier.

Aim

The course aims to introduce students to the basic principles and concepts of electricity, and provide a useful introduction to electrical measurements and the use of ammeters, voltmeters and multimeters.

Prior Knowledge

It is recommended that students have followed the 'Electricity Matters 1' and 'Electricity Matters 2' courses, or have equivalent knowledge and experience of building simple circuits, and using meters.

Learning Objectives

On successful completion of this course the student will have learned to:

- distinguish between series and parallel circuits
- distinguish between the quantities current, emf, pd and resistance;
- calculate currents in all parts of series circuits given the current at any point;
- calculate currents in parallel circuits given sufficient information about currents in other parts;
- use given information to calculate voltages across components in series and in parallel circuits;
- calculate the pd across components in parallel circuits given the emf of the power supply;
- calculate the combined resistance of resistors connected in series, and the resulting voltages and currents;
- calculate the combined resistance of resistors connected in parallel, and the resulting voltages and currents;
- calculate the total resistance of a complex combination of resistors;
- calculate currents and voltages in a circuit containing a complex combination of resistors;
- state Ohm's law and its limitations, and use the Ohm's law formula;
- use the resistor colour code to identify the resistance of four-band and five-band resistors;
- combine the emf's of cells connected in series and in parallel;
- give the advantages and disadvantages of connecting cells in series and in parallel.
- measure the internal resistance of a cell using DC loading techniques;
- describe the significance of internal resistance, and use it to determine the expected current;
- calculate the output voltage of a given voltage divider;
- describe the effect of light on the resistance of a phototransistor;
- describe the effect of temperature on the resistance of a thermistor;
- design a current divider circuit to split up a current into two specified portions.

Tutor's notes

Electricity Matters

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What students will need:

This pack is designed to work with the Locktronics Electricity Matters 3 Kit. The electrical / electronic parts required for this workbook are listed here.

Note that the kit contains parts that are used in other workbooks covering Electricity and Magnetism.

Students will also need either :

- Two multimeters, such as the LK1110, capable of measuring currents in the range 0 to 200mA, and voltages in the range 0 to 200V;
- or equivalent ammeters and voltmeters.

If you are missing any components, or need additional items, please contact Matrix or your local dealer.

Power sources:

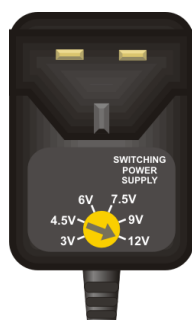
Students will need an adjustable low-voltage DC supply.

The output voltage from the DC power unit supplied with the kit can be adjusted to provide outputs of either 3V, 4.5V, 6V, 7.5V, 9V or 12V, with currents typically up to 1 A. The voltage is changed by turning the selector dial just above the earth pin until the arrow points to the required voltage.

Tutors may decide to make any adjustment necessary to the power supply voltage themselves, or may allow students to make those changes.

Each exercise includes a recommended voltage for that particular circuit.

In the picture below, the DC power supply has been adjusted to provide an output of 12V DC.



psu

Qty	Code	Description
1	HP2045	Plastic tray
1	HP4039	Tray Lid
1	HP4039	Tray Lid
1	HP2666	Adjustable DC power supply
1	HP5540	Deep tray
1	HP7750	Daughter tray foam cutout
1	HP9564	62mm daughter tray
1	LK0123	Small bar magnet
3	LK2347	MES bulb, 6V, 0.04A
1	LK3662	Capacitor, 22,000uF, Electrolytic 16V
1	LK4000	Locktronics User Guide
1	LK4002	Resistor, 100 ohm, 1W, 5% (DIN)
1	LK4003	Capacitor, 1,000 uF, Electrolytic 30V
1	LK4025	Resistor, 10 ohm, 1W 5% (DIN)
1	LK4065	Resistor, 47 ohm, 1/2W, 5% (DIN)
1	LK4123	Transformer, 2:1 turns ratio
1	LK5202	Resistor, 1k, 1/4W, 5% (DIN)
1	LK5203	Resistor, 10k, 1/4W, 5% (DIN)
1	LK5205	Resistor, 270 ohm, 1/2W, 5% (DIN)
1	LK5208	Potentiometer, 250 ohm (DIN)
1	LK5209	Resistor, 5.6k, 1/4W, 5% (DIN)
1	LK5211	Resistor, 3.9 ohm, 3W, 5% (DIN)
1	LK5217	Resistor, 68 ohm 1/2W, 5% (DIN)
12	LK5250	Connecting Link
3	Lk5291	Lampholder, MES
1	LK5299	400 turn induction coil
1	LK5402	Thermistor, 4.7k, NTC (DIN)
1	LK6203	Capacitor, 2,200 uF, Electrolytic, 25V
1	LK6205	Capacitor, 1 uF, Polyester
1	LK6209	Switch, on/off, metal strip
1	LK6211	Resistor, 22k, 1/4W, 5% (DIN)
1	LK6214R2	Choke, 47mH
1	LK6218	Resistor, 2.2k, 1/4W, 5% (DIN)
1	LK6430	LED, red, 12V (SB)
1	LK6492	Curriculum CD ROM
1	LK7290	Phototransistor
3	LK7409	AA battery holder carrier
1	LK7483	1:1 transformer with retractable ferrite core
1	LK8150	Nichrome Wire Carrier, 0.075 x 500mm
1	LK8152	Nichrome Wire Carrier, 0.075 x 250mm
1	LK8154	Nichrome Wire Carrier, 0.21 x 500mm
1	LK8156	Constantan Wire Carrier, 0.075 x 500mm
1	LK8900	7 x 5 metric baseboard with 4mm pillars



