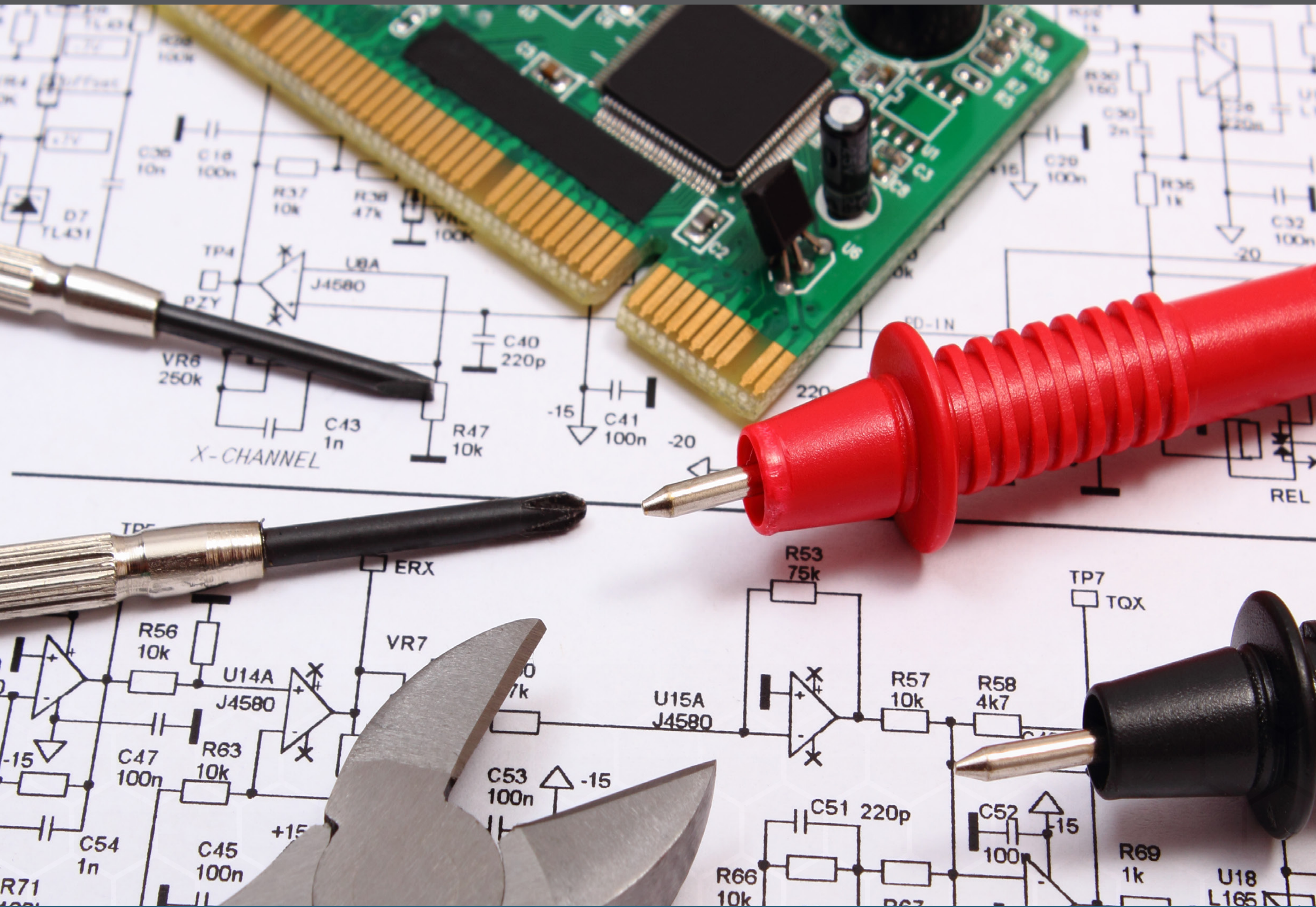
MATRIX | locktronics



ELECTRICAL ESSENTIALS

CP3878

Inspiring The Next Generation Of Engineers

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Contents

Worksheets

WORKSHEETS

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Worksheet 1 – Understand Concepts of Voltage, Current and Power

What is Electricity? Electricity exists in many forms but for the purpose of this course, we will define it as the movement of electric charge in a manner that transfers energy between components. This immediately leads us to the question, 'what is energy?' When we deal with electricity, a number of words like 'voltage', 'current' and 'power' are used. Spending some time at the beginning, to understand exactly what these terms mean will make the concepts that are introduced later much easier to understand.

Energy

Energy is the capacity to do work. Electricity can do work in many forms from heating or lighting a room to moving small toys, larger vehicles or huge railway trains. Electrical engineers working in industrial settings often deal with a lot of energy in large scale machinery. At the other end of the scale, electronic clocks might be designed to run for many years from the energy in a small battery.
To measure amounts of anything, we need units. The unit of energy is the joule, often abbreviated to just the letter J. One joule is the amount work done when a force of one newton (roughly the weight of a small apple) displaces an object by one metre in the direction of the force.
Although the joule is defined in terms of movement, it is equally used to measure the amount of energy used to provide heating, lighting, charging batteries, running electronic devices and all the other work that electricity does for us.

Power

Power is a measure of how fast energy is converted or, to put it another way, how fast work gets done.
Consider the work involved in moving a pile of sand from one place to another: One person might take some time to do that work while a more powerful person might move the same amount of sand in much less time.
Similarly, consider a fire doing the work of converting the chemical energy stored in a pile of wood into heat and light. A small fire gives off a small amount of heat. A larger, more powerful fire would give off more heat but would burn through the pile and run out of wood more quickly.
Power is measured in units of watts, abbreviated to the letter W. One watt is the power to convert one joule per second.
We can write this as a formula: -

Power = Energy / time $\quad P = E / t$

Now that we have these two concepts, we will look at some terms that describe how they relate to electricity.

Charge

Electric charge is the stuff that actually moves in an electric circuit. In most cases, we are thinking about the movement of subatomic particles called electrons that are free to move around conducting materials such as metals. Electrons are very small and one electron can not do much alone. Since we do not wish to deal with 'small change', we invent a larger unit. In the same way that we put one hundred cents together and call it a dollar, we put 6 242 000 000 000 000 000 (6.242 billion billion or 6.242 x 1018) electrons together and call it one coulomb. (Do not worry about memorising that number, we will only ever deal with coulombs.)

Electric Current

Whenever we have some electric charge flowing we call it a current. Current always flows in complete circuits and arrives back where it started. It is the flow of charge and not the charge itself that is doing the useful work.
Think about a water-powered mill. The mill does not use up water, whatever water powers the water-wheel, the same amount of water flows downstream away from the mill. In the same way, electric charge flowing into an electrical component must flow out again. When we design electric circuits, we always provide some means for the current to flow around a closed path.
Electric current is measured in amperes, often abbreviated to 'amps' or simply to the letter 'A'. One ampere of current is defined as one coulomb of charge passing every second. In this course we shall often be dealing with small currents and so we will measure in milli-amperes, abbreviated to 'mA'. One milli-ampere is defined as one thousandth of a coulomb passing every second or one whole coulomb every thousand seconds.
We now know enough to write a simple formula: -

Current = charge / time $\qquad I = Q / t$

(The letter I is used for current and Q for charge.)

Voltage

We said at the start the we are interested in the movement of electric charge as a means to transfer energy. When current flows through a battery or electrical generator, it gains energy. When current flows through other electrical components, it may give up or transfer this energy. Voltage is a measure of the amount of energy that is gained or lost.

Note that we are not interested in the absolute total amount of energy in the electric charge but only in the change. Think about a truck driving over a weighbridge before and after loading. It is the change in weight that matters, not the absolute weight of the truck. In some text books, you will see the term 'Potential Difference' used instead of voltage.

Voltage is measured in volts, abbreviated to the letter 'V'. One volt is defined as one joule of energy gained or lost per coulomb of charge.

A 12V battery gives each coulomb of charge that passes through it 12J of energy.

If the voltage difference across a component is 2V, that means that every coulomb that passes through it loses 2J of energy.

We can write another formula: -

$$\text{Voltage} = \text{Energy} / \text{charge} \qquad V = E / Q$$

Power

We have already said that power is the rate at which energy gets converted but now we can look at how that relates to electrical measurements. Look at the formulas that we have defined so far.

If we multiply voltage and current together we get: -

$$V \times I = (Q \times E) / (t \times Q)$$

The Qs cancel giving: -

$$V \times I = E / t$$

Remember that E / t was the formula for power. Thus, power is the product of voltage and current: -

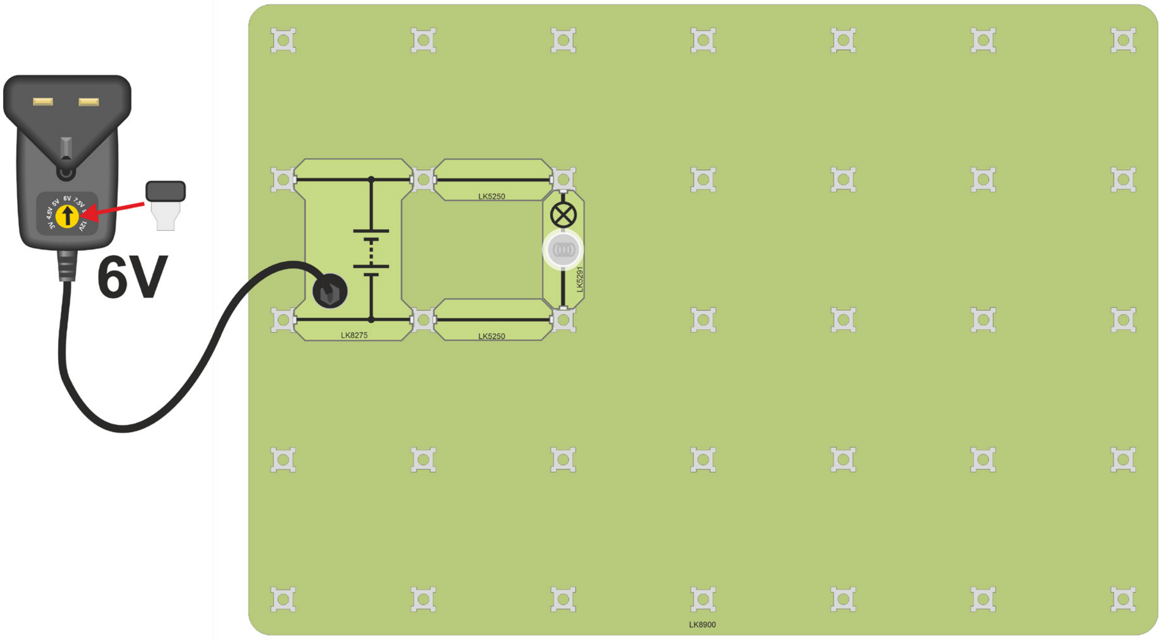
$$P = V \times I$$

Current is the rate at which charge is flowing. Voltage is amount of energy that the charge is transferring. Multiply them together and we get the rate at which energy is being transferred which is power.
Electrical components generally have power ratings. Sometimes devices are developed to use less power. For example; old style of domestic light bulbs had power ratings around 60W. Newer types have a rating of 15W for the same brightness, because they waste less electrical energy to heat but still produce the same amount of light.

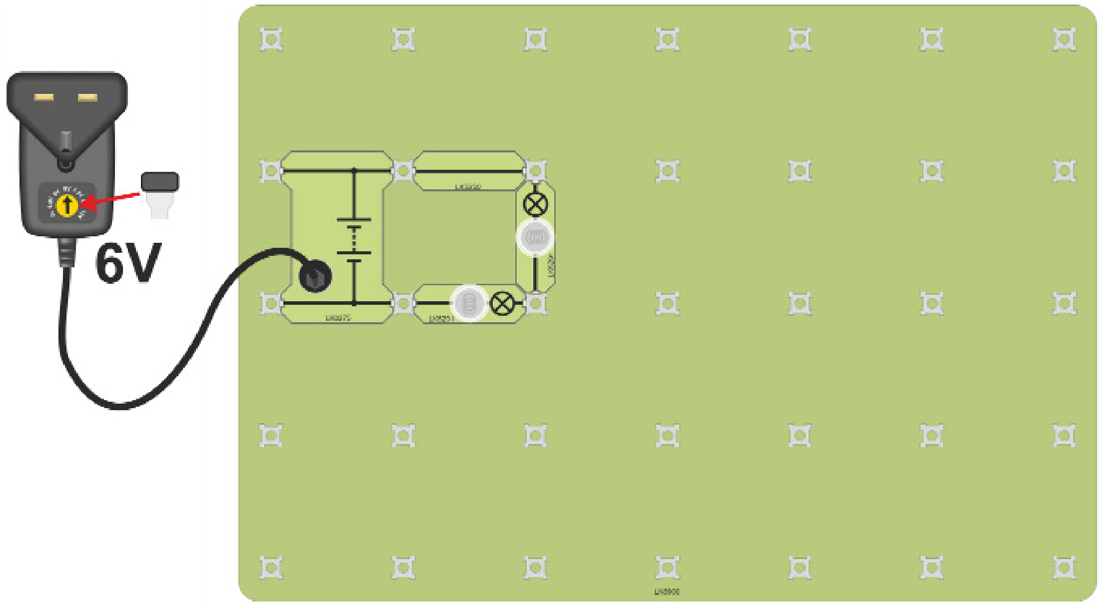
Activity

- Find the Locktronics DC power supply and check set it to 6 V.
- Set up each of the three illustrated circuits in turn.
- Observe the brightness of the bulb in each case.
- Try to work out which circuit is using the most power.
- Try to work out which circuit is using the least power.
- If these circuits were powered by batteries; which would last the longest and which would go flat first.
- For the circuits that have two bulbs, try removing one and observe what happens to the remaining bulb.

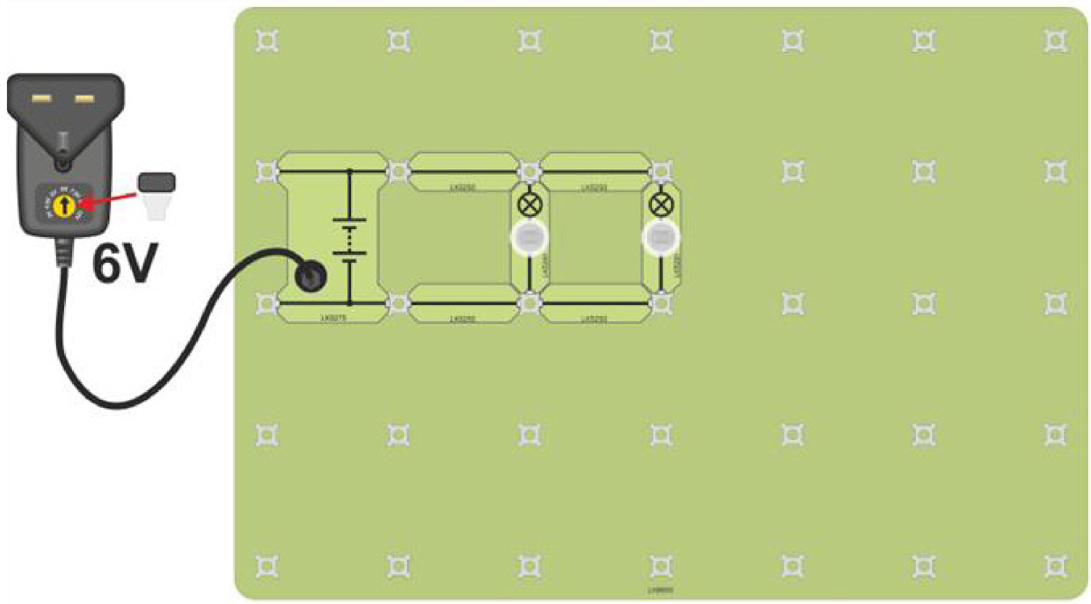
Circuit A



Circuit B



Circuit C



Analysis

This activity has been qualitative, we have simply observed and made guesses.
In the following worksheets, we will make some quantitative experiments.
We will look at how to measure voltage and current. This will allow us to put real figures to what is happening in the circuits. We can then look back and see if our guesses were correct.

Challenge

Think about some real world examples of the uses of electrical lamps. Which of our three experimental circuits do your examples most resemble? Can you think of some advantages and disadvantages of each arrangement.

Have you ever been told not to leave lights on?

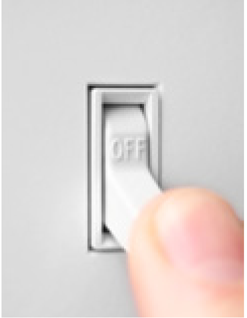
Leaving them on wastes energy, and money!

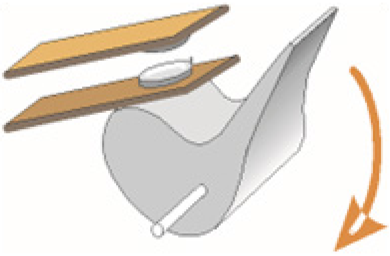
We need something to control the flow of electricity.
A switch does just that!

Look at the drawing! It shows how a switch works.

Can you see what will happen when you press the switch and the lever moves down?

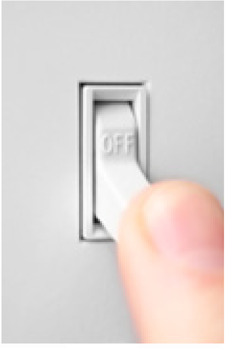
Remember – air is an insulator!

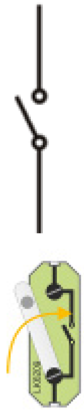




A switch starts and stops the flow of electricity.

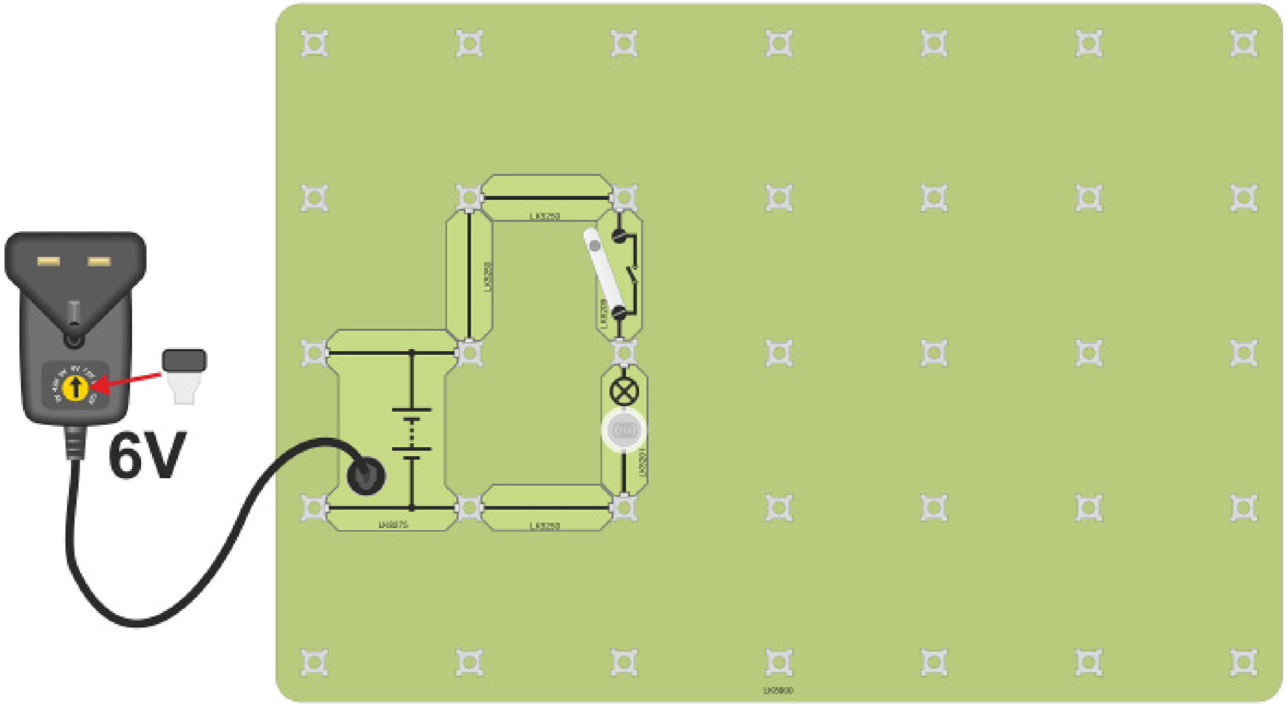
The diagram on the right shows the symbols used for two kinds of switch.
A push switch is 'on' only as long as you are pressing it. When you turn on a toggle switch, it stays on, until you turn it off.
Here are two pictures of switches—a doorbell switch, and a light switch. Decide whether each is a toggle switch or a push switch.