Tutor's notes

Electricity Matters

3

Using this course:

It is expected that the worksheets are printed / photocopied, preferably in colour, for the students' use. Students do not need their own copy of the entire workbook.

Worksheets usually contain:

- an introduction to the topic under investigation;
- step-by-step instructions for the practical investigation that follows;
- a section headed 'So What?' which develops the results obtained in the investigations and challenges students by questioning their understanding of a topic;
- a section headed 'For your records', which provides a useful summary of what has been learned. It can be used to develop ideas and as a trigger for class discussion.

This format encourages self-study, with students working at a rate that suits their ability. It is for the tutor to monitor that students' understanding is keeping pace with their progress through the worksheets and to provide additional work that will challenge brighter learners. One way to do this is to 'sign off' each worksheet, as a student completes it, and in the process have a brief chat with each learner to assess their grasp of the ideas involved in the exercises that it contains.

The results tables for all worksheets have been gathered together as the 'Student Handout', to speed progress through the module. The results of each investigation are compiled into a 'Summary' at the end of the module. The plan is that each student be given a copy of these sections, the 'Student Handout' before they start, and the 'Summary' after they complete the module.

Finally, a set of Revision Questions has been provided to assess progress on each topic. It is recommended that students should attempt these questions under examination conditions and without the use of notes or calculators. Answers are provided.

Time:

It will take most students between six and eight hours to complete the full set of worksheets. It is expected that a similar length of time will be needed to support the learning in a class, tutorial or self-study environment.

Tutor's notes

Electricity Matters

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Worksheet	Notes for the Tutor	Timing
1	<p>In effect, this is an optional investigation. It is a chance for students to revisit work they did much earlier. For teachers meeting students for the first time, it provides a good assessment opportunity to gauge how much remedial work needs to be done.</p> <p>The approach used assumes knowledge of electric current as a flow of electrons, though makes no mention of direction of flow. It introduces series and parallel connections, concepts which may need tutor support and amplification, depending on the previous experience of the students.</p> <p>The investigation assumes that students are able to use multimeters to measure current. The teacher needs to assess this first. The students may have used discrete ammeters instead, in which case, a familiarisation exercise will be needed first. Multimeters can be a fearful mystery even for those who have used them. Help sheets are provided to prompt them and 'hold their hand' through the experience.</p> <p>Beware! It is common to find that the ammeter settings are protected by an internal fuse. This is frequently 'blown' because pupils switch on the multimeter, connected as a voltmeter, with the dial turned to a current range. Teachers should check all fuses prior to this exercise, and be prepared with a supply of replacement fuses!</p> <p>The second page introduces water circuit as analogy for electricity. The teacher may wish to extend this discussion, and question the suitability of other transport phenomena, such as the flow of traffic, or of gas.</p>	30 - 45 minutes
2	<p>Another optional investigation, this worksheet mirrors the structure of the last one, but looks at measuring voltage.</p> <p>The point is made in the introduction, that it is relatively easy to visualise an electric current - millions of electrons slowly squeezing their way along a wire, like crowds of people in a shopping mall, but more difficult to visualise voltage.</p> <p>For the present, the exercise concentrates on measuring voltage, rather than defining it. Pupils use a multimeter for this, by connecting it in parallel with the section of the circuit under investigation.</p> <p>The circuit diagram in part A of the investigation shows three voltmeters. The student does not need three multimeters, but can move one from one voltmeter position to the next to take the three readings.</p> <p>Again, students are asked to look for a pattern in their results. This is that the total of the voltmeter readings in any loop of the circuit is equal to the power supply, or battery, voltage.</p> <p>The worksheet makes the distinction between emf and pd. This is a subtle distinction, which the teacher will need to reinforce by discussion and further examples.</p>	30 - 45 minutes

Tutor's notes

Electricity Matters

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Worksheet	Notes for the Tutor	Timing
3	<p>The aim of the investigation is to justify the formulae for series, and for parallel combinations of resistors.</p> <p>Students will have met series connections before, but the instructor might wish to drive home the issues involved by reminding them of equivalent transport phenomena, such as the flow of water. A series circuit has no junctions and no alternative routes from one power supply terminal to the other. As a result, the same current flows everywhere, as it has nowhere else to go.</p> <p>This may be the student's first experience of using the adjustable power supply. The instructor should check that it is set to 4.5V.</p> <p>For those returning to electricity after a break, it is an opportunity to revisit skills involved in using multimeters. In particular, students should be reminded that voltage measurements can be made without interrupting the circuit, with the multimeter connected in parallel, whereas, to measure current, the circuit must be broken at that point, with the multimeter inserted there to complete the circuit.</p> <p>As pointed out earlier, teachers need to be aware that low current ranges on most multimeters are protected by internal fuses. If a student is having difficulty in getting current readings from a circuit, it may be that this internal fuse has blown. It is worth having some spare multimeters available, and the means to change fuses, to streamline the lesson.</p> <p>The students use their readings to measure the total resistance of the circuit and compare this with the value obtained from the series resistor formula.</p> <p>The same treatment is then used for parallel connections. Again, the vast majority will already have met the idea of parallel connections. These involve junctions in the circuit, allowing different currents to follow different routes from one power supply terminal to the other. It is worthwhile comparing the behaviour of water in an equivalent arrangement, where junctions in the pipes allow water to flow by different routes. Similarly, for traffic flow, a by-pass allows motorists to avoid narrow roads (= high resistance) by choosing a dual-carriageway (= low resistance.) Some still prefer to miss the bustle of the busy by-pass by taking the narrow route.</p> <p>The activities are similar to those for the series circuit, and require similar multimeter skills. Again, the instructor should verify that the correct voltage has been selected on the power supply, and be prepared for multimeter problems resulting from a blown internal fuse.</p> <p>The measurements are processed in a similar way. The total resistance is obtained from the total current flowing, and total voltage. The result is compared with that from the formula for parallel resistors.</p> <p>The summary gives two such formulae, one for combining just two resistors, and the other for combining any number. Teachers may wish to set the task of deriving the first of these from the second.</p> <p>The teacher should contrast the results for series and parallel combinations. In a parallel combination, the current through each resistor varies, but the voltage across each is the same. In a series combination, the current is the same, with different voltages across the resistors.</p>	35 - 50 minutes