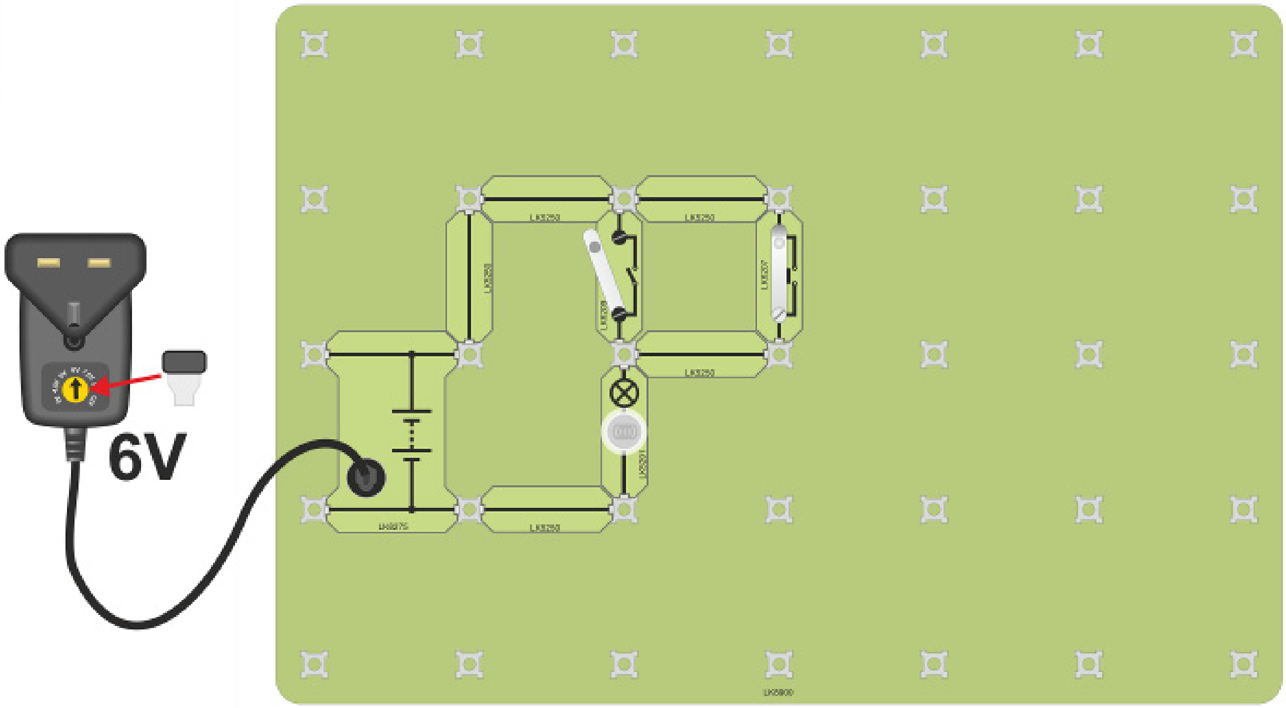
Toggle Switch
Twist on and off

Push Switch
Press down for on



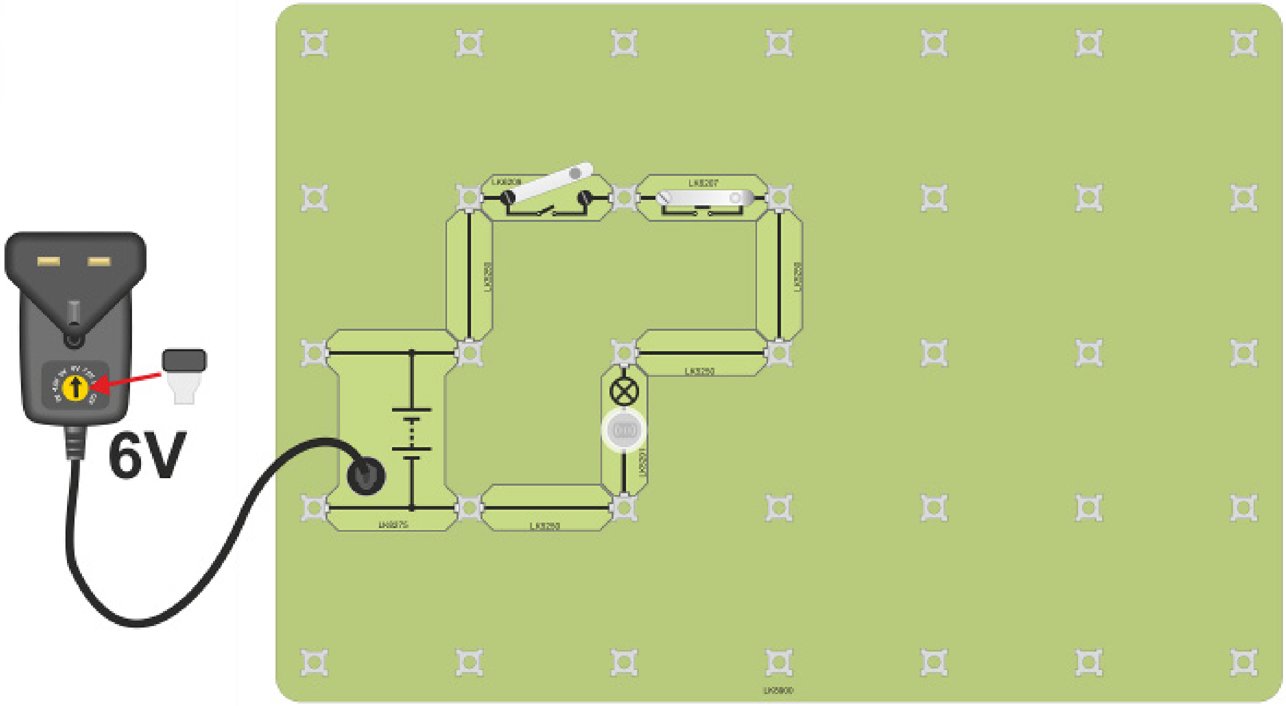
Activity—Circuit A

- Build the circuit shown in the diagram.
- Pay attention to the type of switch in the circuit.
- Set the power supply to 6 VDC and plug it in.
- Close the switch, and see what happens.
- Does it matter where the switch is placed in the circuit?
- Try changing the order of the components in the circuit and see what happens.
- What would happen if there were two bulbs in the circuit?
- Swap one of the links for a second bulb. What happens now?



Activity—Circuit B

- Build the circuit shown in the diagram.
- There are two switches in this circuit, a toggle switch and a push switch.
- Set the power supply to 6 VDC and plug it in.
- Close one switch, and see what happens.
- Close the other switch. Does it matter which switch is closed?
- Try closing both switches and see what happens.
- Record your results in the student handout.



Activity—Circuit C

- Build the circuit shown in the diagram.
- Consider the difference between this circuit and the previous one. See if you can predict how this circuit will behave.
- Set the power supply to 6 VDC and plug it in.
- Close one switch, and see what happens.
- Close the other switch. Does it matter which switch is closed?
- Try closing both switches and see what happens.
- Record your results in the student handout.

Analysis

Electric current flows around circuits. Switches interrupt this flow by breaking the circuit. When switches are alongside each other as they are in circuit B, any switch can complete the circuit. When switches are in line with each other as they are in circuit C, both need to be on because any switch can interrupt the flow causing the circuit to be off. This can be used in safety systems, one switch might be connected to a machine guard and the other might be a start switch. The start switch only works when the guard is in place.

In the first worksheet, we talked about some electrical quantities, especially voltage and current. However, our practical experiments were purely qualitative and did not involve any measurements. In this worksheet and the next, we will introduce the multimeter and learn how to use it to quantitatively analyse circuits.
We will begin by learning how to measure voltage. The picture illustrates one type of multimeter.
There are many makes and models of multimeter and they all appear slightly different. They will all have the same features and basic functions. Some will have a variety of advanced functions.
All multimeters will include both voltage and current in their AC and DC forms.Multimeters will have 4mm sockets to connect either leads or probes.

Manufacturer Name and Model Number
Many manufacturers make the manuals for their devices available online. This can be useful for understanding the nuances of each individual device.

Function Selector
Selects which quantity the meter is to measure. Symbols rather than words are used. Generally these are universal but the manual for each device should describe them all.

Numerical Display
This shows the measurement. Note where the decimal point is as it can move. The display may also show which function is selected and the units of measurement.

Sockets
The number of sockets will vary between devices. Each socket will have one or more symbols above it to indicate its function. The functions of a multimeter will always require two leads. The socket labeled 'COM' provides the second connection.

When using a multimer there are three things to check before switching on the circuit:

- Check that the correct function is selected. In this worksheet we shall be using the voltmeter function, indicated by the letter V.
- Check that the correct range is selected. In this worksheet, we shall be using the DC range indicated by two lines with the lower line dashed as in the illustration to the right. In a later worksheet, we shall use the AC function, indicated by an image of a sine wave. With an auto-ranging multimeter, this is sufficient. If not auto-ranging then there will be several positions on the selector for the same function. Each will have a number indicating the highest quantity that can be measured by that range.
- Check that the leads or probes are plugged into the correct sockets.

AC	∼
DC	⎓

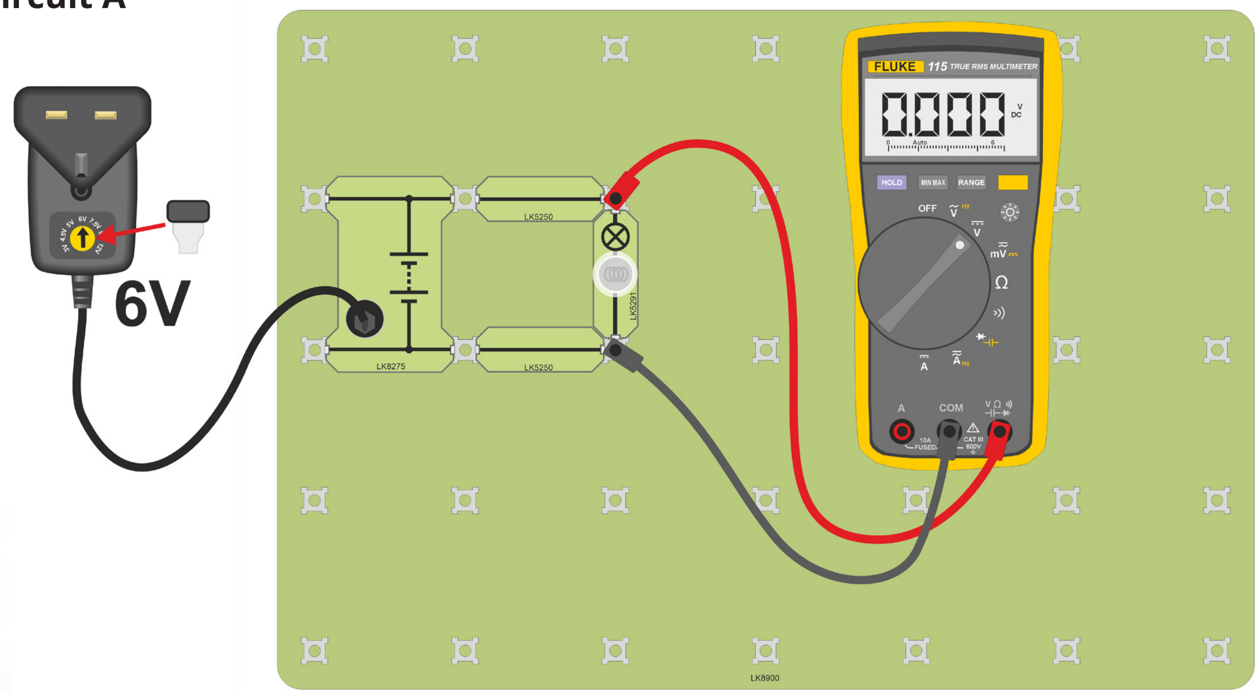
The circuit symbol for a voltmeter is the letter V inside a circle.

voltmeter

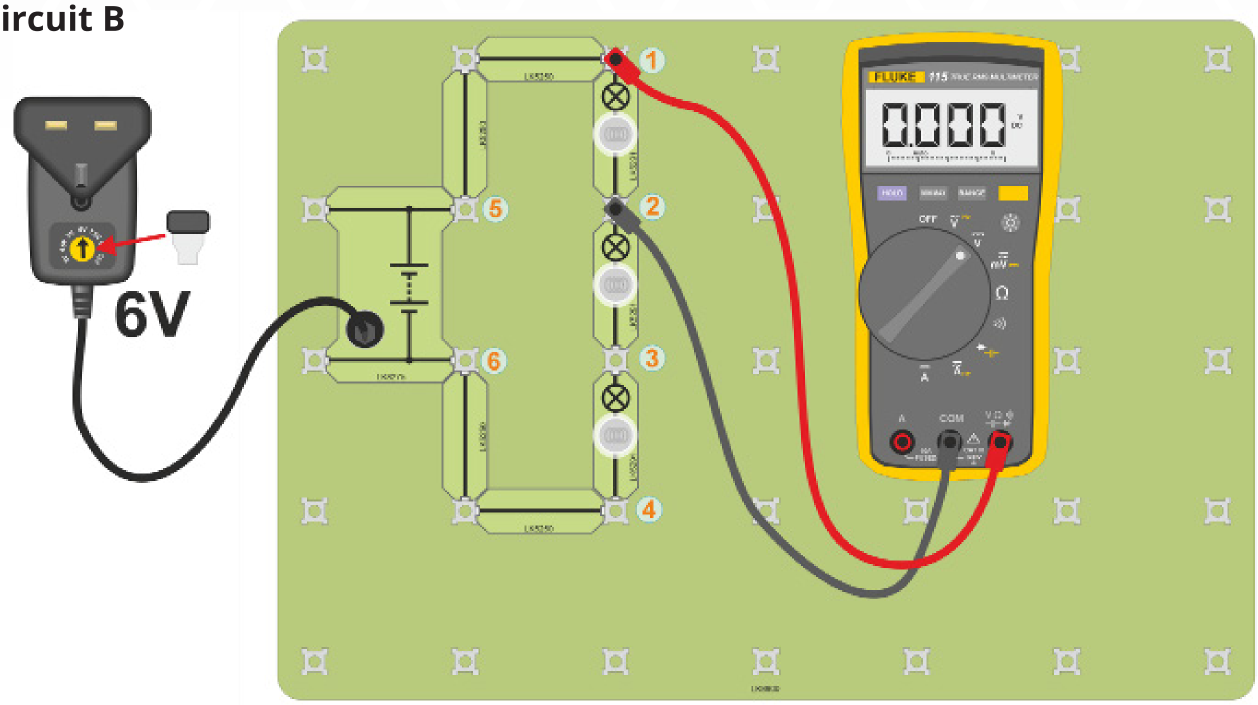
Using a multimeter to measure voltage:

- Plug one lead into the black 'COM' socket.
- Plug another into the red 'V' socket. This socket may have other symbols in addition to the V.
- Select the DC voltage range. If your multimeter is not auto-ranging, then select an appropriate range for the circuit that we are working with. Our circuit is powered by a supply set at 6 V so we will select the first range that is above 6 V. (For example, if our meter has 2 V, 20 V and 200 V ranges, we would pick the 20 V range. If we were not sure what voltage we expected to measure, we would start with the highest range and then adjust downwards.)
- Plug the wires into the posts of the Locktronics board indicated in the diagram. Switch on the power supply when you are ready to take a reading.
- Make a note of the reading. Is it what you expected?
- Move the leads to other posts within the circuit. Does the reading change.
- A '-' sign in front of the reading means that the lead connected to 'COM' is at a higher voltage than the lead connected to the 'V' socket. (Remember that voltage is a relative measurement of the difference between the two points. That difference can be positive or negative.) Whenever you see a '-' sign, swap the leads over to get rid of it!

Circuit A

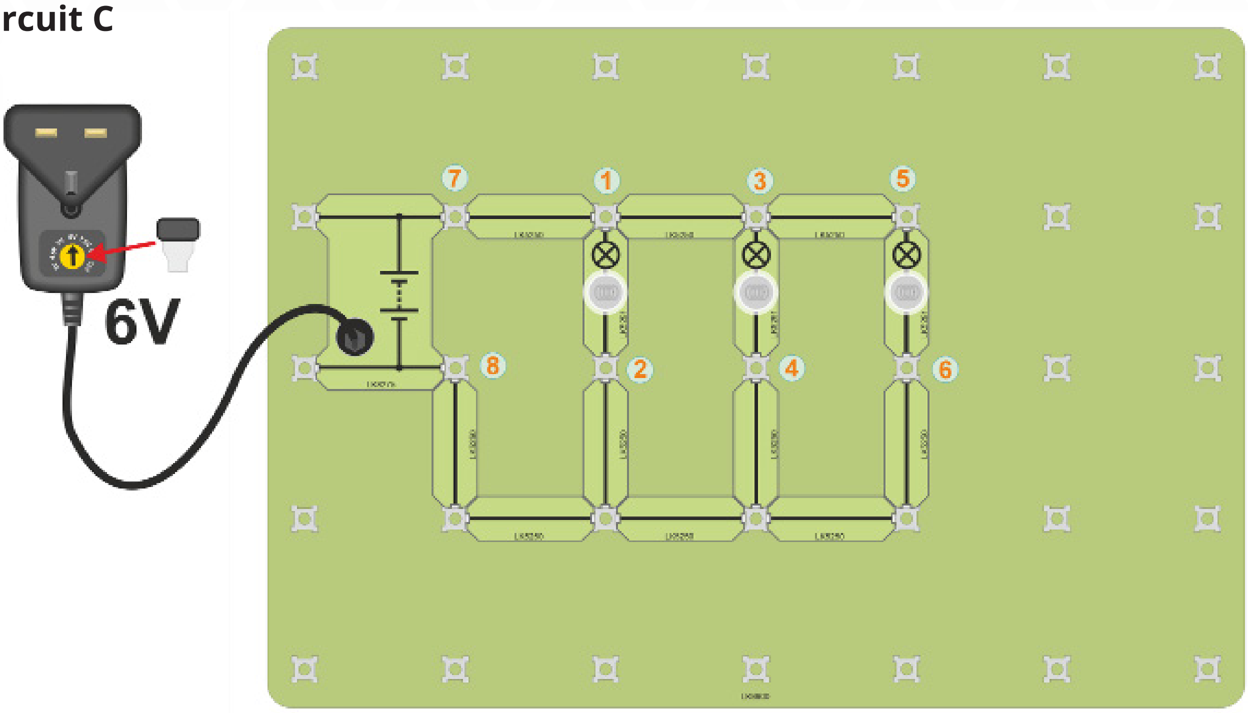


Circuit B



1. Build the layout shown above. This is a series circuit with only one route around it. (More on types of circuit later)
2. Connect the power supply, set to 6V, and switch on.
3. Set up the multimeter to read voltages up to 20V DC - see the previous page.
4. Measure the voltage across the top bulb, by plugging the multimeter leads into posts '1' and '2'.
5. Next, measure the voltage across the middle bulb, using posts '2' and '3'.
6. Then measure the voltage across the third bulb, using posts '3' and '4'.
7. Finally, measure the supply voltage, using posts '5' and '6'.
8. Add together the voltages across the three bulbs and compare it with the supply voltage. What do you notice?
9. Enter all your results into the table in the Student Handout.

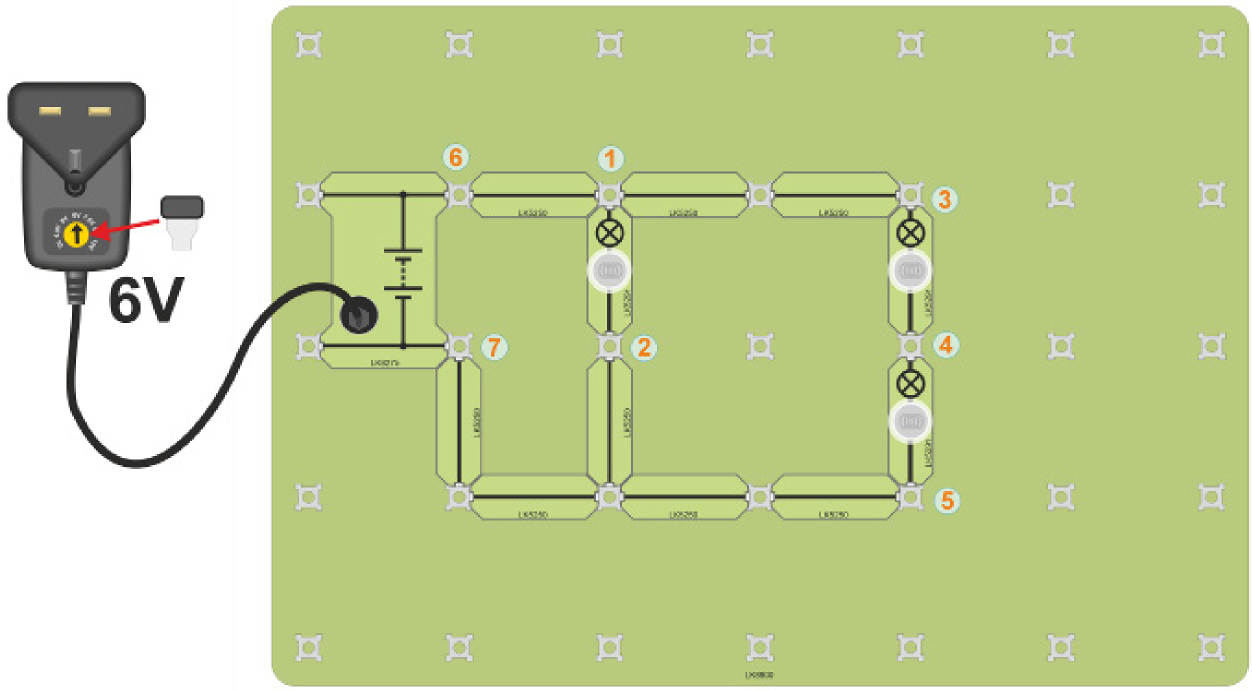
Circuit C



1. Build the layout shown above. This is called a parallel circuit with multiple branches.
2. Connect the power supply, set to 6V, and switch on.
3. Set up the multimeter to read voltages up to 20V DC.
4. Measure the voltage across the first bulb, by plugging the multimeter leads into posts ’1’ and ’2’.
5. Next, measure the voltage across the middle bulb, using posts ‘3’ and ‘4’.
6. Then measure the voltage across the third bulb, using posts ‘5’ and ‘6’.
7. Finally, measure the supply voltage, using posts ‘7’ and ‘8’.
8. Look at the voltages across the three bulbs and across the supply voltage. What do you notice?
9. Enter all your results into the table in the Student Handout and answer the question.

Circuit D

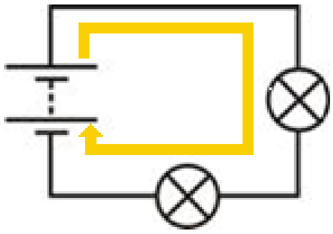
Now we build a circuit that has both series and parallel connections. Compare the brightness of the bulbs to that observed in worksheet one.

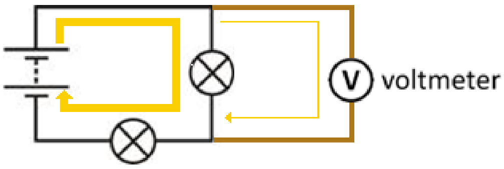


1. Build the layout shown above and switch on the power supply.
2. Measure the voltage across the first bulb, using posts '1' and '2'.
3. Next, measure the voltages across the other two bulbs, using posts '3' and '4' and then '4' and '5'. What is the sum of these two voltages?
4. Finally, measure the supply voltage, using posts '6' and '7'.
5. Look at the voltages across the bulbs. Does this explain the different brightness?
6. What do you notice about the supply voltage and the voltages across the bulbs?
7. Enter all your results into the table in the Student Handout and answer the question.

We have learned to measure voltage, we shall now look at current. Being able to measure both will enable us to calculate all the quantities described in worksheet 1. A multimeter can measure both voltage and current.
At first glance, the technique appears to be the same. We will be using a multimeter and connecting leads to the posts of the Locktronics board. There is, however, an important difference: When measuring voltage, we add the voltmeter to the circuit without altering the circuit that we are measuring. When measuring current, we must alter the circuit so that the whole current flows through the multimeter.

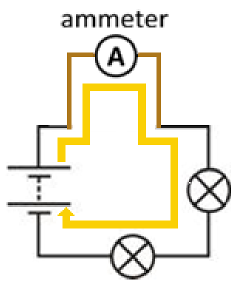
Look at the circuit on the right, the power supply gives a voltage that is shared between the two bulbs. A current flows around the circuit.

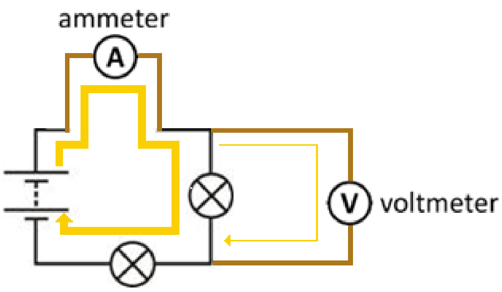




If we want to measure the voltage across one of the bulbs, we add a voltmeter (multimeter in voltage mode) to the circuit without altering it. In fact, a very small amount of current will flow through the voltmeter but it is small enough to be ignored.

If we want to measure the current flowing in the circuit, then we have to create a break in the circuit. Then we connect the ammeter (multimeter in current mode) so that all the current that was flowing in the circuit will flow through the ammeter. The ammeter measures the current but does not alter it so the circuit still behaves as it did before the current was diverted through the ammeter. In fact, an ammeter introduces a very small voltage drop into the circuit but it is small enough to be ignored.



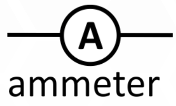


If both voltmeter and ammeter are available (two multimeters) then both measurements can be performed at the same time. Ideal meters measure current and voltage without affecting the circuit. Real multimeters will have a small effect on the circuit but generally this is not significant.