Tutor's notes

Electricity Matters

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Worksheet	Notes for the Tutor	Timing
4	<p>Worksheet 4 expands the work of the previous investigations to circuits containing both series and parallel combinations. It shows that the same rules apply, but now not to whole circuits but to sections where components are either exclusively in series or exclusively in parallel.</p> <p>The teacher can describe the behaviour of these systems using the same parallels as in earlier treatments.</p>	30 - 45 minutes
5	<p>Ohm's law must be one of the most famous in science! It epitomises the power of science to predict unseen behaviour, but also highlights its limitations, in that simple behaviour, like the direct proportionality between current and voltage, applies only in very restricted, and often unrealistic, circumstances.</p> <p>Students use a potential divider, made from a potentiometer, as a variable voltage source. Teachers might wish to elaborate on exactly how it functions. The large laboratory rheostat can be used to demonstrate the principle - that the slider creates two resistors which grow / shrink in size as the slider moves. These share the supply voltage between them, according to their resistance. Moving the slider results in varying voltage being applied to the rest of the circuit.</p> <p>The cardinal rule is that the temperature of the specimen should remain constant. In reality, this cannot happen. Electrons flowing through the resistor warm it up. However, providing that the voltage across the resistor is restricted, the resulting heating will be negligible, and will have no observable effect on the results.</p> <p>The students then plot graphs using their results. Using the format given in the worksheet, the gradient of the graph gives the resistance of the resistor. Some will require help in extracting the gradient. Different groups could be given slightly different resistors to investigate, and the results could then be compared across the class.</p> <p>Students are then shown how to interpret the resistor colour code. This could be tested in a number of ways, using samples of resistors. The students could use a multimeter to confirm their results. This could lead to a discussion of manufacturing tolerance, and the significance of the E12 and E24 resistor series.</p>	45 - 75 minutes
6	<p>In this worksheet, students investigate the series and parallel connection of cells in order to produce batteries. They should first be introduced to different types of cell, the distinction between primary and secondary types, and the basic characteristics of common types of cell, e.g. lead-acid, alkaline, nickel-cadmium and zinc-carbon types.</p> <p>Series and parallel connection of batteries should be described along with their circuit diagrams. Students need to be aware that the same load current flows through all of the cells in a series-connected battery but is shared between the cells in the case of a parallel-connected battery.</p> <p>They are asked to test three arrangements of series-connected cells and three arrangements of parallel-connected cells. Their results should confirm what they have previously learned about the series and parallel combination of individual cells.</p>	30 - 45 minutes

Tutor's notes

Electricity Matters

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Worksheet	Notes for the Tutor	Timing
7	<p>First, we convey the significance of internal resistance, the opposition to the flow of current inside the battery. Many concern themselves only with emf, and possibly capacity when buying batteries. However, internal resistance limits the current delivered, and may make a battery unsuitable for a given task. It means that the 'freshness' of a battery cannot be tested by simply connecting a voltmeter across the terminals!</p> <p>Internal resistance is not constant, and depends on the testing regime. Here, the resulting terminal voltage is measured when the battery delivers a current to a load. Sometimes it is deduced from voltage measurements across the terminals when a very low resistor is connected across the battery. Alternatively, it is measured by delivering rapid pulses of current, or from readings taken when a high frequency AC current flows through the battery. Internal resistance increases with use, and as the temperature drops. A battery goes 'flat' more as a result of an increase in its internal resistance than from a drop in its source voltage.</p> <p>The 'easiest' task is to measure the internal resistance of a zinc-carbon cell - because it is so big! However, the method works even for alkaline cells. Again, different groups can be given cells of different types and different ages, and their results can be combined afterwards.</p> <p>³With students that have limited mathematical backgrounds, it may be necessary to work through the theory given on the second page. The result comes from plotting a graph, and calculating the gradient.</p>	20 - 30 minutes
8	<p>Voltage dividers are a very important topic. They form the basis for many sensing subsystems, such as light-sensing units.</p> <p>They can also appear difficult to students. The aim is to overcome that aura of difficulty by reducing the treatment to two simple stages:</p> <ul style="list-style-type: none"> • the voltages across the components add to make the supply voltage; • the bigger the resistance of a component, the bigger its share of that supply voltage. If one resistor is four times bigger than the other, it gets four times as much voltage. <p>This approach is tested with three different pairs of resistors, and using two supply voltages. The output voltage depends only the supply voltage and the <i>relative</i> (not absolute) resistance. One made from a 2Ω and a 1Ω resistor behaves like one made from a 2MΩ and a 1MΩ resistor.</p> <p>However, the absolute values of resistance are important in two ways.</p> <ol style="list-style-type: none"> 1. Using low values of resistance increases the current through the voltage divider, and so increases the power dissipation in the resistors. This is usually undesirable. 2. When another subsystem, connected to the voltage divider output, draws an appreciable current, this extra loading can change the output voltage of the voltage divider. This extra current flows through the upper but not the lower resistor in the voltage divider. A useful rule of thumb says that the current flowing through the unconnected voltage divider should be at least ten times bigger than the current that will be drawn from it when the next subsystem is connected to its output. <p>It may be worth discussing these points with the students once they have completed this exercise.</p>	25 - 40 minutes

Tutor's notes

Electricity Matters

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Worksheet	Notes for the Tutor	Timing
9	<p>This worksheet introduces two components widely used in sensing circuits - the photodiode and the thermistor, a temperature-dependent resistor.</p> <p>To begin with, students look at the effect of changing temperature on the resistance of a thermistor. Then, they design an experiment to investigate how light intensity affects the resistance of a phototransistor.</p> <p>Be aware that the first investigation uses hot water, which might pose a hazard! The set up requires either a liquid-in-glass thermometer, another potential hazard, or a temperature probe and associated digital meter.</p> <p>They design the experiment to study the effect of light intensity on the resistance of the phototransistor. They may need to be reminded of the need to make it a fair test, in particular, to keep all other possible influences constant throughout.</p> <p>The teacher may wish to provide them with a light-meter to measure the intensity. The students use whatever units the meter is calibrated in!</p> <p>Remember that the phototransistor has a polarity and needs to be connected the right way around. Alternatively, an LDR could be used, although legislation (RoHS) in some countries means this component may not be available.</p> <p>The treatment goes on to show the temperature behaviour of the thermistor as a graph. It describes both ntc and ptc thermistors and gives applications of both.</p>	25 - 40 minutes
10	<p>This worksheet investigates current divider circuits, and it mirrors the approach taken for voltage dividers earlier. It compares and contrasts the behaviour of these two systems.</p> <p>In an approach parallel to that used for voltage dividers, the treatment looks at two simple ideas:</p> <ul style="list-style-type: none"> • the sum of the currents through the components equals the supply current; • the bigger the resistance of a component, the smaller its share of the current, so that if one resistor has four times the resistance of the other, it passes a current four times smaller. <p>As before, it may be helpful to reinforce the theory given on the second page of the worksheet, and the comparison between voltage and current divider circuits.</p> <p>Current dividers do not have as many obvious applications as voltage dividers, though they are used in current measurement. It is often useful to measure only a fixed portion of the total current, and from that deduce the total current flowing. For example, if a current divider sends 10% of the total current through an ammeter, which then registers a current of 2.5A, then the total current flowing was 25A.</p>	25 - 40 minutes

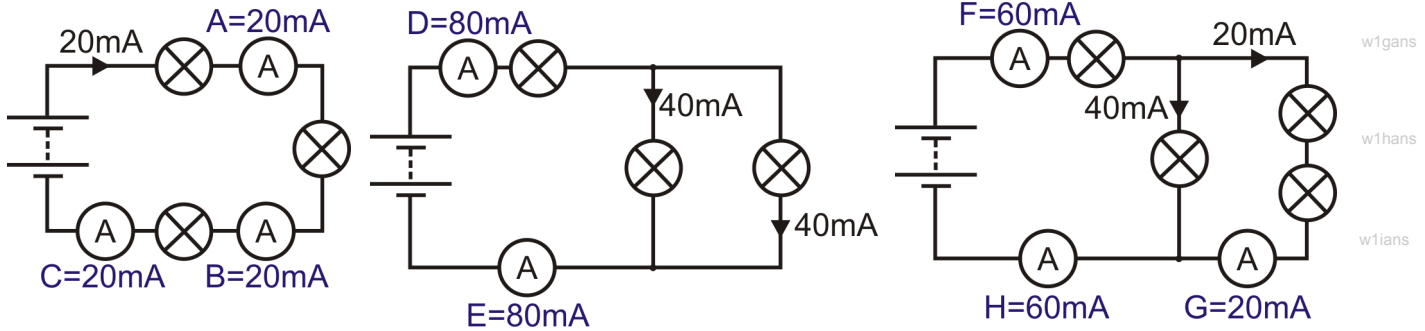
Answers

Electricity Matters

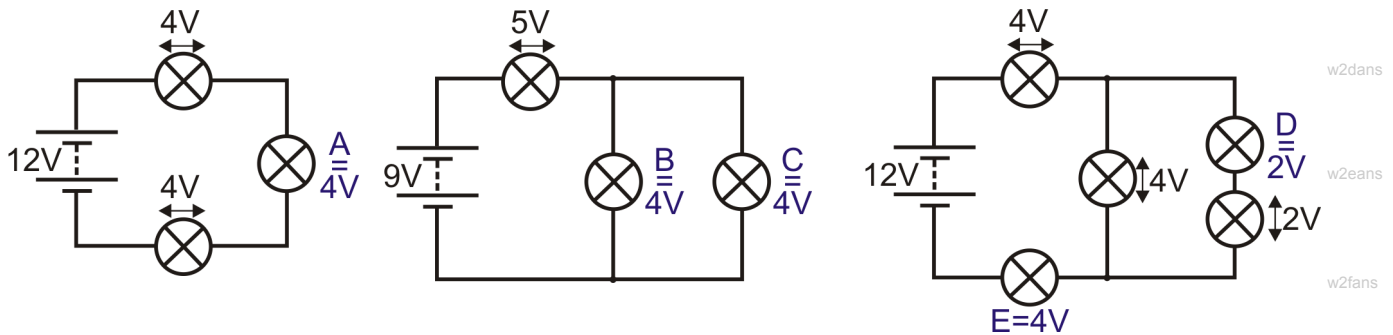
3

(See questions on pages 23 and 24.)