WORKSHEETS

Worksheet 4 – Measuring Current

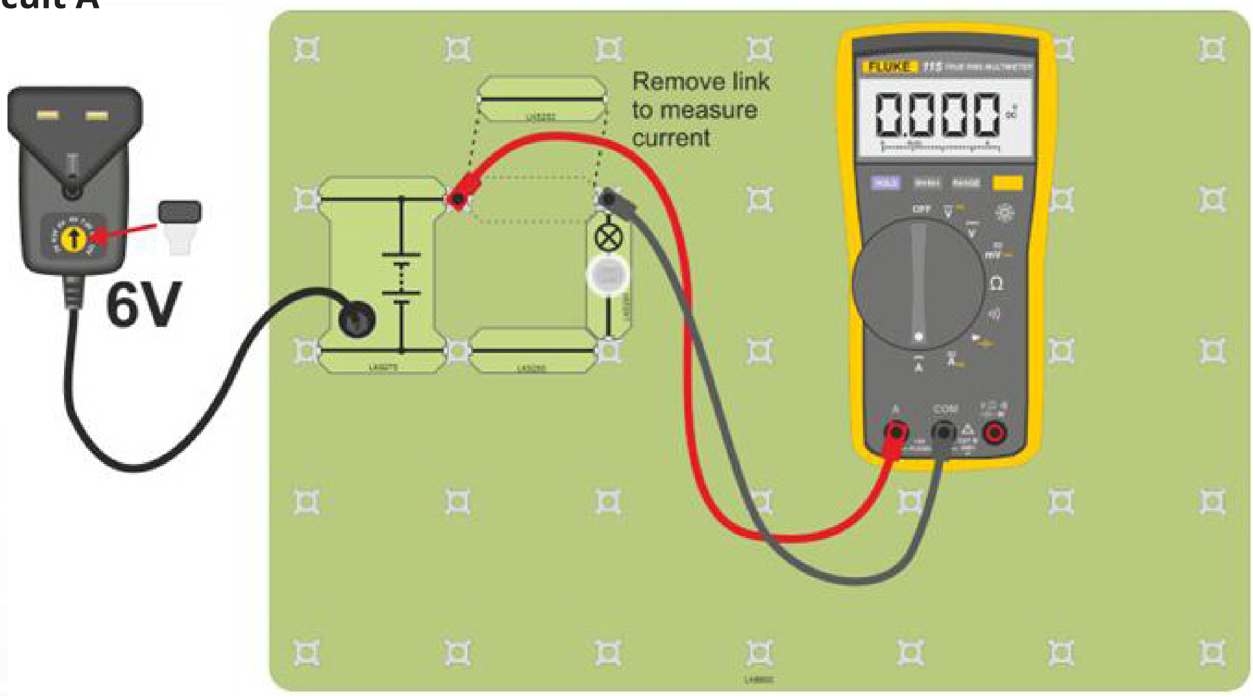
The circuit symbol for an ammeter is the letter A inside a circle.



Using a multimeter to measure current:

- Plug one wire into the black ‘COM’ socket.
- Plug another into the red ‘A’ socket.
    - On some multimeters, this socket may have other symbols in addition to the A.
    - On some meters, there is one socket for general current measurements and another for the highest current range. These could be labelled ‘A’ and ‘10A’. Use the highest range.
- Select the DC current range. If your multimeter is not auto-ranging, then select an appropriate range for the circuit that you are working with. Note that most multimeters will have some ranges marked in amps (A) and some in milli-amps (mA).
- Always start by setting the meter to the highest current range available. On most multimeters, this will be 10A. If the reading turns out to be smaller than the next range then try using that. This might mean using a different socket.
- Since we need the whole of the current that we are measuring to be diverted through the meter, remove a link from the circuit.
- Plug the wires into the posts of the Locktronics board either side of the removed link. (indicated in the diagram). Switch on the power supply when you are ready to take a reading.

Circuit A

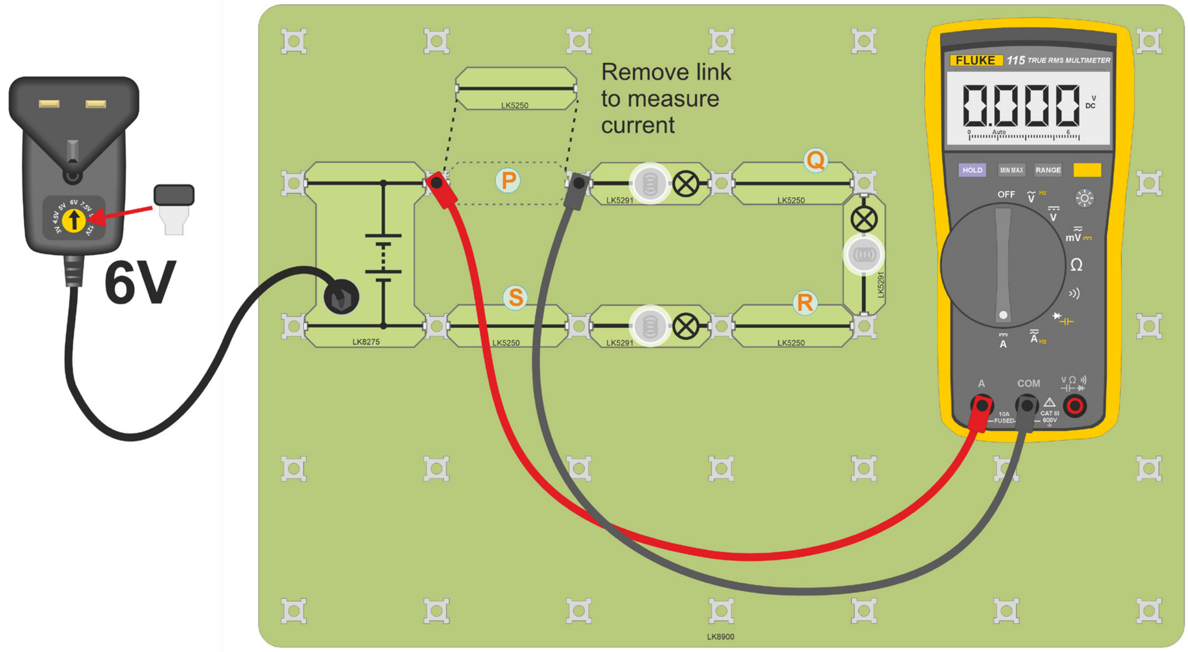


- A possible problem - The ammeter range is protected by a fuse located inside the body of the multimeter. This may have 'blown', in which case the ammeter will not work. Report any problems to your instructor so that it can be checked.
- Make a note of the reading.
- Try putting the leads in place of the other link in the circuit. Does the reading change?
- A '-' sign in front of the reading means that the lead connected to 'COM' is at a higher voltage than the lead connected to the 'V' socket. (Remember that voltage is a relative measurement of the difference between the two points. That difference can be positive or negative.) Whenever you see a '-' sign, swap the leads over to get rid of it!

Worksheet 4 – Measuring Current

1. Build the layout shown below - a series circuit of three lamps spread out to allow easy insertion of the ammeter when needed.
2. Connect the power supply, set to 6V, and switch on.

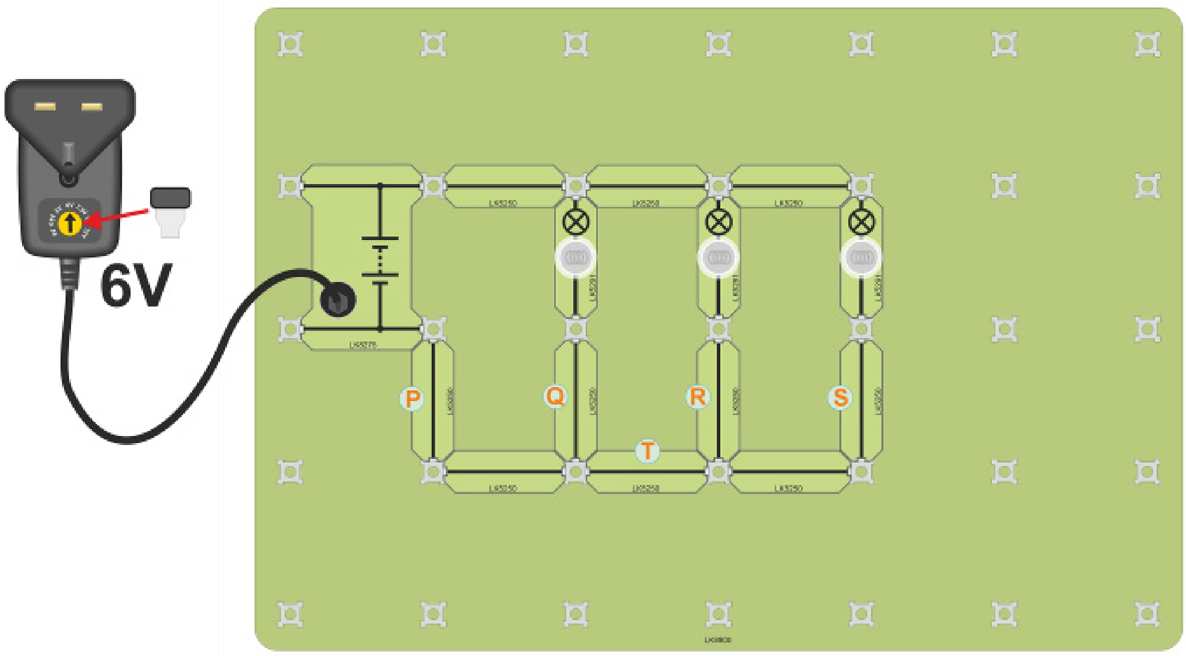
Circuit B



3. Set up the multimeter to read currents up to 10A DC - see the previous page.
4. Measure the current at point ‘P’, by removing the connecting link and plugging the multimeter leads into the posts at either end of it.
5. In the same way, measure the current at points ‘Q’, ‘R’ and ‘S’. Remove power to the circuit while moving the multimeter between points. You could say that the current at ‘P’ is the current delivered by the power supply, or the current flowing into the first bulb. Equally, the current at ‘Q’ is that leaving the first bulb, or entering the second one - and so on.
6. What do you notice about all the current readings?
7. Enter all your results into the table in the Student Handout.

1. Build the layout shown below - a parallel circuit of three lamps, again spread out to allow easy insertion of the ammeter when needed.
2. Connect the DC power supply, set to 6V, and switch on.

Circuit C

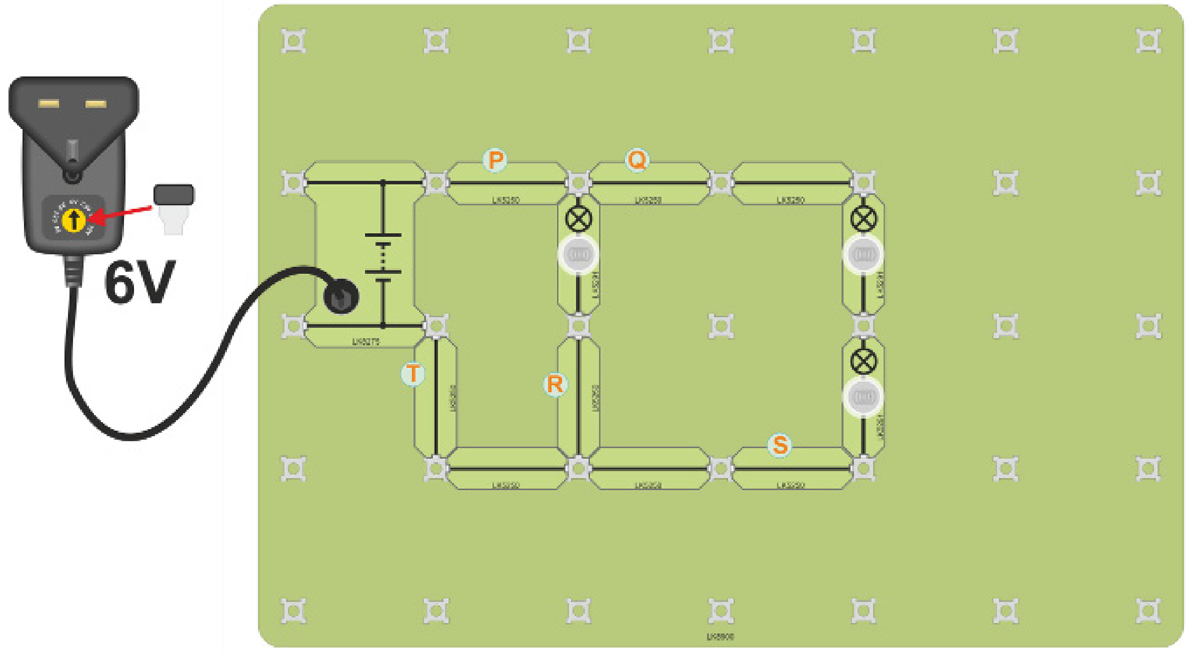


3. Set up the multimeter to read currents up to 10A DC as before.
4. Measure the current at points ‘P’, ‘Q’, ‘R’ and ‘S’, by removing the connecting links and inserting the ammeter.
5. Enter your results into the table in the Student Handout and answer the question.
6. Use your results to guess what the current flowing at point ‘T’ might be.
7. Now measure it. Were you correct? Write its value in the Student Handout.

Now we look at the currents flowing in a circuits that has both series and parallel connections.

1. Build the layout shown below.
2. Connect the DC power supply, set to 6V, and switch on.

Circuit D



3. Measure the current at points 'P', 'Q', 'R', 'S' and 'T'.
4. Enter all your results into the Student Handout.
5. Explain why the current readings at points 'P' and 'T' are equal.
6. Explain why the current readings at points 'Q' and 'S' are equal. What does this imply for the brightness of the two bulbs between these points?
7. Compare these readings with the current at point 'R'. What does this mean for the brightness of the bulb above it?

WORKSHEETS

Worksheet 5 – Understand Resistance and Apply Ohm's Law

So far, we have learned that current is a measure of how much electrical charge is flowing in a circuit and voltage is a measure of how much energy is gained or lost throughout the circuit. Now we will look at how the two quantities are related in each circuit component.

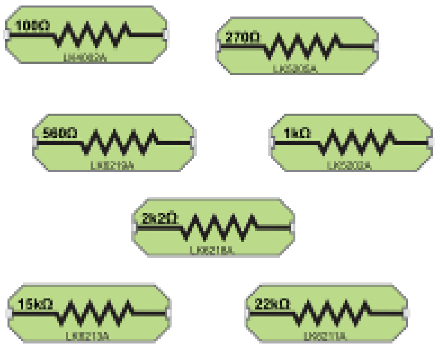
The photograph shows Georg Simon Ohm—a significant figure in this study!

Look back at the last circuit of the previous worksheet. We observed that more current flowed through the single lamp than through the two lamps wired in series (one after the other). Intuitively, it seems that going through a single a single lamp must be easier than going through two. We might say that the majority of the current follows the path of least resistance.

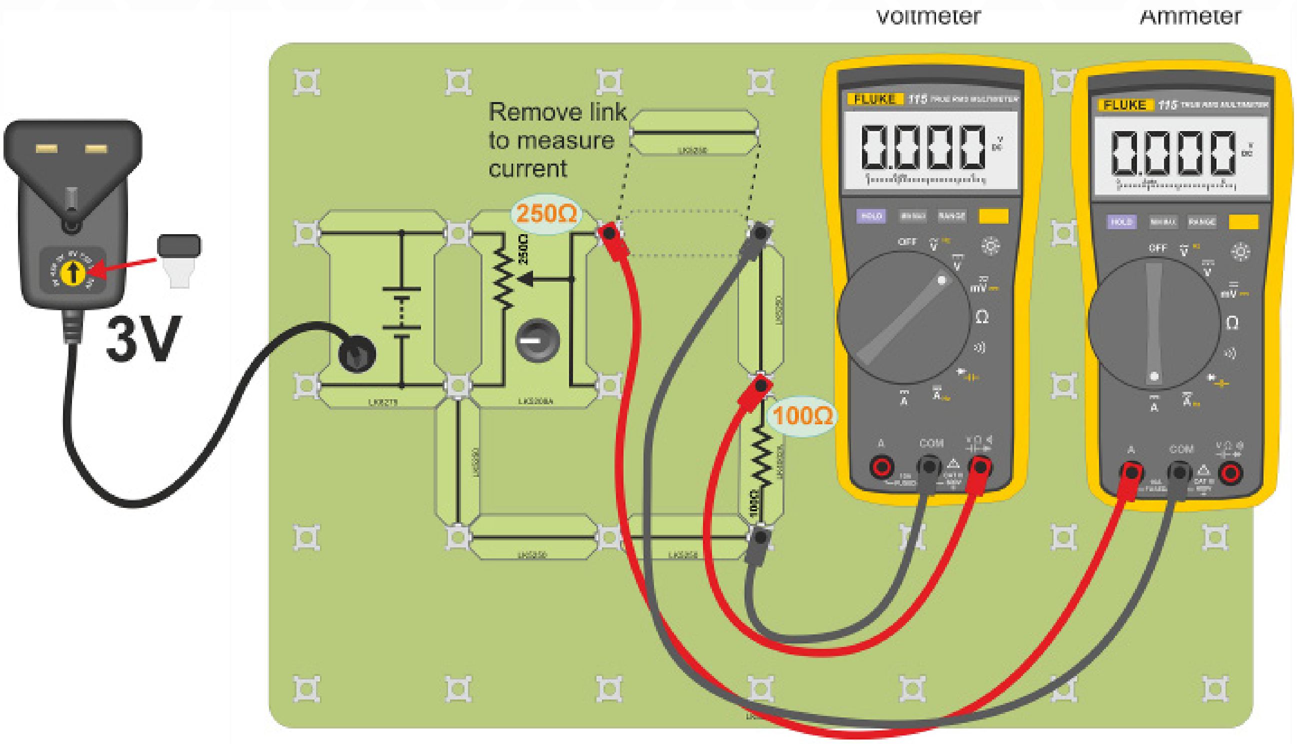
The word 'resistance' has a specific meaning when dealing with electrical circuits. In this worksheet, we will learn about this. Firstly, we introduce a new component; the resistor.

The image on the right shows a number of Locktronics resistors. The circuit symbol for a resistor is a zig-zag line or a rectangle depending on the standards being used. Find some of these components in your kit, turn them over and look at the actual component soldered underneath.

What does a resistor actually do?



A resistor converts electrical energy to heat. In the components that we are dealing with, the amount of heat produced is very small. There will be no danger of burning ourselves and in most cases we will not even feel the component getting hot. The useful thing about resistors is that they behave in very predictable way. This behaviour can be very useful for controlling voltage or current within a circuit and will be studied here.



Activity

- Change the voltage of the power supply to 3V.
- Set up the diagram shown opposite. If only one multimeter is available, put a link in place of the ammeter when measuring the voltage.
- The variable resistor allows us to change the voltage across the 100Ω resistor.
- Before you switch on, set the multimeter that is used as an ammeter to the 200mA DC range. Set the multimeter that is used as a voltmeter to the 20V DC range. Notice the positions of the red and black connecting wires. This ensures that the meters are connected the right way round to avoid '-' signs on the readings.
- Turn the knob on the variable resistor fully anticlockwise, to set the voltage supplied to a minimum.
- Turn the knob slowly clockwise until the voltage across the resistor reaches 0.2V. Then read the current flowing through the resistor.
- Turn the voltage up to 0.4V, and take the current reading again.
- Keep doing this until the voltage reaches 2.0V.
- Write your results in the table in the student handout.
- Replace the 100Ω resistor with the 270Ω resistor and repeat the experiment.
- Repeat the experiment again with the 560Ω resistor.
- Note that it can be difficult to adjust the voltage exactly. It is acceptable to record voltages close to the target that you are aiming for. For example; 0.207V and 0.389V rather than 0.200V and 0.400V.

Analysis

You should have found that the more voltage is applied across the resistor, the more current flows. Plot your results on the graph paper in the student handout. You should find that the results for each resistor all lie on a straight line. The slope of the line for each resistor is different. Measure the slopes and write the results in the table in the student handbook.
The relationship between voltage and current is a straight line for a resistor. The slope of this line is called Resistance.
The unit of measurement of resistance is the ohm, its symbol is the Greek letter omega, Ω.
One ohm is one amp per volt.
This relationship between voltage and current is called "Ohm's law" and can be expressed by the equation: -

$$R = V / I$$

It can be rearranged as: -

$$I = V / R \quad \text{and} \quad V = I R$$

Since we have already seen that power is voltage multiplied by current: -

$$P = V^2 / R \quad \text{and} \quad P = I^2 R$$

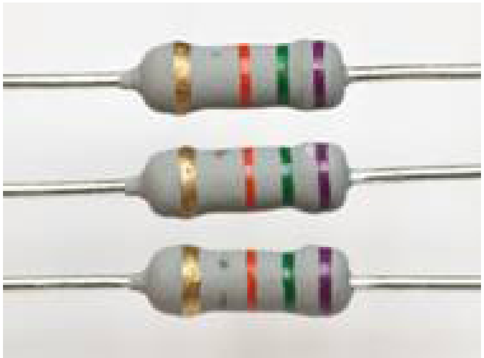
Challenge

Replace the resistor in you circuit with a lamp and repeat the experiment. What shape does the graph have? Plot your results on the graph as you go. It might be necessary to take measurements at more voltage points than before to properly see the shape. Do the same for the LED.
Not all components behave according to Ohm's law. Components that do not give straight lines for the plot of current against voltage are called "non-ohmic".
Look back over the previous experiments. The units of Ohm's law are volts, amps and ohms (V,A and Ω). What happens if you use milliamps and kilo-ohms, (V, mA & kΩ)? Does it still work and can you explain why?

Although the resistor is a simple component, it is very common in electronic circuits. Resistors are available in a very wide range of values. The resistors that are soldered under the Locktronics carriers are cylindrical in shape with leads coming out of each end. You might come across resistors with their resistance printed on them but it is more common to find them with coloured bands. Each colour represents a digit.

To read the resistance value of a resistor, start from the opposite end to the gold or silver band. The first band is the first digit, the second band is the second digit. The third band is the number of zeros that follow.
The final band (usually gold, (5%) or silver (10%)) shows you the tolerance (how accurately made it is.)

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



For example, the resistors in the photograph have a resistance of:
Violet = 7
Green = 5
Orange = 000 (three zeros)
=> 75000Ω
and a tolerance of 5%

If we have larger resistances, we would use the prefix, k, for kilo. 75000Ω = 75kΩ.
In circuit diagrams, you will often see the 'k' doing double duty as both the kilo prefix and as the decimal point. 2200Ω could be written as 2.2kΩ or 2k2Ω. It might also be written as simply, 2k2, with the Ω symbol omitted.
As well as 'k' for kilo, you may see 'M' for mega. 1500000Ω = 1500kΩ = 1.5MΩ = 1M5Ω.

WORKSHEETS

Worksheet 6 – Measuring Resistance

We have already learned how to use a multimeter to measure voltage and current. Now we will add a third function, resistance. When we work with the Locktronics kits, all the components are clearly labelled so that we know what they are. In other situations, we might not be so fortunate. This is especially true in electrical maintenance where components may have identifying marks worn away or covered in grime. Even new components are not always easy to identify; markings may be unclear or red and orange bands could be hard to distinguish under poor lighting.
We will be using a multimeter to measure Locktronics components. Even though they are clearly labelled, they are sometimes not quite what they seem!

- When measuring voltage, the meter is simply added to the circuit without altering anything.
- When measuring current, a link in the circuit must be removed so that all the current is going through the meter.
- When measuring resistance, generally we remove the component from the circuit completely. **Resistance is never measured in a powered circuit.**

It is unusual to see a circuit symbol for an ohmmeter because they are used with components that are removed from a circuit.

Using a multimeter to measure resistance:

- Plug one wire into the black 'COM' socket.
- Plug another into the red 'Ω' socket. This socket is often the same socket used for voltage.
- Select the resistance range. If your multimeter is not auto-ranging, then select an appropriate range for the component. If you are unsure what range to use then there is no harm trying all the available ranges one after another until the best range is found.

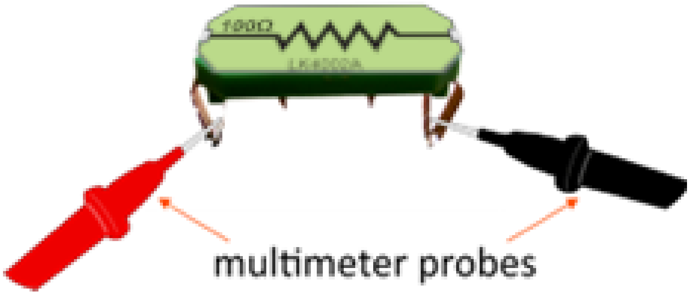
Some things to note:

- Many multimeters have a sounder either associated with the lowest resistance range or as a separate function. This will cause the meter to make a noise whenever it detects a resistance below a certain value. This function can be very useful in checking wiring to find broken connections.
- Multimeters are usually supplied with probes that can be pressed against the component being measured. Alternately, the component can be placed in a spare area of the board and leads plugged into the posts either side of it.

Worksheet 6 – Measuring Resistance

Activity

- Set the multimeter to the resistance (Ω) function.
- Make sure that the probes are plugged into the 'W' and 'COM' sockets.
- Press the tips of the probes against the metal clips on the 100Ω resistor, as shown in the diagram.



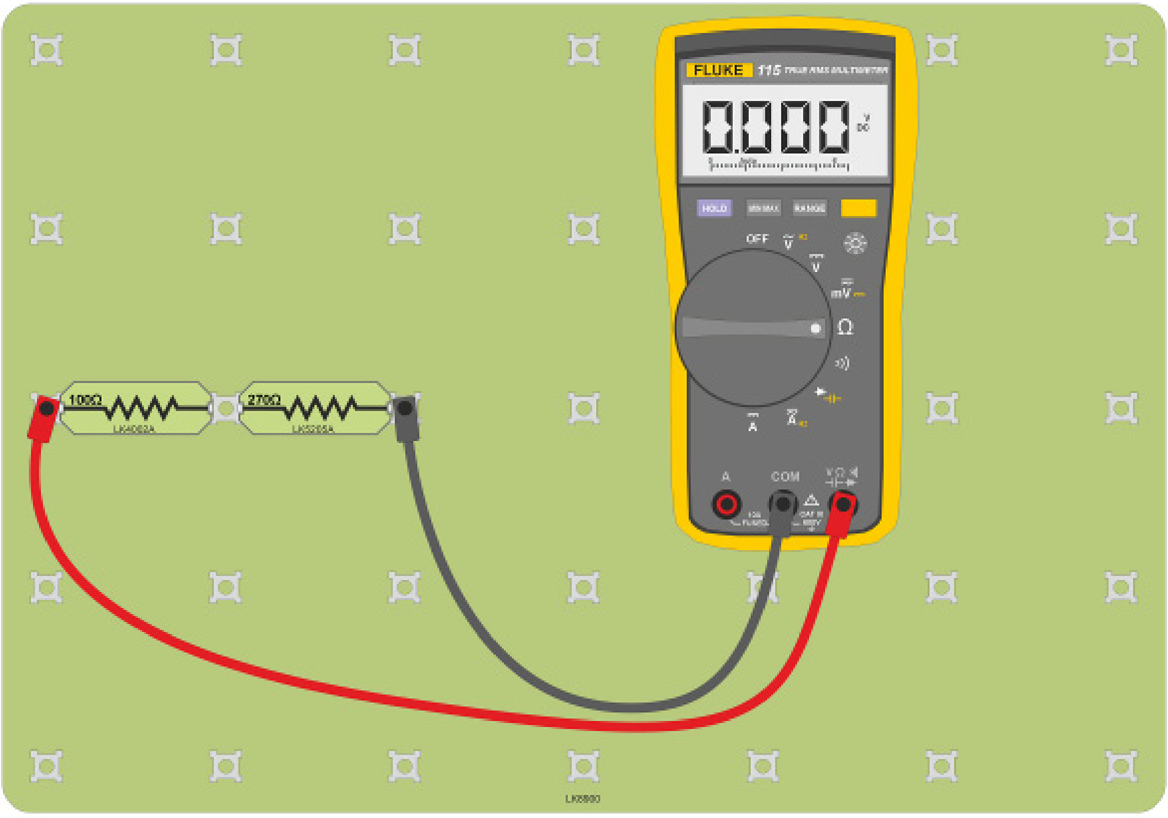
- Read the value of resistance shown on the multimeter.
- Record this value in the Student Handout
- Next, do the same for the other resistors used in the previous worksheet.
- For each resistor record the resistance value printed on the carrier, the value obtained experimentally in the previous worksheet and the value measured using the multimeter. What do you notice?
- Using the multimeter, measure the resistance of the lamp that you tested in the previous worksheet. How does the reading relate to the measurements that you made? Does this tell you anything useful? Why might it be useful to measure the resistance of a non-ohmic component such as a lamp?

Analysis

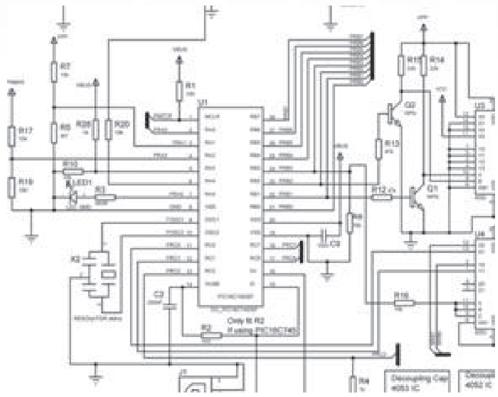
In the previous worksheet, we found the resistance of each component by plotting current against voltage and finding the slope. If we are confident that the component is ohmic (behaves according to ohm's law), then we could measure at a single point and infer the slope using the equation R = V / I.
The multimeter in ohmmeter mode will do this for us. It will measure V and I at one point, do the division and report the resistance value.

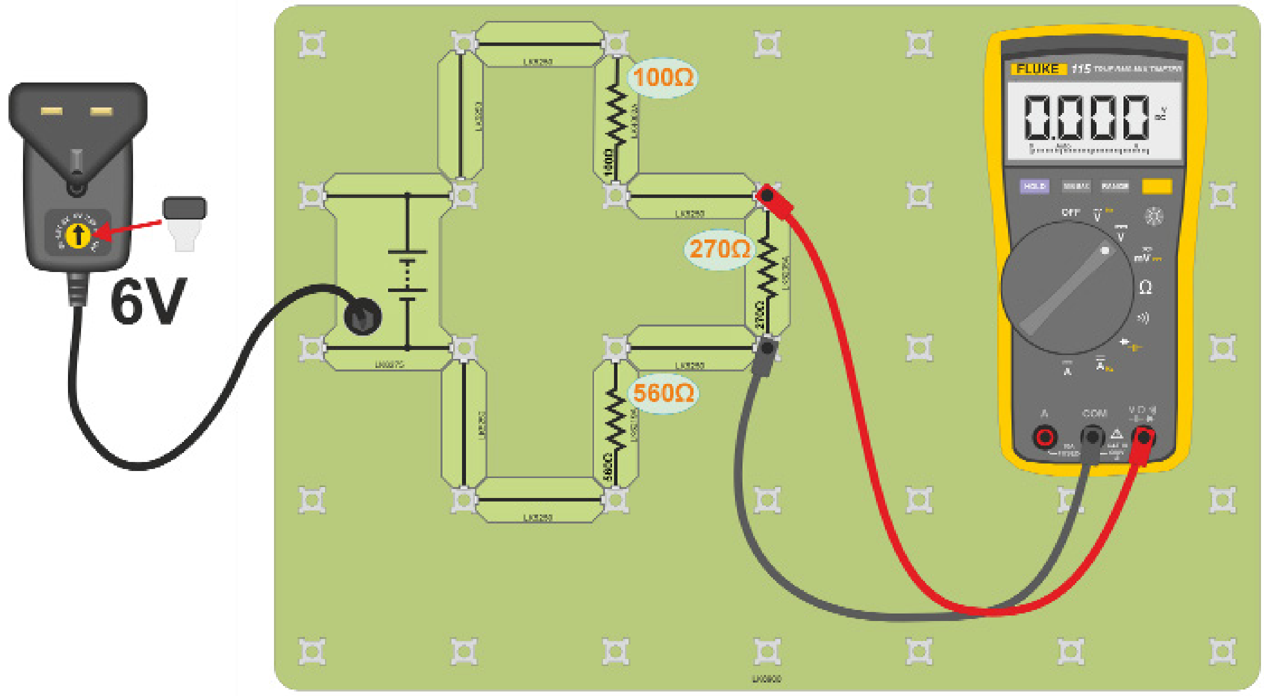
Challenge

- Place the 100Ω and the 270Ω resistor on the Locktronics board in line with each other as shown. What value do you think the multimeter will read? Try this for other combinations of resistors and record the results in the student handout.


100Ω
LK4062A
270Ω
LK5265A
FLUKE
115
HOLD
RANGE
OFF
COM
A
LK8900

In some circuits, there is only one route that the electric current can follow to get from one side of the power supply to the other. In others, the current has a choice of route.
A circuit where the same current must flow through a series of components one after the other is called a series circuit.
A circuit where the current splits up and flows down different branches is called a parallel circuit.





Activity

- Set up the circuit shown opposite.
- Set the power supply to 6 Volts.
- Look back at the worksheet on measuring voltage. Measure the voltage of the power supply. It is set to 6V but you may find that the multimeter is more accurate than the power supply. Record the value in the student handout.
- Now measure the voltage across each of the individual resistors and record the values.
- Using your knowledge of Ohm’s law, calculate the current flowing through each resistor. What do you notice?

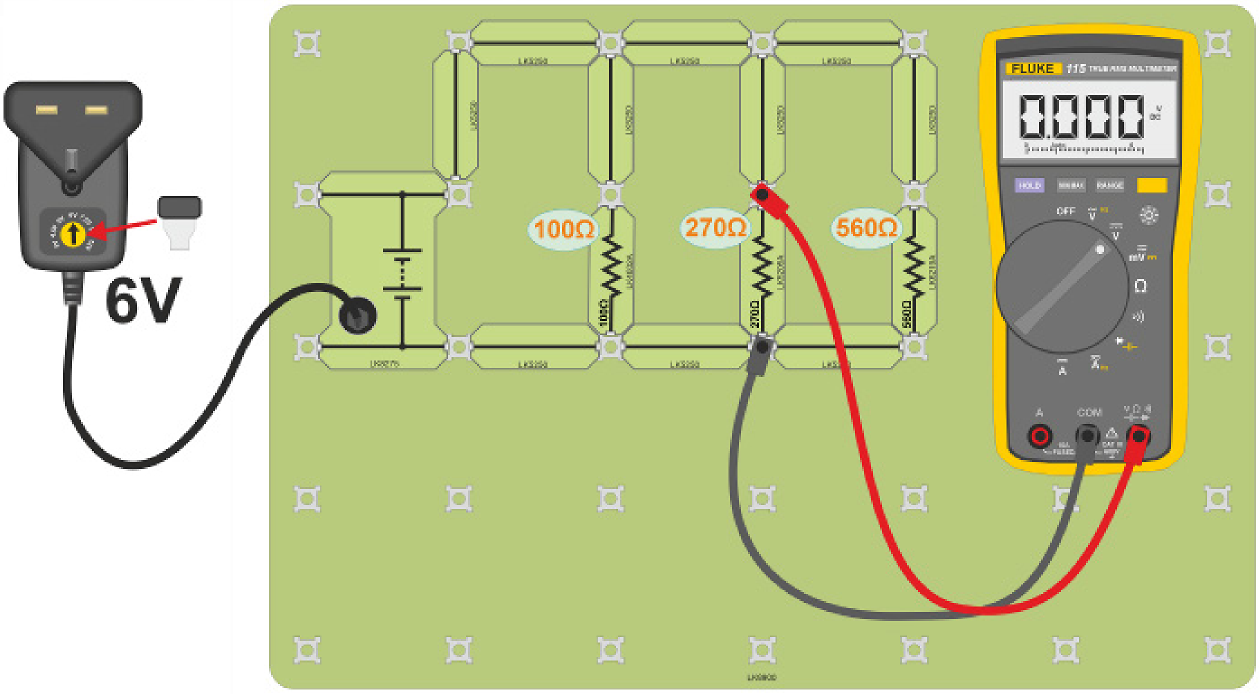
- Look back at the worksheet on measuring current. Remove one of the links from the circuit and insert an ammeter (multimeter in current mode). Record the value. Is it what you expected? Try inserting the ammeter at other locations in the circuit. Does it make a difference where the ammeter is placed?
- With the ammeter in place, try removing one of the resistors. What happens, does it make a difference which resistor is removed?
- Try swapping the positions of some of the components. Does the current change? Measure the voltage across each resistor. Does the position of the resistor in the circuit affect the voltage across it?
- Recall the equation for power: P = V I Calculate the power for the whole circuit and for each individual resistor.

Analysis

In a series circuit there is only one path around the circuit. The same current flows through each of the components. Each component has a share of the total voltage. The voltage across each component depends on its resistance and not on its position in the circuit. Since there is only one path around the circuit, removing any component or link will stop the all the current from flowing.

Challenge

Recall the exercise on measuring resistance where you measured the resistance of two resistors together. Now look at the 100Ω and 270Ω resistors in our series circuit. What is their total voltage and total resistance? Does this still fit with Ohm's law? Do the same for other pairs of resistances and also for the three resistors together? Is there a general rule for how resistors behave when they are connected in series?



Activity

- Set up the circuit shown.
- Set the power supply to 6 Volts.
- Measure the voltage of the power supply and record the value in the student handout.
- Measure the voltage across each of the resistors.
- For each resistor in turn, remove the link immediately above it and insert an ammeter (multimeter in current mode). Record the values.
- Measure the total current using the link immediately after the power supply. What do you notice?
- Verify that each resistor behaves according to Ohm's law.
- Calculate the power for each resistor and for the whole circuit. What do you notice?
- With the ammeter measuring the total current in the circuit, remove one of the resistors. What happens to the total current?

Analysis

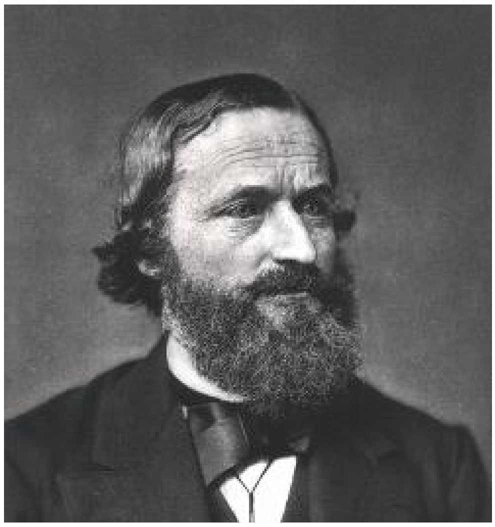
In a parallel circuit there is more than one path around the circuit. The same voltage is applied to each branch. The current in each branch depends on its resistance. When one branch of the circuit is interrupted, current continues to flow in the other branches .

Challenge

- Remove the 560Ω resistor from the circuit leaving just the 100Ω and the 270Ω.
- Measure the total current and record the value.
- Using Ohm's law, calculate what value of single resistor would behave the same as the 100Ω and 270Ω in parallel.
- Remove the power supply from the circuit and use the multimeter to measure the resistance of the two resistors in parallel. Does it match your calculation?
- The rule for resistors in parallel is not as easy as the one for resistors in series. Can you see it? Try calculating 1 / R for each individual resistor and for the total resistance.
- Repeat this exercise for other combinations of two resistors and then for all three resistors together. Does the rule still hold?

Worksheet 8 – Understand and Apply Kirchhoff's Laws

At this point, we have a good understanding of how basic circuits work. We can recognise series circuits and parallel circuits and we can use Ohm's law to understand what is happening in these circuits. In this worksheet we will introduce two more laws that can be used to analyse circuits. These laws are useful in analysing circuits that are not entirely series or parallel but a combination of the two. They are equally useful in situations where we are unable to measure voltage and current at absolutely every part of a circuit and need to use measurements from one part of the circuit to deduce what is happening in another part.

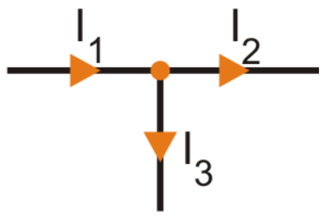


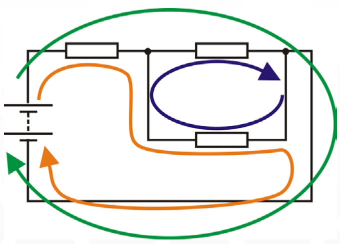
The German physicist Gustav Kirchhoff described two laws for analysing circuits, one for current and one for voltage.
The current law describes the behaviour of nodes in a circuit. A node is point in a circuit where a number of connections come together. Kirchoff's current law states that:

The total current flowing into a node is equal to the total current flowing out of the node.

Remembering that current can be positive or negative depending on the direction of flow, we could also state: The total sum of positive and negative currents at a node is always zero.
Intuitively, we can see that this law makes sense. Think about a road junction, the total number of cars entering the junction must equal the total number leaving. Similarly, consider a junction in a network of water pipes; the total amount of water flowing into the junction equals the total flowing out. Electric current behaves the same way, what flows into the node must flow out.

In this diagram, I_1 flows into the node while I_2 and I_3 flow out. I_2 and I_3 must add up to the same amount of current as I_1.



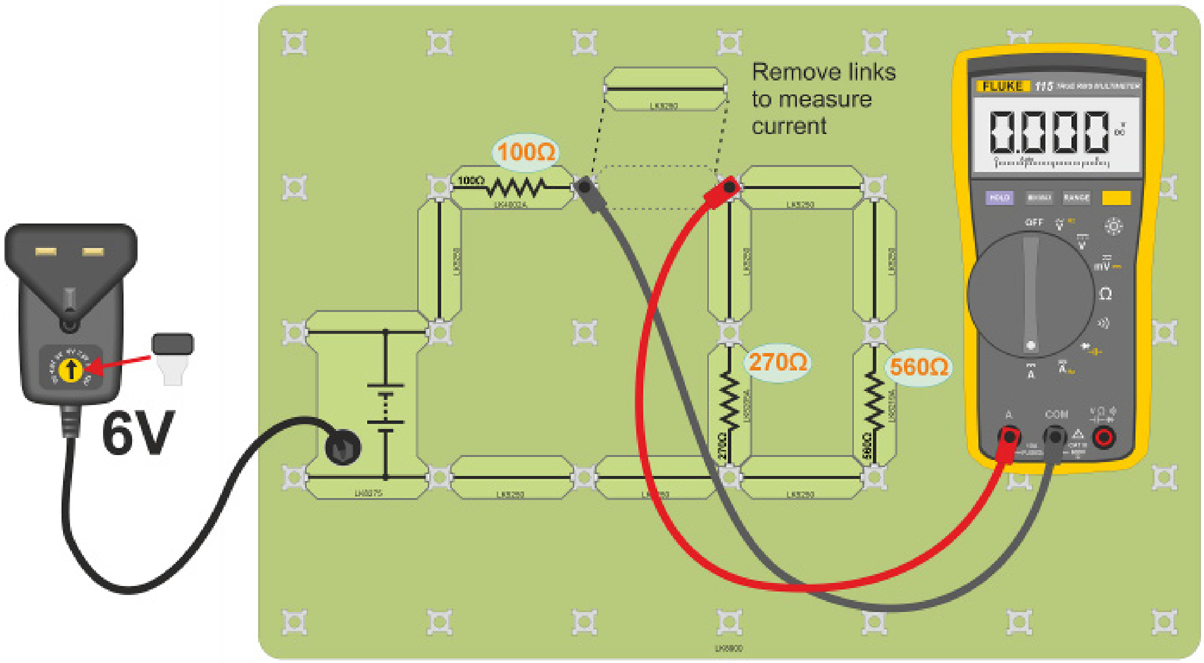


The voltage law describes the behaviour of loops in a circuit. A loop is any path that can be drawn around a circuit that finishes up at the point where it started. A loop does not cross over itself but it may have smaller loops inside itself. In the circuit pictured, there are three possible loops that can be drawn.

Kirchoff's voltage law states that:

The sum of voltages around any closed loop is zero.

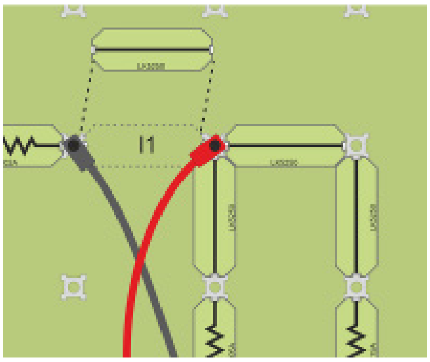
This assumes that we take into account whether the voltmeter is showing a negative sign. For any component in the loop, place the black lead of the meter on the anti-clockwise end and the red lead on the clockwise end. Add up the voltages including the negative signs. The sum of the positive voltages is the same as the sum of the negative voltages so the total is zero.
Again, this law makes sense intuitively. Consider taking a circular walk around a hilly landscape. When we get back to our starting point, the total height of the uphill sections must be the same as the downhill sections. Similarly, working around a loop of a circuit there will be some steps up in voltage and some steps down. When we get back to the start of the loop, the steps up must be the same as the steps down.

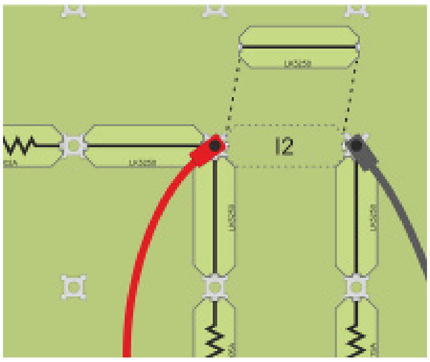


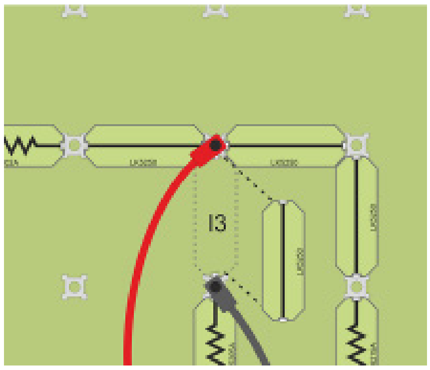
Activity

- Construct the circuit shown.
- Check that the voltage of the power supply is set to 6V.
- Look at the node where three links come together near the top-right of the circuit diagram.
- Set the multimeter to DC current mode.

- Connect the 'A' socket of the multimeter to the node using a red 4mm lead.
- For each link in turn, remove the link and connect the 'COM' socket of the multimeter so that the meter replaces the link. Record each reading in the student handout. Remember that when measuring current, we must remove a link so that the current goes through the meter.
  - (If three multimeters were available then it would be possible to measure all three currents at the same time. All three links would be removed and all three 'A' sockets would be connected to the node by stacking the 4mm plugs.)
- Add up the three currents, taking into account any negative signs. Check that they add up to zero.







Analysis

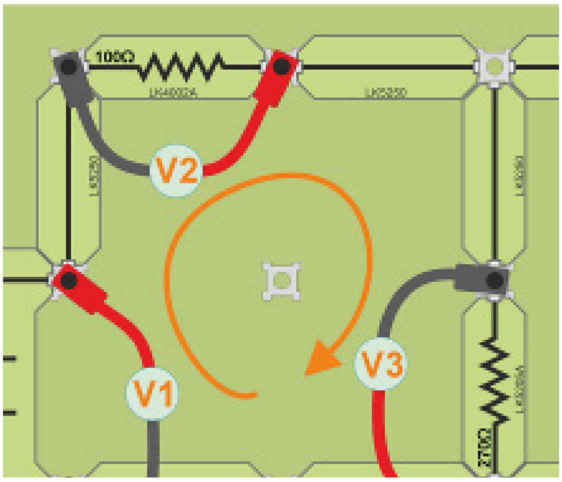
This exercise gives a simple demonstration of the current law. In a practical circuit there may be more that three connections to a node. In fact, the law holds for any number of connections. There may be situations where it is not possible to measure every connection to a node and so, we measure the other connections and infer the current in the one we can not measure.