Worksheet 1:



Worksheet 2:



Worksheet 4:

- Total resistance = **4Ω**
- Current at P = **1.5A**
- Voltage across R₃ = **6V**
- Current at R = **1.0A**
- Current at Q = **0.5A**
- Voltage across R₁ = **4V**

Worksheet 6:

- Twenty** nickel-cadmium cells are required in a series-connected 24V battery?
- Each battery supplies **90A**.
- The emergency lamp produces **12V**.
- The 24V battery supplies **2700mA**.

Worksheet 7:

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

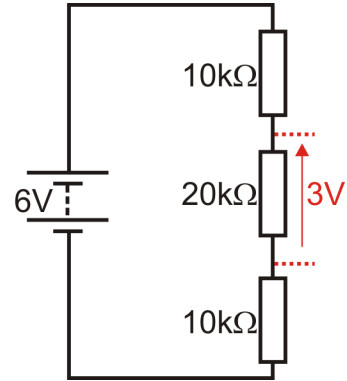
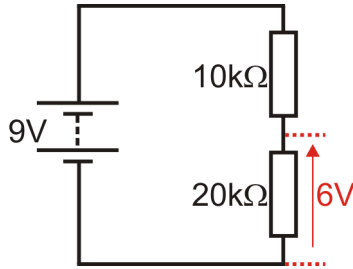
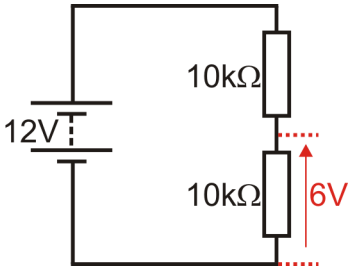
- Output voltage when delivering a current of 1A = **1V**
- Maximum current that can be drawn from the cell = **3A**
- Pd across a 2.5Ω resistor connected across the cell = **1.25V**

Answers

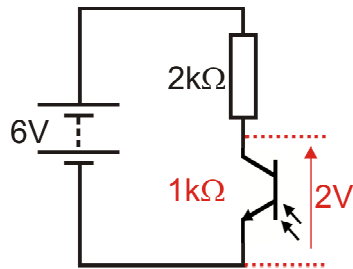
Electricity Matters 3

(See questions on pages 23 and 24.)

Worksheet 8:



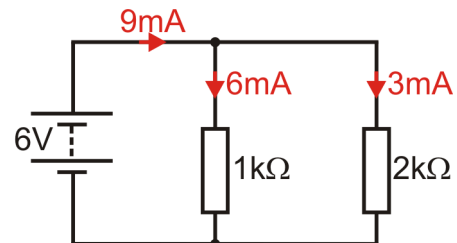
Worksheet 9:



Worksheet 10:

Voltage across 1kΩ resistor = 6V

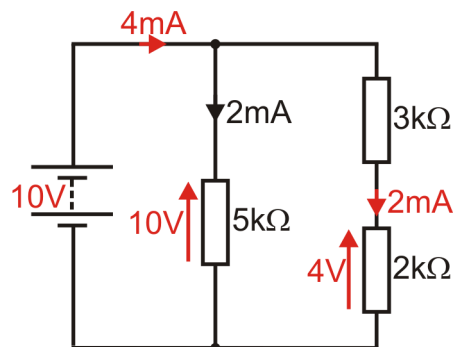
Voltage across 2kΩ resistor = 6V



Worksheet 8 and 10:

For the circuit shown opposite, calculate:

- voltage $V_1 = 2\text{mA} \times 5\text{k}\Omega = 10\text{V}$;
- supply voltage $V_s = V_1 = 10\text{V}$;
- current at **a** -
 Total resistance in limb = $3\text{k}\Omega + 2\text{k}\Omega = 5\text{k}\Omega$;
 Current = $10\text{V} / 5\text{k}\Omega = 2\text{mA}$
- current at **b** = $2\text{mA} + 2\text{mA} = 4\text{mA}$;
- voltage $V_2 = 2\text{mA} \times 2\text{k}\Omega = 4\text{V}$.