Challenge

Try swapping around the resistors, replacing one or more resistors with lamps or using other resistor values from the kit. Does the current law still hold?
Try designing and constructing a circuit which includes a node with four connections. Measure the four currents and check that the law still holds.

Activity

- Set up the circuit as shown at the beginning of the previous activity.
- Check that the power supply is set to 6V.
- Set the multimeter to DC voltage mode.
- Pick one of the three loops that can be drawn around the circuit.
- Connect a black 4mm lead from the 'COM' socket of the meter to any post in the loop.
- Working clockwise around the loop, connect a red 4mm lead from the next post to the 'V' socket of the multimeter.
- Record the measured voltage in the student handout.
- Now move each of the leads to the next post moving in a clockwise direction.
- Continue around the loop, recording the voltage across each component until the red lead comes back to the start point.
- Note that the voltage across a link is always zero so these steps can be ignored.
- Check that the recorded voltages add up to zero.
- Repeat for the other two loops.
- Try swapping components around, does the voltage law still hold?

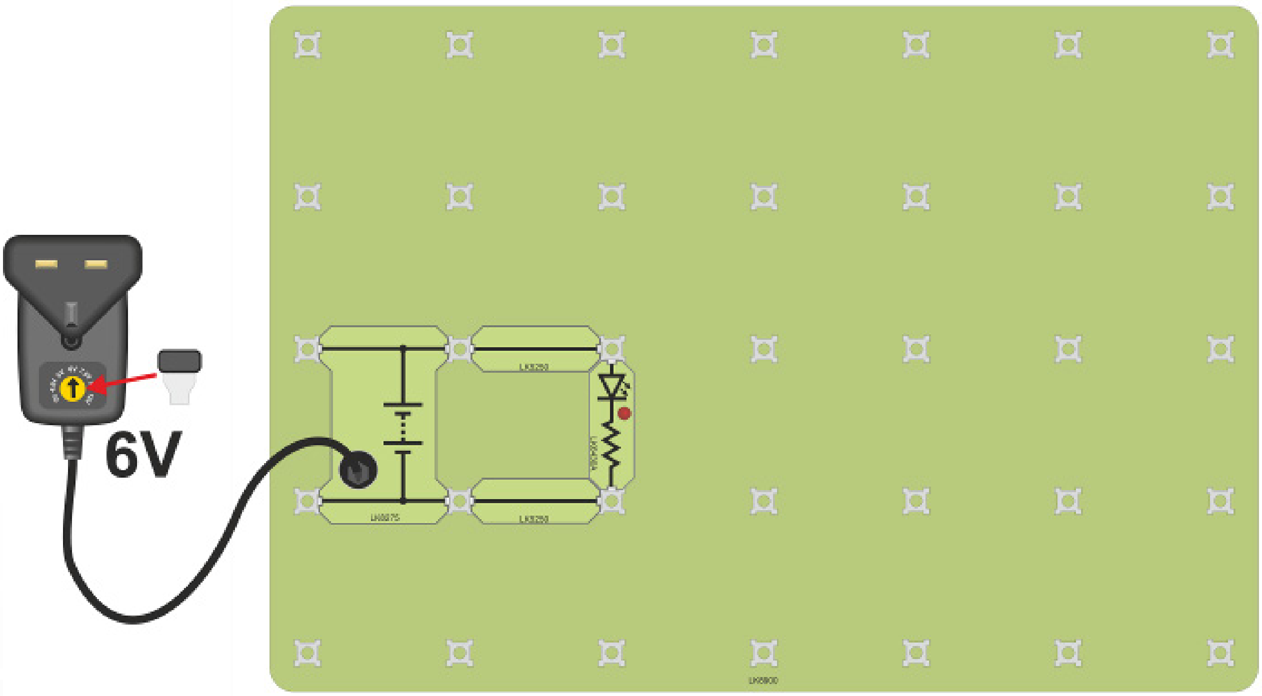


Analysis

In the loop illustrated, the power supply measured a positive voltage while the two resistors measured negative. This is arbitrary, it would have been the other way round if we had chosen to put the black lead clockwise of the red lead. Equally, we could change the sign of all the measurements by turning the power supply component by 180 degrees. The important thing is that, when the signs are included, all the voltages around a loop add up to zero.

Challenge

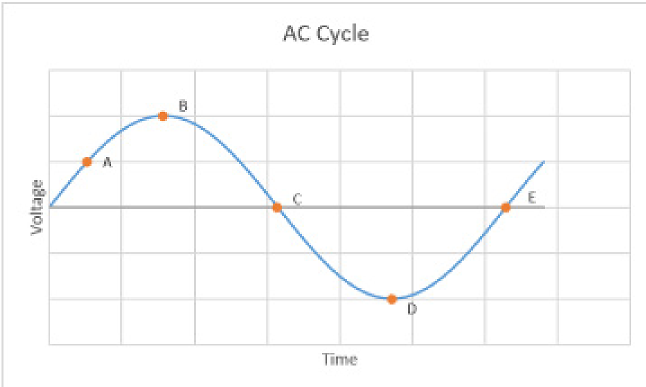
- Build the circuit shown.
- Check that the power supply is set to 6V.
- The LED carrier is made up of an LED in series with a 470Ω resistor.
- Using the multimeter, measure the voltage across the power supply and the current flowing in the circuit.
- What is the voltage across the LED component?
- It is not possible to measure the LED on its own as the carrier includes the resistor as well. However, with your knowledge of Ohm's law and Kirchhoff's law, you should be able to deduce the LED voltage from the measurements that you are able to make.



Worksheet 9 – AC versus DC

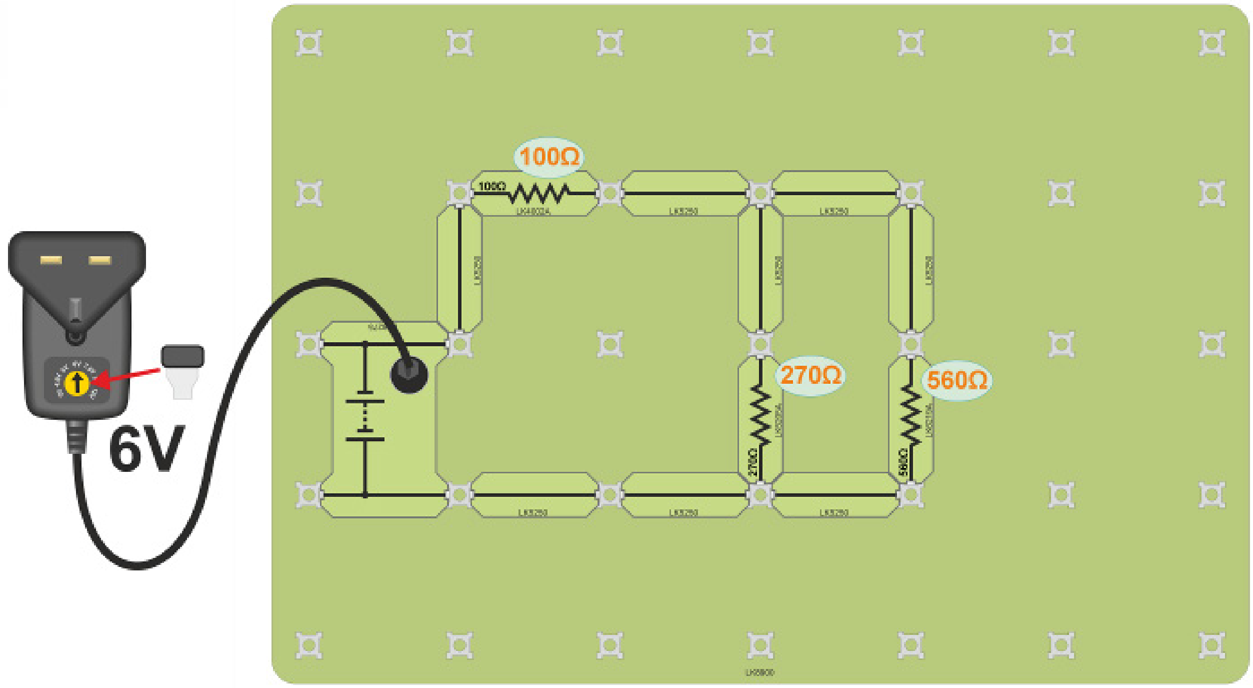
In all the circuits that we have studied so far, we have used direct current (DC). We found that current flowed from the positive end of the power supply, around the circuit and back to the negative end.
Now we will introduce alternating current (AC). With an AC power supply, the voltage is not steady. It rises, peaks, falls, becomes negative, peaks and falls back to zero. This cycle takes place many times each second. Depending on the territory, mains electricity may run at 60 cycles per second (60 Hz) or 50 cycles per second (50 Hz).

This graph shows how the voltage of an AC waveform changes over the a cycle. The shape of the waveform is a sine wave. That is, when voltage is plotted against time it follows the shape of the trigonometric sine function. At point A, the voltage has risen to half of its peak value. By point B, it has risen to its peak (maximum) value. At point C, the voltage has dropped to zero. By point D, it has reached its negative peak—the same voltage as B but with a negative sign. After the negative peak, the voltage rises and at point E, the cycle is complete and the next cycle begins.



Activity

- Look back at the worksheet on Kirchhoff's laws. Build the first circuit but rotate the DC power supply carrier by 180 degrees as shown on the next page.
- Repeat the first activity and compare the currents to those recorded in the previous worksheet.
- Repeat the measurement of the voltages around one of the loops and compare with the previous results.
- Calculate the power dissipated in the 100Ω resistor for both cases.
- What is the effect of reversing the power supply?

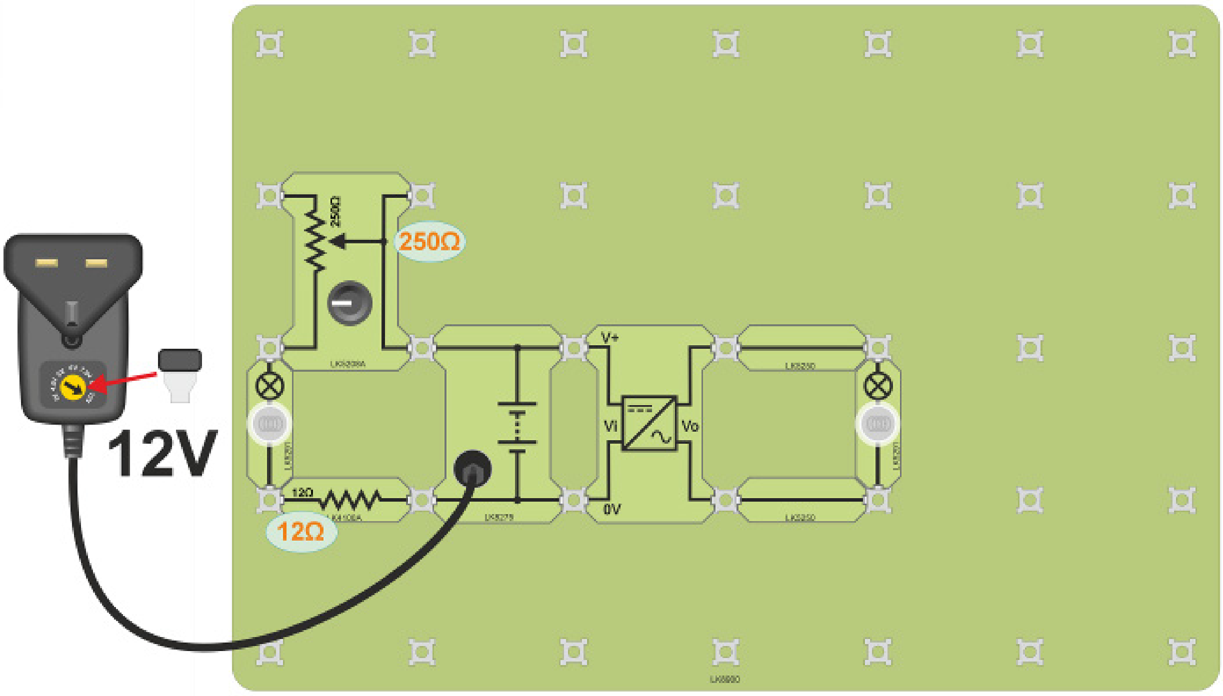


Analysis

Recall that P = VI. If we multiply a positive voltage by a positive current, we get a positive power. If we multiply a negative voltage by a negative current, we also get a positive power. The resistor converts electrical energy to heat regardless of which way the current is flowing.
If we set up the circuit and then continually swap the DC power supply between positive and negative, the resistor would continue to dissipate a positive power except at the moments where we are changing over the power supply. This is very like what happens in an AC system except that in an AC system, the transitions are a lot smoother.

Challenge

Construct a circuit with a lamp. Is there anyway to tell, just by looking at the lamp, which way round the power supply is? Try the same thing with the LED.



Activity

- Build the circuit shown.
- In this circuit, we use an inverter to convert from DC to AC and power one of the lamps. The other lamp is powered by DC.
- Set the multimeter to measure AC volts and measure the voltage across the lamp on the right.
- Set the multimeter to measure DC volts and measure the voltage across the lamp on the left.
- Adjust the potentiometer until the DC voltage is the same as the AC voltage.
- Compare the two lamps; do they appear to be the same brightness?

Analysis

We know that the lamp will appear the same whether the current through it is positive or negative. However, the AC voltage waveform is constantly varying, sometimes near its positive peak, sometimes near its negative peak and sometimes close to zero. To compensate for this, the multimeter does not give us the peak voltage but instead gives us an average. Of course, since the AC voltage is negative for half the time, the simple mean average would be zero. The multimeter takes this into account and gives us a type of average called 'root-mean-square' (RMS). The RMS value of a sine wave is equal to the peak voltage divided by the square root of 2. The RMS voltage of an AC power source is equal to the DC voltage that would provide the same amount of power into a simple circuit. Since this is a more useful measure than the peak voltage, this is what the multimeter measures.

Challenge

Try driving the LED using the AC power supply. Even though the LED is off during the negative part of the cycle, the pulsing to is too fast to be seen by the human eye. What DC voltage makes the LED as bright as the AC power supply?

AC versus DC

In this worksheet, we have found that the basic task of lighting a light bulb works the same whether the power supply is AC or DC. In later worksheets, we will discover that there are differences in the way the two work. The principles that we have learned so far apply to both but both have their own domains and applications in the wider world.

Power Sources

Batteries always supply DC. This is useful for portable applications. Solar panels also produce DC.
Generators from small portable devices up to wind turbines and power stations produce AC.

Conversion

The AC inverter carrier in our circuit converts DC to AC. Larger versions produce AC from batteries or solar panels. The output is not always a perfect sine wave.
Rectifiers convert AC to DC. Simple rectifiers either block or invert the negative half of the cycle. To get a better DC source we have to smooth and regulate the output of the rectifier.

Advantages and Disadvantages

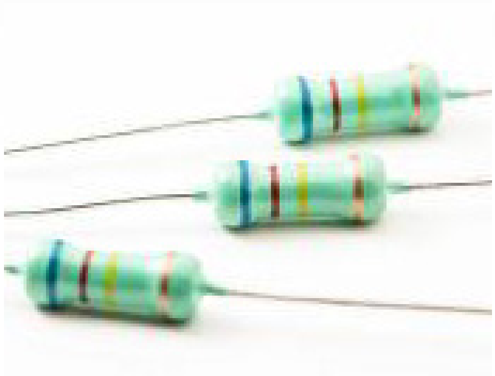
AC is easier to generate from rotating mechanical energy. It is also easier to distribute in large systems and over large distances. This is why most mains electrical grids are AC.
DC is produced by batteries, this makes it more suitable for small or portable devices. In more complex devices, DC is easier to regulate and control.

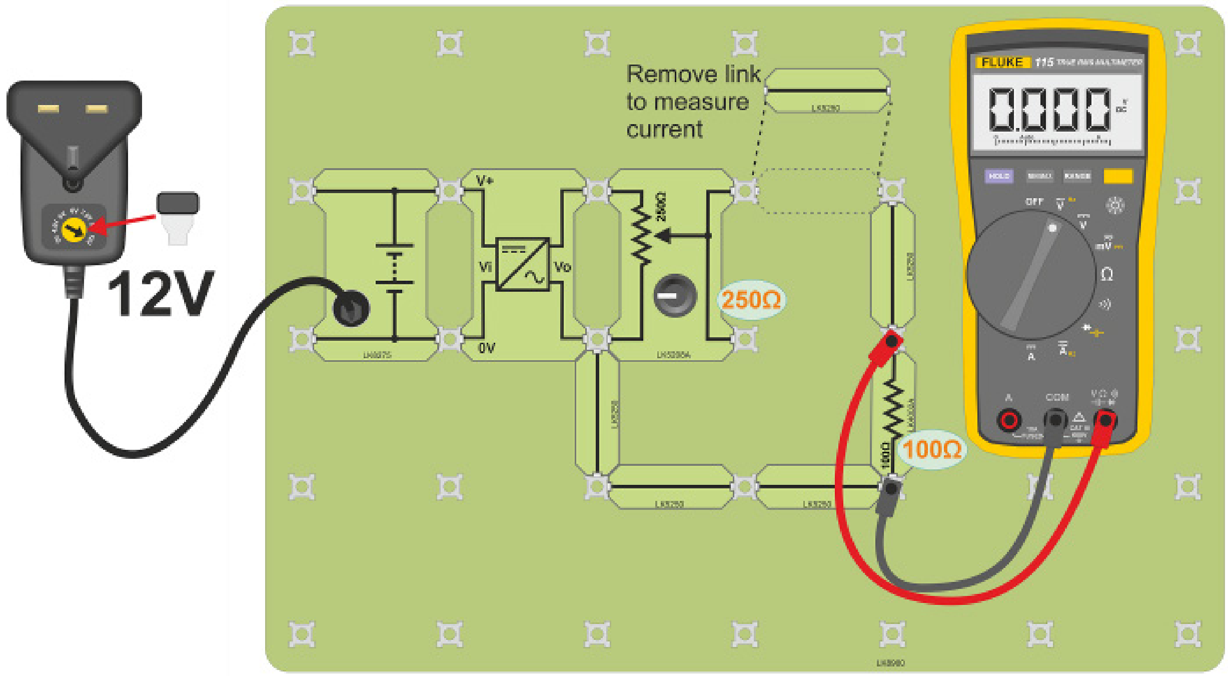
Applications

Industrial devices generally use AC. AC is particularly suited to driving large motors. It is also used in heating and lighting. Larger domestic devices such as washing machines and refrigerators usually use AC.
Electronic devices generally use DC. Digital or microprocessor devices always use DC. Very small electric motors are generally DC while the largest motors are AC. In the middle ground, motors are available in both AC and DC variants and the most suitable is chosen for any particular application.

Worksheet 10 – AC Behaviour of Resistors

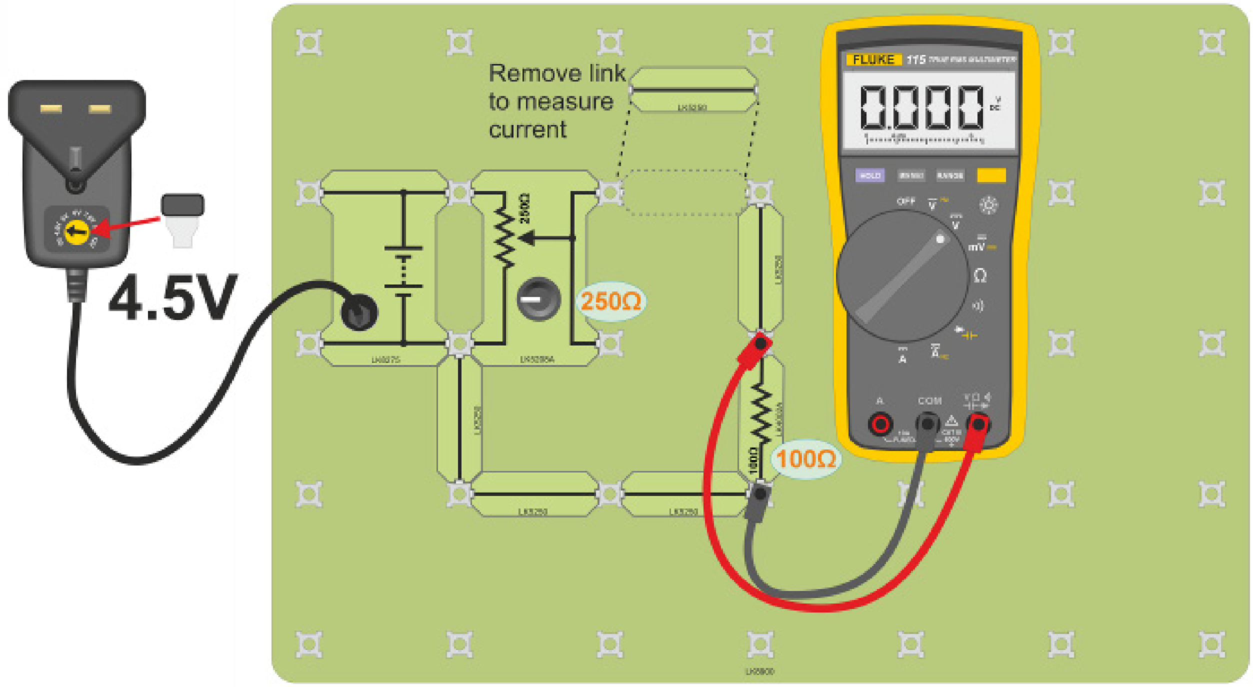
We have already studied resistors using DC and understood Ohm's law. Now that we have begun to look at AC, we want to know whether Ohm's law still applies. In this worksheet we will repeat our study of Ohm's law and Kirchhoff's laws with an AC voltage source.





Activity

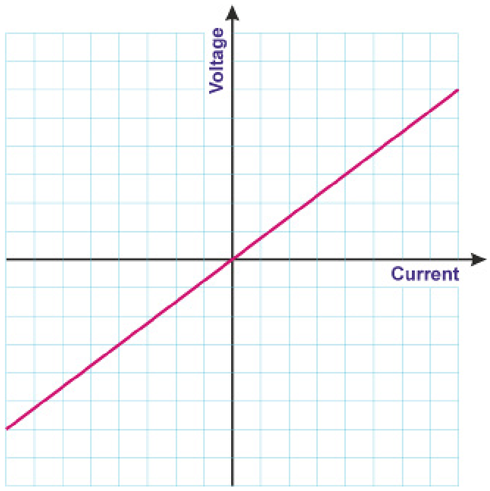
- Build the circuit shown.
- Set the power supply to 12V and switch it on.
- Turn the potentiometer knob fully anti-clockwise.
- Set the multimeter to measure AC voltage.
- Record the voltage across the 100Ω resistor.
- Set the multimeter to measure AC current.
- Record the current flowing in the circuit.
- Turn the potentiometer a few degrees clockwise and again record the voltage and current.
- Record a few pairs of voltage and current and plot them on a graph.
- Replace the resistor with a 270Ω resistor and repeat the measurements.
- Once again, record them in the Student Handbook.



- Build the circuit shown.
- Set the power supply to 4.5V and switch it on.
- Turn the potentiometer knob fully anti-clockwise.
- Set the multimeter to measure DC voltage.
- Record the voltage across the 100Ω resistor.
- Set the multimeter to measure DC current.
- Record the current flowing in the circuit.
- Rotate the DC Power Supply carrier by 180 degrees and repeat the measurements.
- Turn the potentiometer a few degrees clockwise and again record the voltage and current with the DC Power Supply in both positions.
- Record a few pairs of voltage and current and plot them on a graph.
- Replace the resistor with a 270Ω resistor and repeat the measurements.

Analysis

We have already learned that in DC circuits, voltage and current in resistors are related in a simple way. The relationship is known as Ohm's law. Now we have discovered that the behaviour in AC circuits is no different. We have also discovered that the slope of our voltage-current graph continues through the zero point and that Ohm's law can be applied to negative voltages.



Current = Voltage divided by resistance   I = V / R

The current flowing in the resistor is directly proportional to the voltage across it. If the voltage doubles then so does the current. This is true whether the voltage is positive or negative and still true in AC circuits where the voltage oscillates between positive and negative.

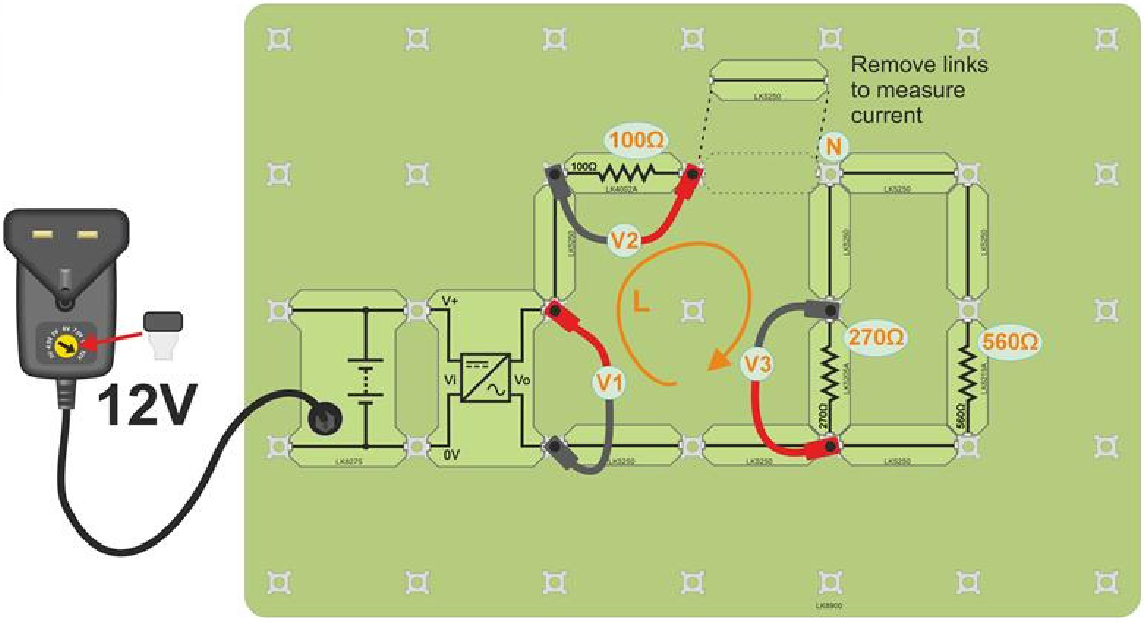
A large resistance limits the current flowing in a circuit, it takes a lot of voltage to make a small current flow. A small resistance allows more current to flow, a little voltage can make a lot of current flow.

Be careful!
Sometimes these graphs are plotted with current on the vertical axis and voltage on the horizontal axis. In that case, a shallow slope would represent a big resistor - a high voltage needed for even a small current.

Challenge

We know that the multimeter measures the RMS voltage and current. Assuming that the AC inverter is producing a sine wave, the peak voltage will be √2 times the RMS voltage. Also the peak current will be √2 times the RMS current.
For each pair of RMS measurements, calculate the peak voltage and current. Plot these on the same graph as before. What do you notice?

Now that we have seen that Ohm's law still holds in an AC circuit, we shall look at Kirchhoff's laws.

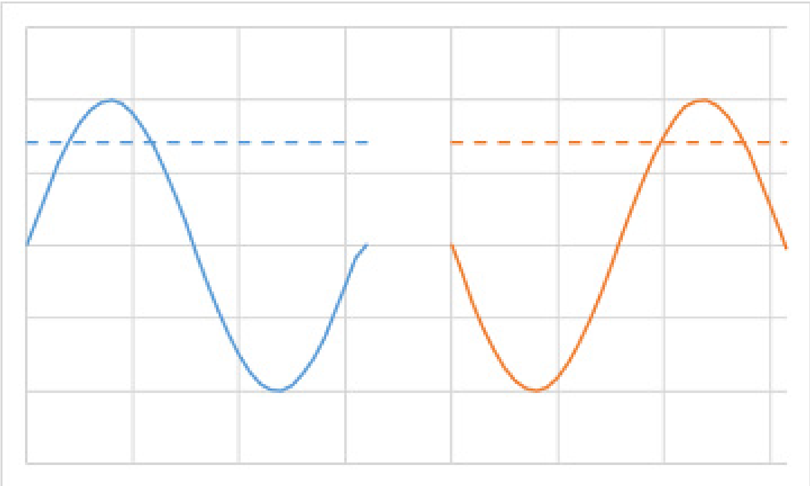


Activity

- Set up the circuit shown.
- Measure the three currents at the node labelled 'N': -
  - Set the multimeter to read AC current.
  - Plug the lead connected to the 'A' socket of the multimeter into the post labelled 'N'.
  - For each of the three links in turn, remove the link and plug the lead connected to the 'COM' socket of the multimeter so that the meter takes the place of the link.
  - Record the three currents in the student handout.
- Measure the voltages around the loop labelled 'L': -
  - Set the multimeter to read AC voltage.
  - Plug the lead connected to the 'COM' socket of the multimeter into the post at the bottom of the AC inverter.
  - Plug the lead connected to the 'V' socket of the multimeter into the post at the top of the AC inverter.
  - Move the leads clockwise around the loop and measure the voltages 'V2' and 'V3'
  - Record all three voltages in the student handout.
- Compare the results with the activity where you investigated Kirchhoff's laws with a DC supply. What do you notice?

Analysis

When we measure DC voltage or current, the multimeter gives a positive or negative reading depending on the polarity (which way around the leads are). When we measure AC, the multimeter simply gives us the RMS value and can not tell us whether the signal is positive or negative.
If we were able to look at the waveforms, we might see that the waveform of one measurement is inverted compared to another but the multimeter simply gives us the RMS reading.



RMS of sine is 1/√2 RMS of inverted sine is also 1/√2

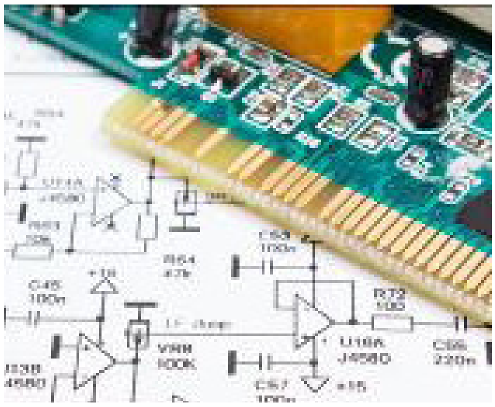
If we look back at our measurements for the circuit powered by DC, we can see which measurements were negative. If we assume that the same measurements should be negative in our AC circuit then we see that Kirchhoff's laws still hold.

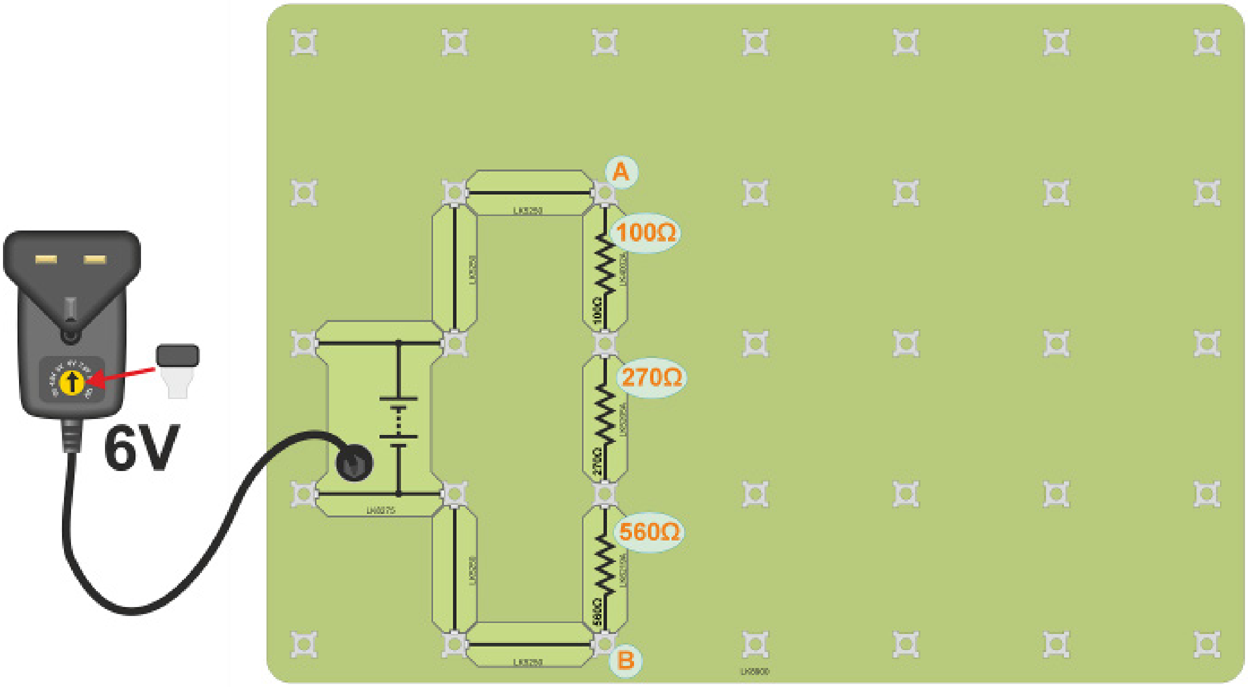
Challenge

Look back at the earlier worksheet on Kirchhoff's laws. What other node and loops can be drawn for our circuit? Make AC measurements of each. Which measurements should be given negative signs? Do Kirchhoff's laws still hold?

Worksheet 11 – Combinations of Resistors

There are two types of connection in electronics, series and parallel.
In a series connection, there are no alternative routes and no junctions - the electric current must pass through each resistor in turn. Combining resistors in series increases the total resistance.
Components connected in parallel offer different routes for the current. Combining resistors in parallel reduces the total resistance, allowing more current to flow.





Activity

- Build the series circuit shown.
- Set the multimeter to resistance mode.
- With the power supply removed, measure the resistance of each individual resistor.
- Connect the multimeter to the points labelled ‘A’ and ‘B’ and measure the total resistance of the circuit.
- Change the multimeter to DC voltage mode.
- Set the power supply to 6V and plug it in.
- Measure the voltage across the circuit between points ‘A’ and ‘B’.
- Set the multimeter to DC current mode and connect it in place of one of the links.
- Measure the current flowing in the circuit.
- Having measured the voltage and current, use Ohm’s law to calculate the total resistance. How does it compare to the resistance value that you measured?
- Try changing the order of the resistors. Does it make any difference?

Resistors in Series

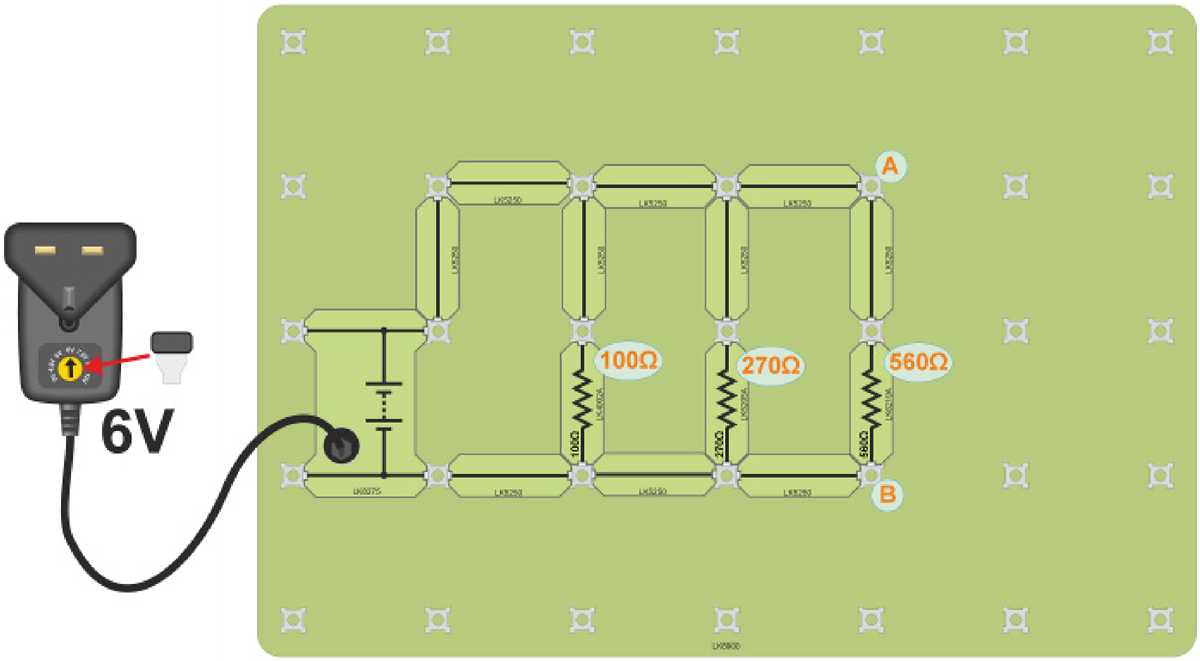
When resistors are connected in series, the rule is simple. The total resistance is the sum of all the individual resistances.

R_total = R1 + R2 + ... + Rn

The order of the resistors does not matter, R1 + R2 + R3 = R3 + R2 + R1 = R3 + R1 + R2

Challenge

Take some other resistors from the kit and try other combinations. Try making series circuits with two resistors or with four or more resistors. Does the rule still hold.



Activity

- Build the parallel circuit shown.
- Set the multimeter to resistance mode.
- Remove each resistor in turn, measure its resistance and then return it to the circuit.
- With the power supply removed, connect the multimeter to the points labelled ‘A’ and ‘B’ and measure the total resistance of the circuit.
- Change the multimeter to DC voltage mode.
- Set the power supply to 6V and plug it in.
- Measure the voltage across the circuit between points ‘A’ and ‘B’.
- Set the multimeter to DC current mode and measure the total current flowing from the power supply.
- Having measured the voltage and current, use Ohm’s law to calculate the total resistance. How does it compare to the resistance value that you measured?
- From Kirchhoff’s law, we know that the current flowing in each branch of the circuit must add up to the same value as the total current. Measure the current in each branch and check that they add up.
- Try changing the order of the resistors. Does it make any difference?

Analysis

In a parallel circuit, the total current splits and goes down each of the branches. From Ohm's law, we know that current equals voltage divided by resistance. For each individual branch, the current is set by the voltage of the circuit and the resistance of that branch. For the whole circuit, the current is set by the voltage and the total resistance.

$$I\_total = I1 + I2 + \ldots + In$$

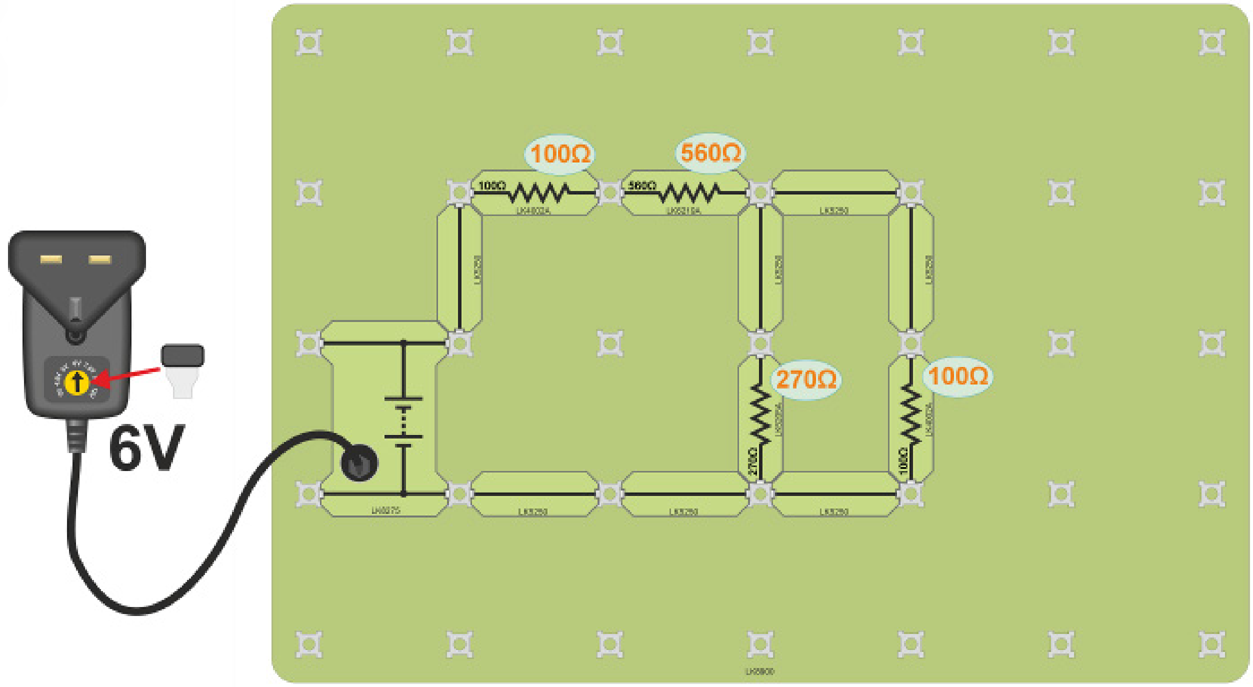
$$V / R\_total = V / R1 + V / R2 + \ldots + V / Rn$$

Since the voltage appears on both sides of the equation, we can eliminate it.

$$1 / R\_total = 1 / R1 + 1 / R2 + \ldots + 1 / Rn$$

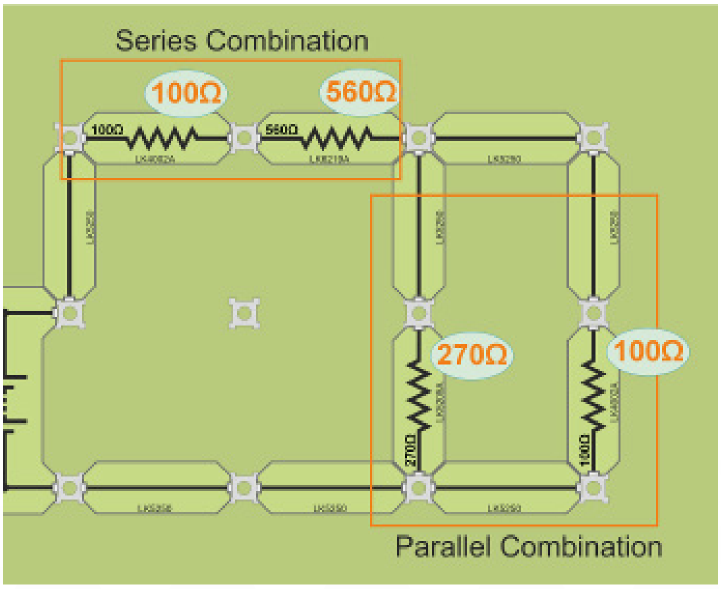
Challenge

Using the equation above, calculate the total resistance for the parallel circuit. Does it match your experimental results? Try other combinations of resistors. Try constructing circuits with two or four parallel branches; does the rule still hold?



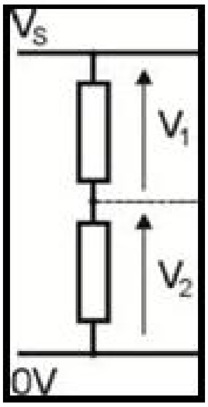
Activity

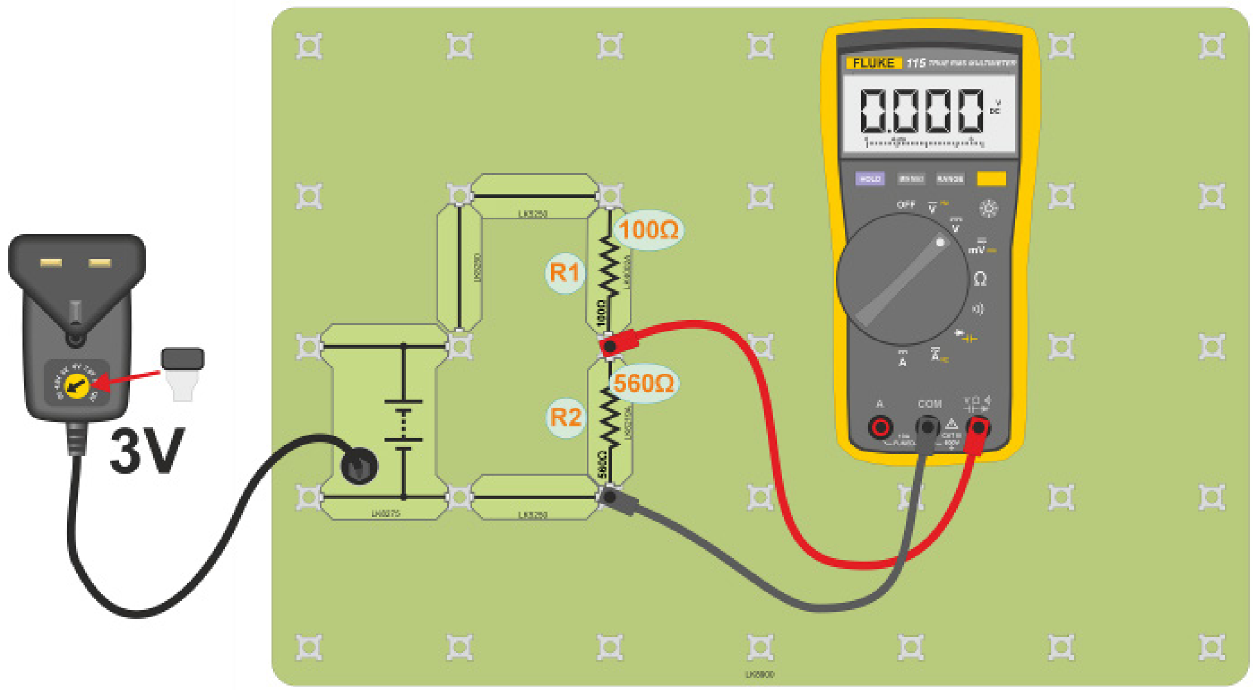
Construct the circuit shown above and study it. The circuit has both series and parallel elements. Can you work out what the total resistance of this circuit is?
When dealing with a more complex circuit, the best approach to break it down into simpler units.



The part labelled 'Series Combination' consists of two resistors in series. We can easily calculate the equivalent resistance of this part.
The part labelled 'Parallel Combination' consists of two resistors in parallel. We can easily calculate the equivalent resistance of this part.
The two parts are in series with each other so we can simply add the two equivalent resistances together.
Having calculated the total equivalent resistance of the circuit, test with a multimeter to verify the result.