Multimeter Help

Electricity Matters


3

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 .



mh1

mh2

mh3

mh3

Multimeter Help

Electricity Matters

3



mh1

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

Electricity Matters 3

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 R₁	
Voltage across R₂	
Voltage across R₃	

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 R₁	
Voltage across R₂	
Voltage across R₃	

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 point A in mA	
Current at point B in mA	
Current at point C in mA	
Current at point D in mA	
Voltage across R₁ (270Ω resistor)	
Voltage across R₂ (1kΩ resistor)	
Voltage across R₃ (2.2kΩ resistor)	

Student Handout

Electricity Matters 3

**Worksheet 4
continued:**

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 R₁ and R₂ (=V _s)	
Total resistance $R_T = V_s / I$	
Combined resistance of R₁ and R₂ (in series) (=R _C)	
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	Series battery	Output voltage	Parallel battery	Output voltage
E1		(b) 2-cell		(d) 2-cell	
E2		(c) 3-cell		(e) 3-cell	
E3					

Worksheet 7:

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

Student Handout

Electricity Matters 3

Worksheet 8:

R ₁ = 10kΩ, R ₂ = 10kΩ			R ₁ = 1kΩ, R ₂ = 10kΩ		R ₁ = 2.2kΩ, R ₂ = 22kΩ	
Power supply	6V	9V	Power supply	9V	Power supply	9V
Current at A in mA			Current at A in mA		Current at A in mA	
Voltage V ₁ across R ₁			Voltage V ₁ across R ₁		Voltage V ₁ across R ₁	
Voltage V ₂ across R ₂			Voltage V ₂ across R ₂		Voltage V ₂ across R ₂	

Part	Circuit	R _T	I	V ₁	V ₂
1	R ₁ = 10kΩ, R ₂ = 10kΩ, V _s = 6V				
2	R ₁ = 10k Ω, R ₂ = 10kΩ, V _s = 9V				
3	R ₁ = 1kΩ, R ₂ = 10kΩ, V _s = 9V				
4	R ₁ = 2.2kΩ, R ₂ = 22kΩ, V _s = 9V				

Worksheet 9:

Temp in °C	Resistance in kΩ

Worksheet 10:

R ₁ = 10kΩ, R ₂ = 10kΩ		R ₁ = 1kΩ, R ₂ = 10kΩ		R ₁ = 1kΩ, R ₂ = 10kΩ	
Power supply	6V	Power supply	9V	Power supply	9V
Current at A , I ₁ , in mA		Current at A , I ₁ , in mA		Current at A , I ₁ , in mA	
Current at B , I ₂ , in mA		Current at B , I ₂ , in mA		Current at B , I ₂ , in mA	

Circuit	I ₂ , in mA
R ₁ = 10kΩ, R ₂ = 10kΩ, V _s = 6V	
R ₁ = 10kΩ, R ₂ = 10kΩ, V _s = 9V	
R ₁ = 1kΩ, R ₂ = 10kΩ, V _s = 9V	

Student Handout

Electricity Matters

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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: $R_T = R_1 + R_2 + R_3 + \dots$

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, R_T 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.

Student Handout

Electricity Matters

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Summary continued:

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 $\sim 0.2\text{s}$ 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

Electricity Matters

3

Summary continued:

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.

$$\text{When } R_1 = R_2 \quad V_1 = V_2 = \frac{1}{2}V_S.$$

$$\text{When } R_2 = 10 \times R_1, \quad V_2 = 10 \times V_1.$$

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:

$$I = I_1 + I_2$$

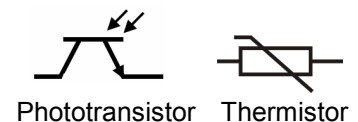
- The *bigger* the resistor, the *smaller* its share of the current.

$$\text{When } R_1 = R_2 = 10\text{k}\Omega: \quad I_1 = I_2 = \frac{1}{2} I$$

$$\text{When } R_2 = 10 \times R_1 \quad I_1 = 10 \times I_2.$$

LDR and thermistor:

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



W9d_rohs

- 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.