We have seen that in series circuits, the same current flows while the voltage is divided between the components. This provides a useful means of deriving a smaller voltage from a larger one.
The simple means of splitting up a voltage by using two components in series has a number of useful applications. It is often used in with measurement components.
This type of circuit is called a voltage divider, you may also see the term potential divider.
In this worksheet, we will learn how a voltage divider works and also discover its limitations.
The diagram shows how a power supply voltage VS can be split into two smaller voltages, V1 and V2, by a voltage divider made up of two resistors.





Activity

- Set up the circuit shown in the diagram.
- Using a multimeter, measure the resistance of the resistor labelled R2 and the total resistance of the two resistors in series together.
- Set the power supply voltage to 3V and plug it in.
- Use the multimeter to measure the total voltage provided by the power supply.
- Use Ohm’s law to calculate the current flowing in the circuit and then check your calculation using the multimeter.

- Knowing the resistance R2 and the current, use Ohm's law to calculate the voltage across the resistor R2. Check your calculation using the multimeter.
- Using your knowledge of Ohm's law, calculate what the voltage across R2 would be if the power supply was set to 6V or 12V. Set the power supply to each voltage in turn and check you calculation.
- Swap R2 for the 270Ω resistor.
- Calculate what the voltage across R2 would be with the power supply set to 3V, 6V or 12V. Test your calculations.

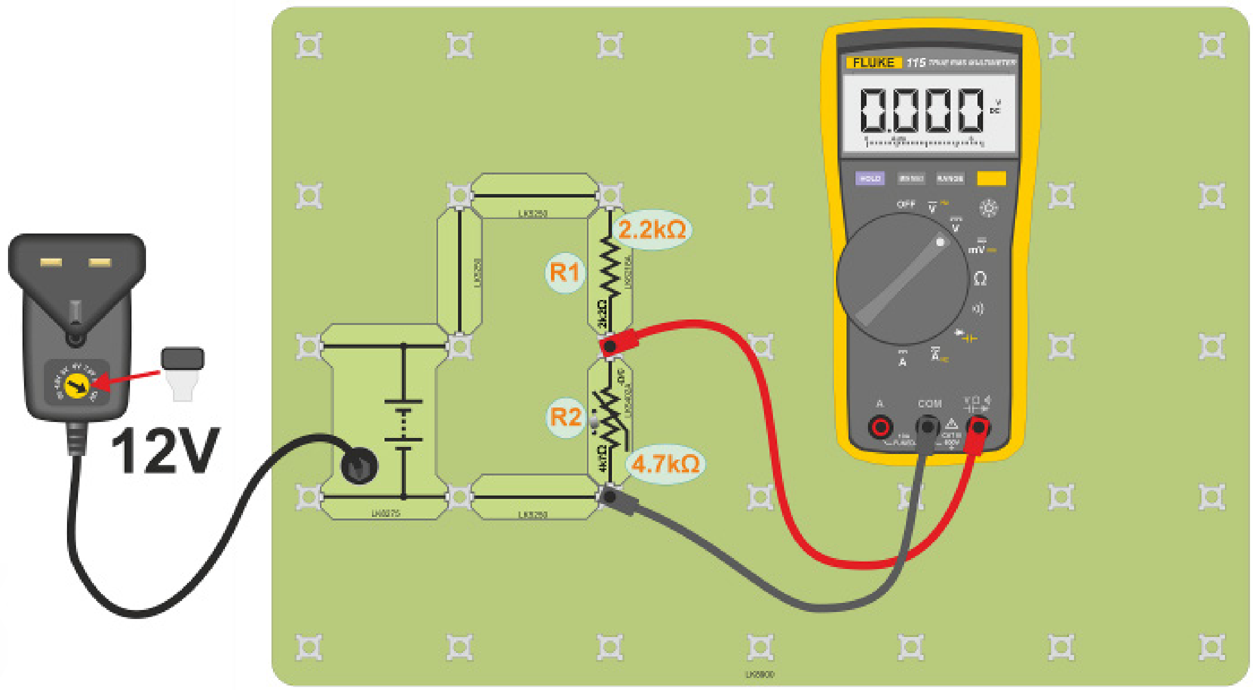
Analysis

The output voltage of a voltage divider (the voltage across R2) is dependant on the input (supply) voltage and the values of the resistors. The equation can be derived from Ohm's law: -

- Output voltage equals resistance R2 times current. $V2 = I \cdot R2$
- Current equals supply voltage divided by total resistance. $I = Vs / (R1 + R2)$
- Putting the equation for current into the first equation gives us the equation for a voltage divider.

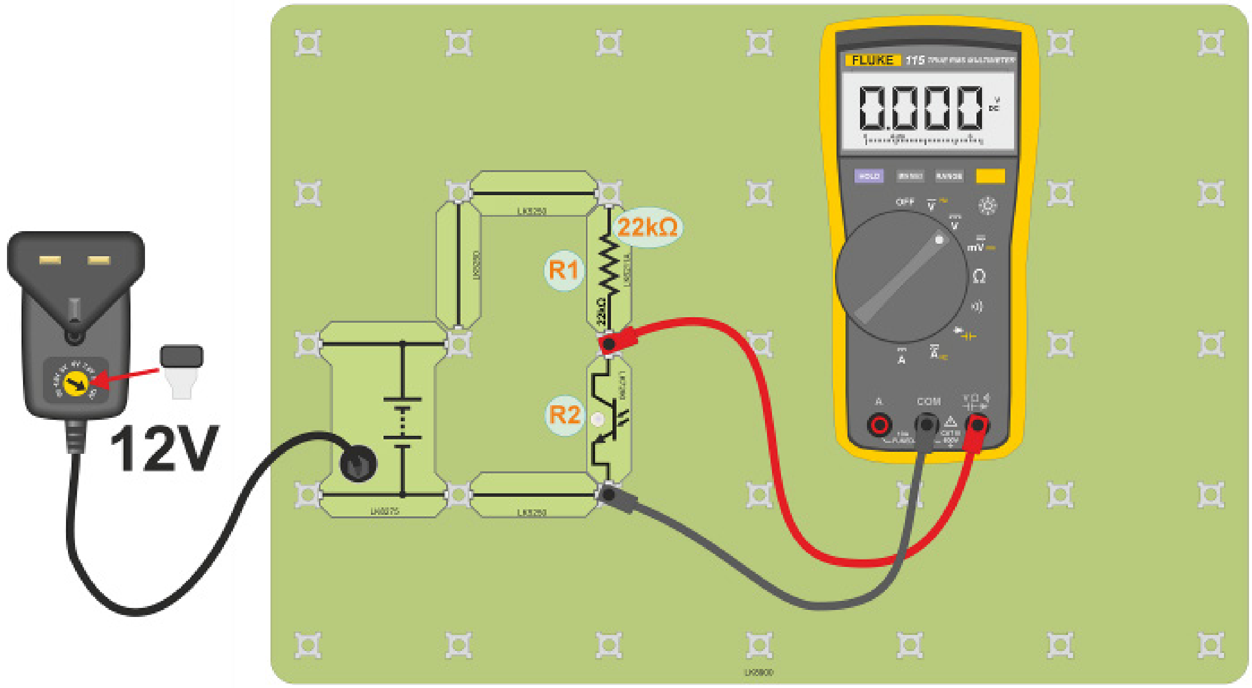
$$V2 = Vs \cdot R2 / (R1 + R2)$$

Challenge



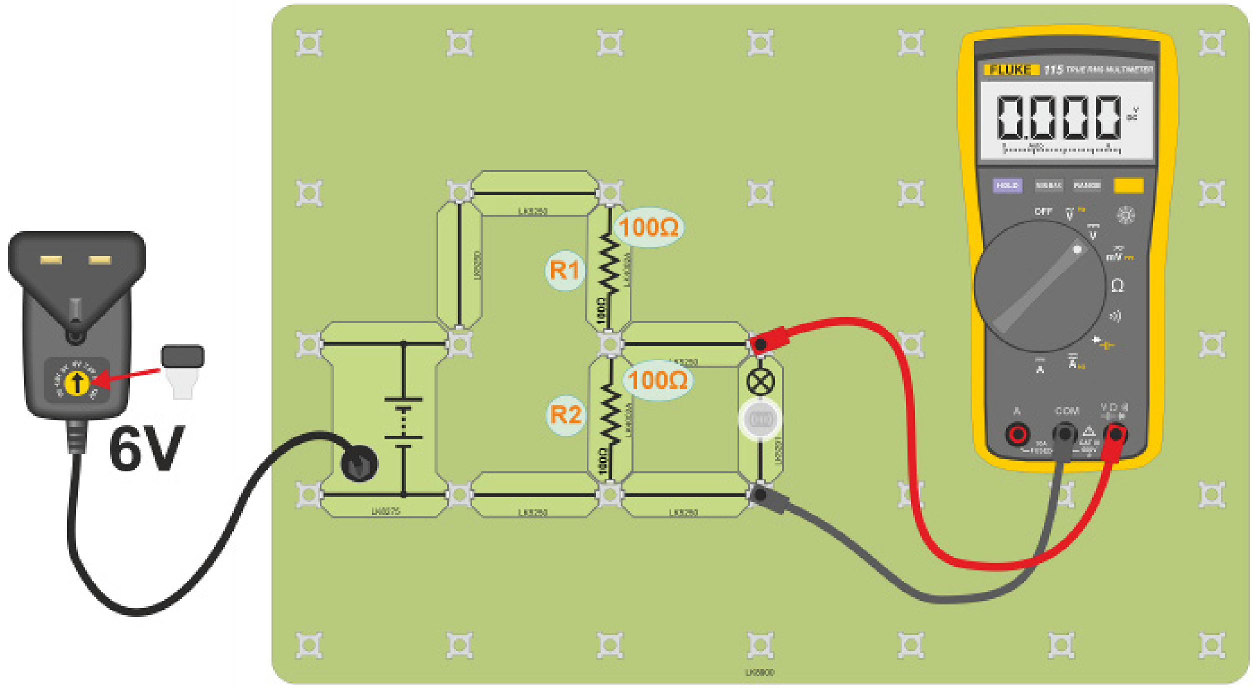
Replace R1 in the circuit with the 2.2kΩ resistor. Replace R2 with the thermistor.

The resistance of the thermistor changes as its temperature changes. What happens to the output voltage as the thermistor is heated?
The voltage divider circuit is a common way of interfacing a measurement component that changes resistance with an instrument that measures voltage.



Replace R1 with a 22kΩ resistor and R2 with the phototransistor. What happens to the output voltage as the phototransistor is covered? What happens when a light is shone at it?
Unlike the thermistor, the phototransistor does not have a linear resistance. However, it still works the same way in a voltage divider circuit.

Activity

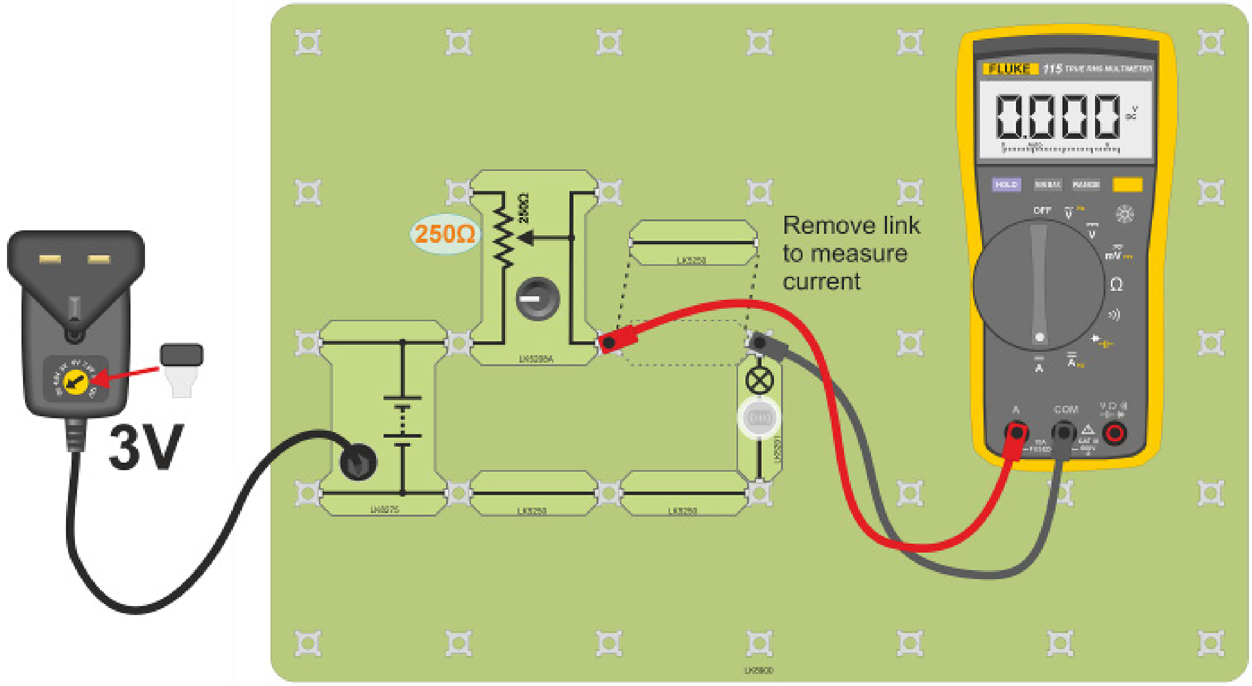


- Set up the circuit shown in the diagram.
- Set the power supply to 6V and plug it in.
- Measure the voltage across the lamp. Is it what you expected?
- Measure the current flowing in the lamp.
- Remove the lamp from the circuit and measure the voltage again.

Analysis

The equation that we worked out for the output voltage of a voltage divider assumes that the same current flows through each resistor. When the lamp is added into the circuit, some current flows through the lamp. This means that the current flowing through R1 is more than that flowing through R2. The current flowing through R1 is equal to the current flowing through R2 plus the current flowing through the lamp. This means that the voltage across R1 will be larger and the voltage across R2 will be smaller.

This is a limitation of voltage divider circuits. When the output voltage is measured using a multimeter, the multimeter draws a very small amount of current and its effect on the circuit is negligible. When a lamp is connected, it draws a significant current and has a noticeable effect on the circuit. In practical applications, voltage dividers usually feed into an amplifier that draws a very small current so that the equation still holds.



Challenge

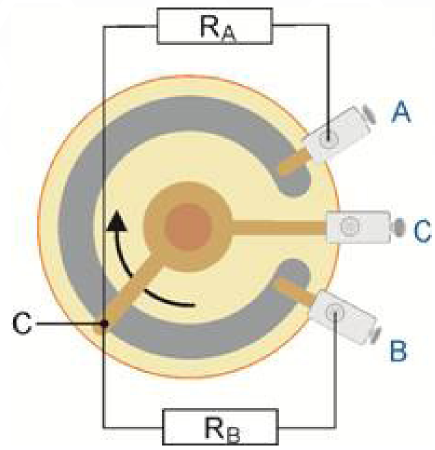
- Set up the circuit shown in the diagram.
- Set the power supply to 3V and plug it in.
- Adjust the variable resistor until the current flowing through the lamp is the same as the current that you measured in the last activity.
- Measure the voltage across the lamp. How does it compare to the voltage that you measured across the lamp in the last activity?
- Remove the power supply and measure the resistance of the variable resistor.

Further Analysis

- Compare the circuits in the last activity and challenge. The power supply voltage in the circuit with the variable resistor is the same as the output of the unloaded voltage divider. The voltage and current of the lamp are the same in each case. Imagine if the two circuits were hidden inside identical boxes with only the lamp exposed. By measuring the voltage across the lamp and the current flowing through it, would it be possible to tell which circuit was which?

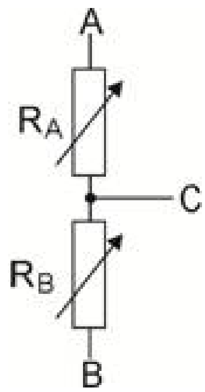
Worksheet 13 – Potentiometers

We have already encountered variable resistors in earlier worksheets. Now we will look at them in more detail.
We are now very familiar with the function of resistors. The Locktronics kit contains a number of resistors with different resistances and we have seen that the operation a circuit changes as one value of resistor is changed for another. Our kit only contains a few different resistors. However, a potentiometer can be continuously adjusted to give any value we want.

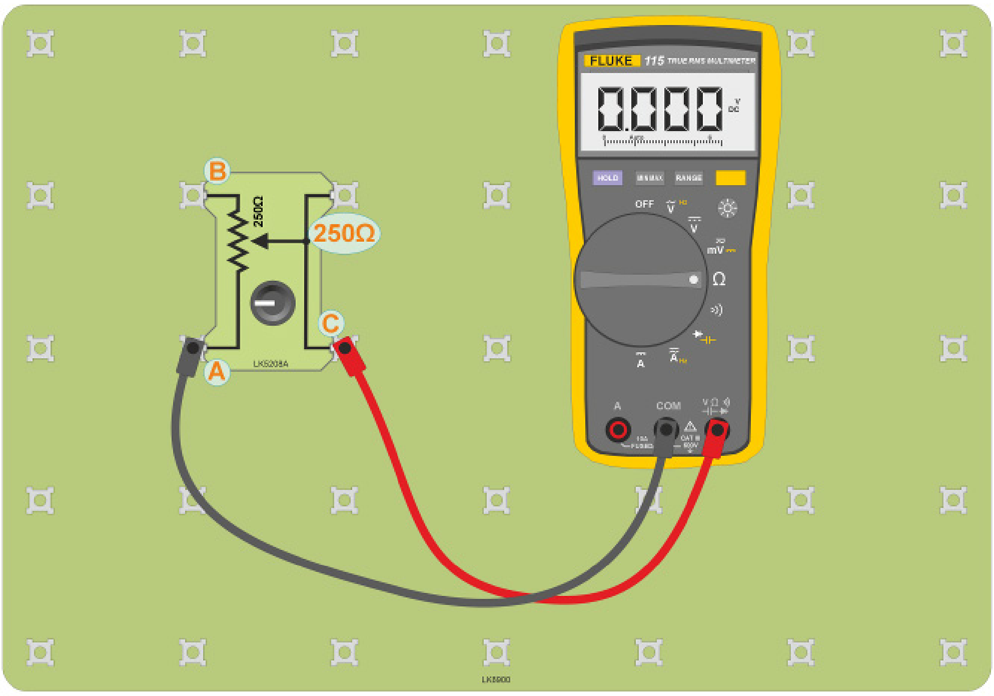


Variable resistors are also called potentiometers (often shortened to 'pot'), or rheostats (when they are designed to carry high current.)
They are used in a wide range of electronic appliances, typically where the end user will want to adjust the operation of the device. They act as volume controls in radios and hi-fi, lighting dimmers, mixers in karaoke and recording desks, and adjustable thermostats in heating systems.
Find the potentiometer component in the Locktronics kit and look at the electronic component on the underside of the carrier. The diagram above shows the inner workings.
There are three solder tag terminals, A, B and C. A and B are connected to the ends of a carbon track,
shaped, in the diagram like a letter 'C'. This track has a fixed resistance, it is very like a fixed resistor opened out and shaped into a curve. C is connected to a 'wiper', that slides around the carbon track, when the knob on the component is turned.

In effect, this makes two resistors, RA and RB. RA is the resistance of the track between
A and C, and RB is the resistance of the track between B and C. When the knob is turned clockwise, the wiper is close to A and RA is small compared to RB . When the knob is turned anti-clockwise, the wiper is close to B and RA is large compared to RB. When the wiper is in the middle, RA and RB are the same.
The ratio between RA and RB can be continuously varied and set to any value that is desired.



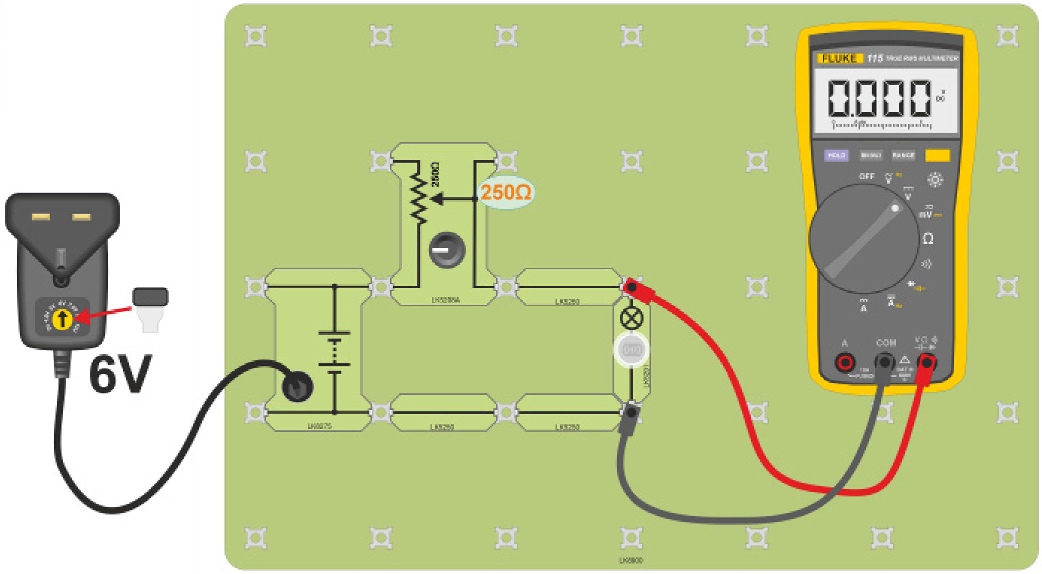
The potentiometers in the Locktronics kit are called rotary potentiometers because they are adjusted by rotating the control knob. In some applications, linear potentiometers are used. In these, the carbon track is laid in a straight line and the control knob likewise travels in a straight line. Potentiometers that are designed to handle high currents are physically large and bulky. In contrast, potentiometers that are designed for occasional adjustments are often very small in size and must be turned using a jeweller's screwdriver.



Activity

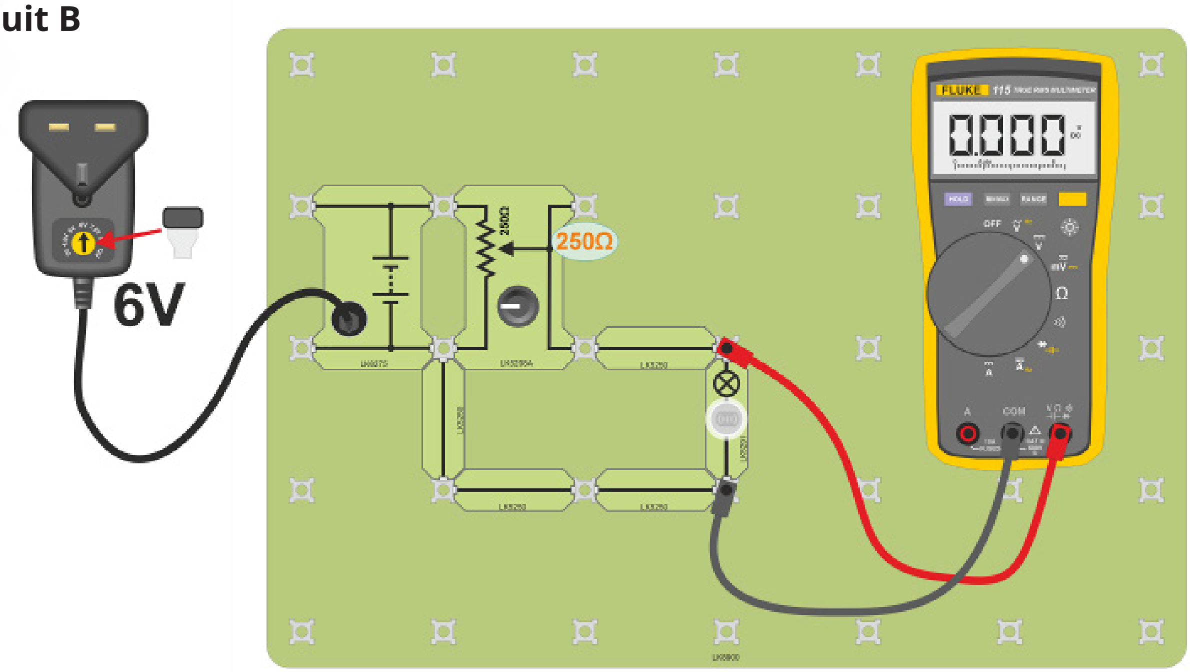
- Place the 250Ω potentiometer on the Locktronics board.
- Use a multimeter in resistance mode to measure the resistance between points A and C.
- Rotate the control knob from fully clockwise to fully anti-clockwise. Does the resistance change?
- Look at how much movement there is in the control knob. Due to the construction of the potentiometer, it does not turn a full 360°.
- With the control knob fully anti-clockwise, measure the resistance between points A and C and between points B and C.
- Turn the control knob a quarter of its travel and measure the resistances again.
- Measure again at half, three-quarters and at fully clockwise.

Circuit A



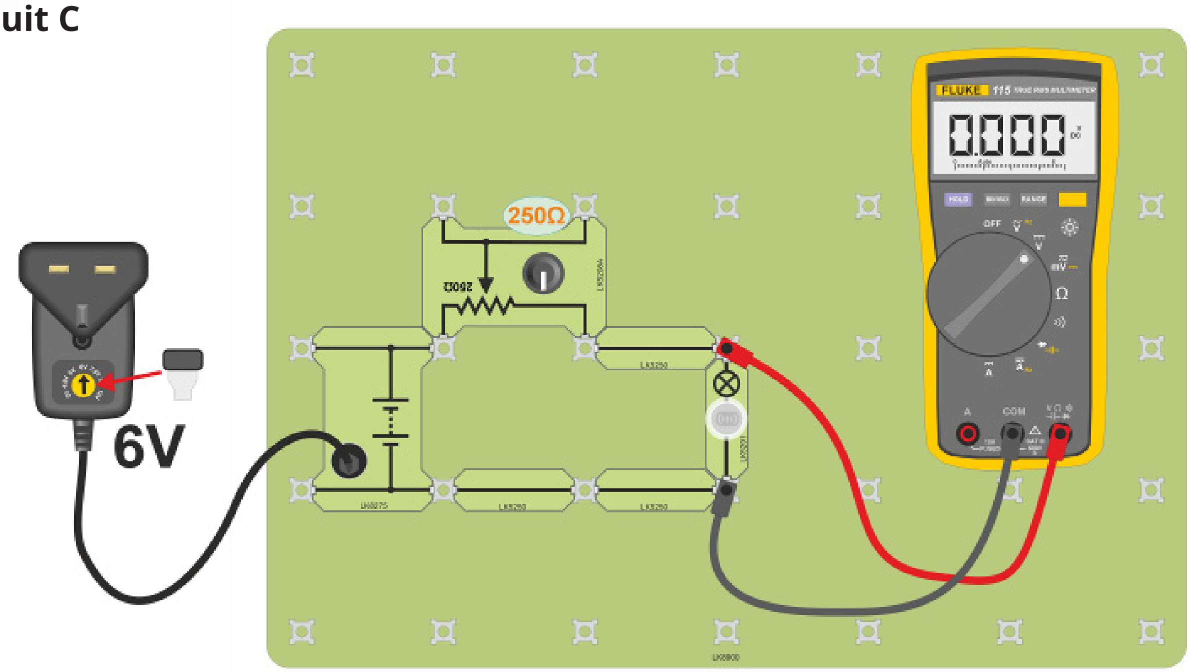
- Set up the circuit shown in the diagram.
- Set the power supply to 6V and plug it in.
- Turn the control knob fully anti-clockwise and measure the voltage across the lamp.
- Measure the voltage across the lamp with the control knob at a quarter, half-way, three-quarters and fully clockwise.

Circuit B



- Change the position of the potentiometer as shown in the diagram above.
- Measure the voltage across the lamp at the same five positions of the control knob.

Circuit C



- Change the position of the potentiometer as shown in the diagram above.
- Does rotating the control knob have any effect in this position? Can you explain why?

Analysis

There is an important difference in the way the component is used in the three exercises.
As a variable resistor, it controls the current flowing through the bulb. They are in series, so whatever current flows through the bulb also flows through the variable resistor. This current may be very small when the device is set to maximum resistance, but it is never zero.
As a voltage divider, it controls the voltage applied to the bulb. The current through the bulb will now be zero when the knob is turned to one extreme. However, there is always a current flowing through the 'pot' itself. It is important to make this current large, compared to the current flowing through the bulb.
In the final configuration, the variable resistor was connected so that the end connections were in the circuit but not the wiper. In this configuration it behaves exactly like a fixed resistor since the total resistance does not change.
Strictly speaking, the component should be called a 'variable resistor' when connected in the first configuration. The circuit uses only two connections of the component and resistors have only two connections. It is called a 'potentiometer' when it is connected in the first configuration using all three connections. It is common, however, to find the terms used interchangeably.

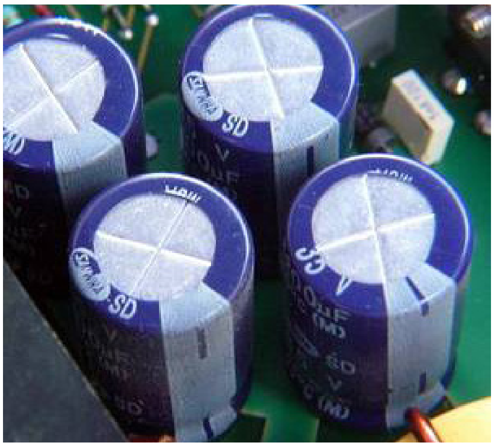
Challenge

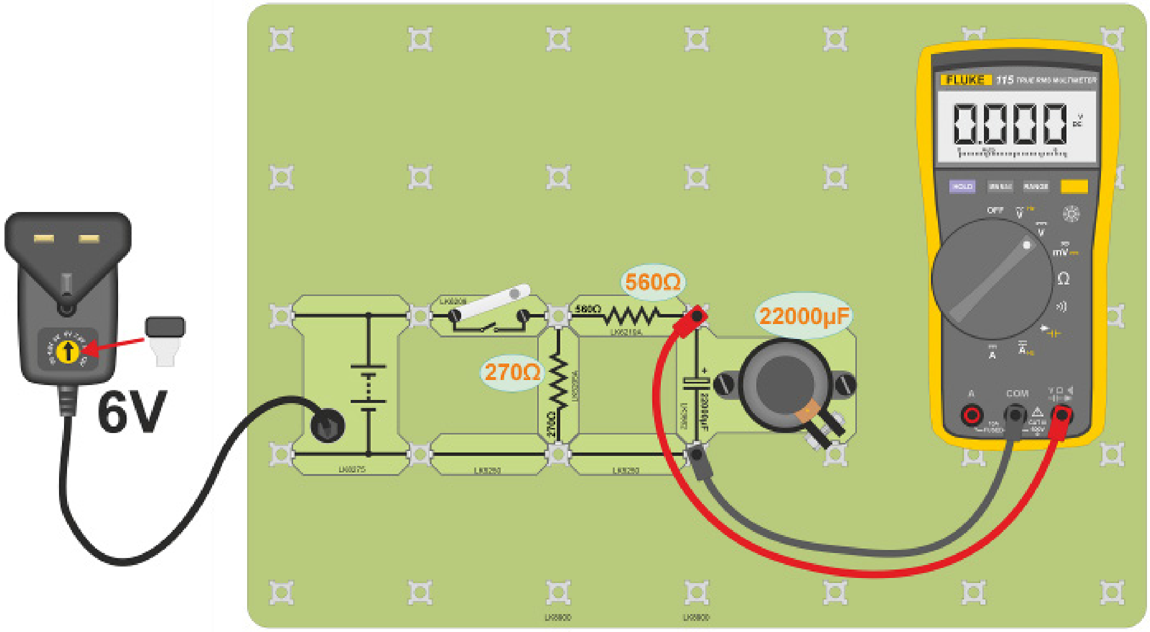
For each of the three circuits, replace the 250Ω potentiometer with the 10kΩ one. How does this affect the operation of the circuit and why? Which arrangement and potentiometer value is best for controlling the brightness of the lamp?

Worksheet 14 – Capacitor Charge and Discharge

In our studies of resistors, we have used a number of techniques for analysing circuits. Resistors have two properties that have made our studies easier. Firstly, their behaviour is the same whether the power supply is AC or DC. Secondly, when we apply power to a circuit built with resistors, we can make measurements straight away or wait a short while. The measurements do not change with time.

In this worksheet we will introduce the capacitor. This component introduces a time dependence to a circuit. It also behaves differently between AC and DC circuits. To begin with, we will study time dependence in a DC circuit.





Activity

- Build the circuit shown above.
- Set the multimeter to DC voltage mode.
- Make sure that the DC power supply is set to 6V and plug it in.
- Start a stopwatch as you close the switch.
- Watch the multimeter and stop the stopwatch when the voltage reaches 4V.
- Open the switch and watch what happens to the voltage.
- Replace the 22000μF capacitor with the 4700μF capacitor.
- Time how long it takes from the closing the switch until the voltage gets to 4V.
- Remove the 270Ω resistor and replace it with an LED.
- How long does the LED remain lit after the switch is opened?
- Repeat the experiment with the 33μF capacitor. What effect does the value of the capacitor have?

Analysis

Resistors convert electrical energy into heat. This heat is simply lost to the surrounding air. Capacitors also convert energy but they do not loose it. The electrical energy that flows into a capacitor is converted into an electric field. This electric field acts as a reservoir for electrical energy. This energy is then available to the circuit some time after it was stored.

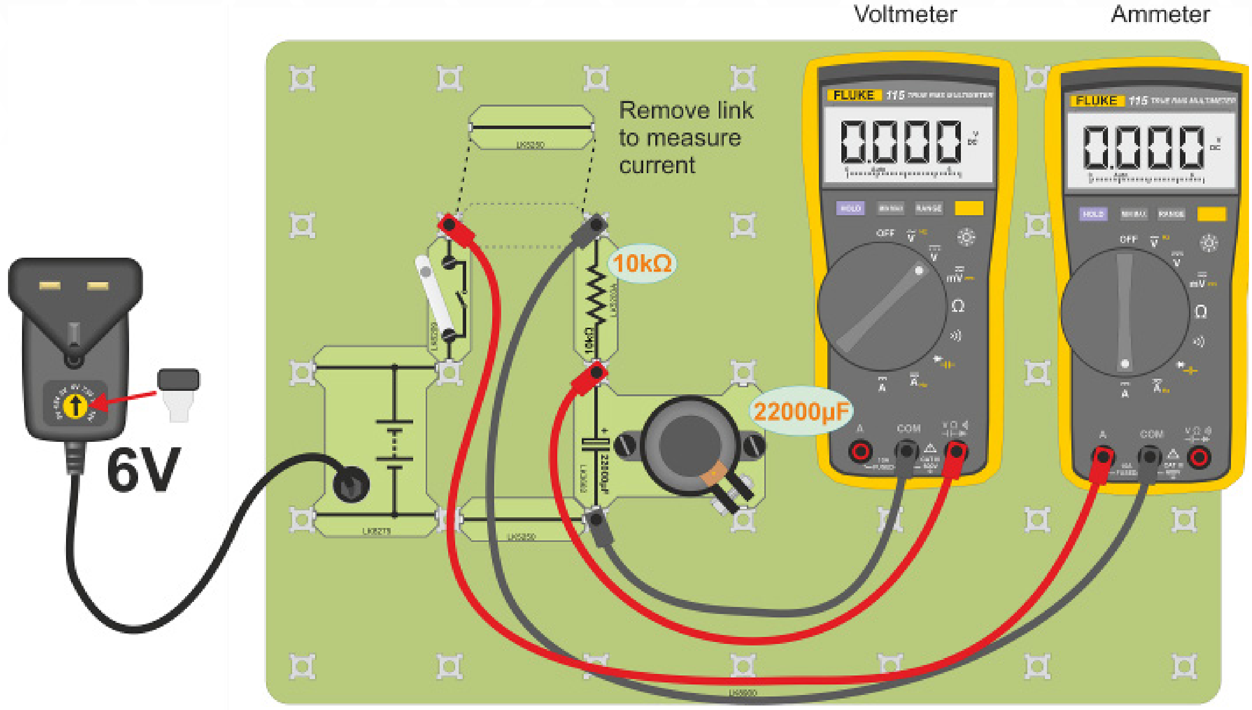
In some ways a capacitor is similar to a rechargeable battery; it can be charged and then later discharged. The difference with batteries is that they convert the electrical energy into a stable form of chemical energy. Capacitors are generally not used to store energy for long periods of time. However, it is worth noting that high voltage capacitors can remain charged many days after a circuit has been powered off.

When our circuit was switched on, a current flowed into the capacitor. As current flowed into the capacitor, the voltage across the capacitor increased. Once the capacitor was charged, the energy was available and could be used to power the LED. The capacitor with the largest value powered the LED for several seconds while the smallest gave only a brief flash.

The larger the capacitor, the more time it takes to charge through the resistor and the more energy is available for powering the LED. The unit of capacitance is the Farad, abbreviated to the letter F. In practical electric circuits, it is common to find capacitances measured in micro-Farads, nano-Farads and pico-Farads.

Unit	Symbol	Farads
micro-Farads	μF	1 μF = 0.000 001 F
nano-Farads	nF	1 nF = 0.000 000 001 F
pico-Farads	pF	1 pF = 0.000 000 000 001 F

Worksheet 14 – Capacitor Charge and Discharge



Activity

- Build the circuit shown above.
- Set the multimeter to DC voltage mode and connect it across the capacitor.
- If a second multimeter is available, set it to DC current mode and connect it as shown. If not, replace the ammeter in the circuit with a link.
- Make sure that the DC power supply is set to 6V but do not connect it yet.
- Start a stopwatch as you connect the power supply.
- Every 30 seconds, for ten minutes, record the voltage reading. Record the current as well if a second multimeter was used.
- After ten minutes, remove the power supply and replace it with a shorting link.
- For a further ten minutes, record the voltage and current every 30 seconds.
-
- If only the voltage has been recorded, derive the current by calculation: -
    - Use the multimeter to measure the exact power supply voltage and the exact value of the resistor.
    - For each measurement point, calculate the voltage across the resistor. That is, the power supply voltage minus the recorded capacitor voltage.
    - For each point, calculate the current. That is, the voltage across the resistor divided by the resistance.
- Plot the voltage and current values on the same graph.

Analysis

At the beginning of the experiment, the voltage across the capacitor was zero. The full voltage of the power supply was applied across the resistor and the maximum current flowed into the capacitor. As current flowed into the capacitor, the voltage across the capacitor increased. This meant that less of the power supply voltage was applied across the resistor and, by Ohm's law, less current flowed. This means that charging occurs rapidly at first and slows down as the capacitor charges up.
When plotted against time, the voltage and current follow exponential curves. When charging, the voltage starts at zero, rises rapidly at first and then slows down as it approaches but never quite reaches the power supply voltage. The current starts at a value determined by the resistance, falls rapidly at first and then slows down as it approaches but never quite reaches zero.

When discharging, the voltage starts at some voltage, falls rapidly at first and then slows down as it approaches but never quite reaches zero. The current starts at a value determined by the resistance, falls rapidly at first and then slows down as it approaches but never quite reaches zero. Note that the current changes sign since its direction changes depending on whether the capacitor is charging or discharging.

In the first activity, we saw that the charging time depends upon the capacitance. It also depends on the resistance since the resistor is controlling the current. Multiplying the resistance and the capacitance together gives a value known as the 'time constant' for the circuit. This is normally represented by the Greek letter tau, **τ**.

$$\tau = R \cdot C$$

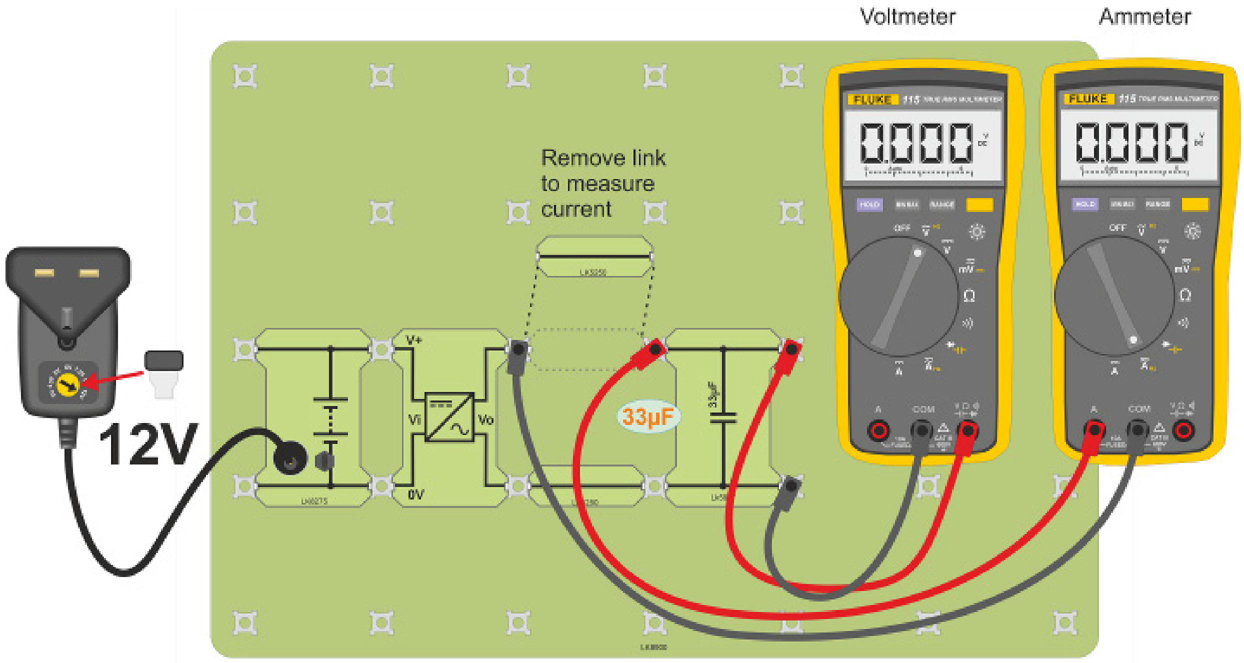
The time constant is the time taken for the capacitor to charge to 63% of the power supply voltage when charging or the time taken to fall to 37% of its initial value when discharging.

Challenge

In the first activity, you recorded the time taken for each capacitor to reach 4 V. This is roughly 63% of the power supply and so the time that you recorded ought to be roughly equal to the time constant. Calculate the time constant for each capacitor and see how close your measurements were. Try changing the resistor for some of the other values in the kit. Calculate the time constant and check it to see if the circuit behaves as you predict. Note that you must make sure that the capacitor is completely discharged at the start of each measurement.

Worksheet 15 – Capacitors in AC Circuits

We have seen that capacitors can store electrical energy and release it later. This introduces a time dependence into a DC circuit. When charging and discharging the capacitor through a series resistor, we saw that the voltage did not change instantly but took time to respond. We also saw that the current was highest when the voltage was lowest.
An AC voltage source is constantly changing. In this worksheet, we shall see what happens when a capacitor is placed in an AC circuit.



Activity

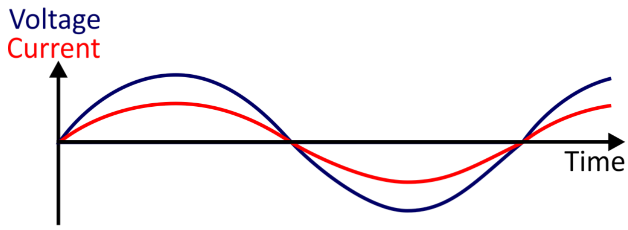
- Build the circuit shown above.
- Set the multimeter to AC voltage mode and connect it across the capacitor.
- Place both links in the circuit while measuring voltage.
- Make sure that the DC power supply is set to 12V and plug it in.
- Measure the AC voltage across the capacitor.
- Some multimeters have a function to measure frequency. If your multimeter has this function, measure the frequency and record it.
- Unplug the multimeter and set it to AC current mode.
- Remove the link as shown and connect the multimeter in its place.
- Measure the AC current flowing in the circuit.

Analysis

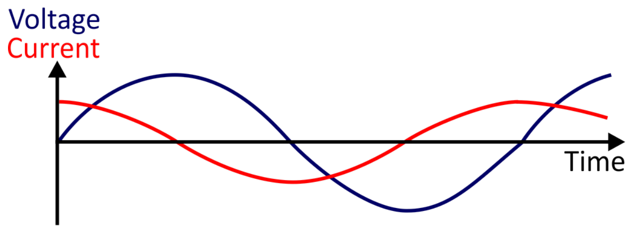
At this point, the circuit seems to be straight forward. We have measured the voltage, we have measured the current. Since we know Ohm's law, we should be able to calculate resistance. However, something is not right! Resistance is the measure of how much electrical energy a component converts to heat. We have already seen that capacitors do not loose energy as heat but store it be released later. We have also seen from our studies with DC, that the voltage and current do not follow the same curves as the capacitor charges and discharges.

In an AC circuit, the capacitor is constantly going through a cycle of charging, discharging and then charging in the opposite polarity as the AC voltage follows its sinusoidal pattern. The multimeter gives us the RMS values of voltage and current with no reference to timing.
However we know that the current would be a maximum when the voltage is changing most quickly. When the voltage is not changing, the current must be zero. If we consider the shape of an AC waveform, the voltage is changing at its fastest rate as the voltage crosses zero. At the positive and negative peaks of the waveform, the voltage briefly stops changing and the current must be zero.

Resistor: Current and voltage are in-phase.



Capacitor: Current and voltage are out-of-phase.



With resistors, when you increase the voltage across the resistor, you increase the current flowing through it. This is true for both DC and AC circuits.
When a capacitor is placed in an AC circuit, the voltage and current are related similarly to the way they are with resistors. Since the current is out of phase with the voltage and energy is stored rather than consumed, we use the term **capacitive reactance** rather than resistance. The symbol is an X rather than an R and often has the subscript c to denote capacitive, $\mathbf{X_c}$. It is defined, in the same way as resistance:

$$\mathbf{X_c = V / I}$$

The units of reactance are ohms and the equation can be rearranged to find any quantity given the other two.
With resistors, the resistance is simply the value of the resistor. With capacitors, there is an extra step required to find the reactance. Capacitors oppose a *changing* voltage.

The faster the rate of change of voltage, the greater the current that must flow to charge or discharge the capacitor. With a sine wave, the fastest rate of change of voltage is when the wave crosses zero. Two factors affect the rate of change of voltage; the peak amplitude and the frequency. In other words: how far the voltage has to go and how quickly it needs to get there.
This means that the reactance depends on the frequency of the AC supply. The frequency of an AC supply is the number of positive and negative cycles it makes every second. The unit of frequency is the Hertz, abbreviated to Hz.

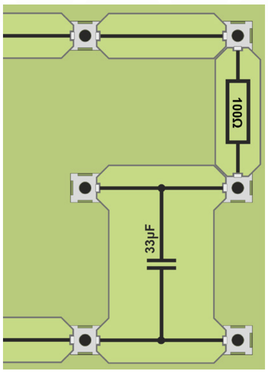
The formula for capacitive reactance is:

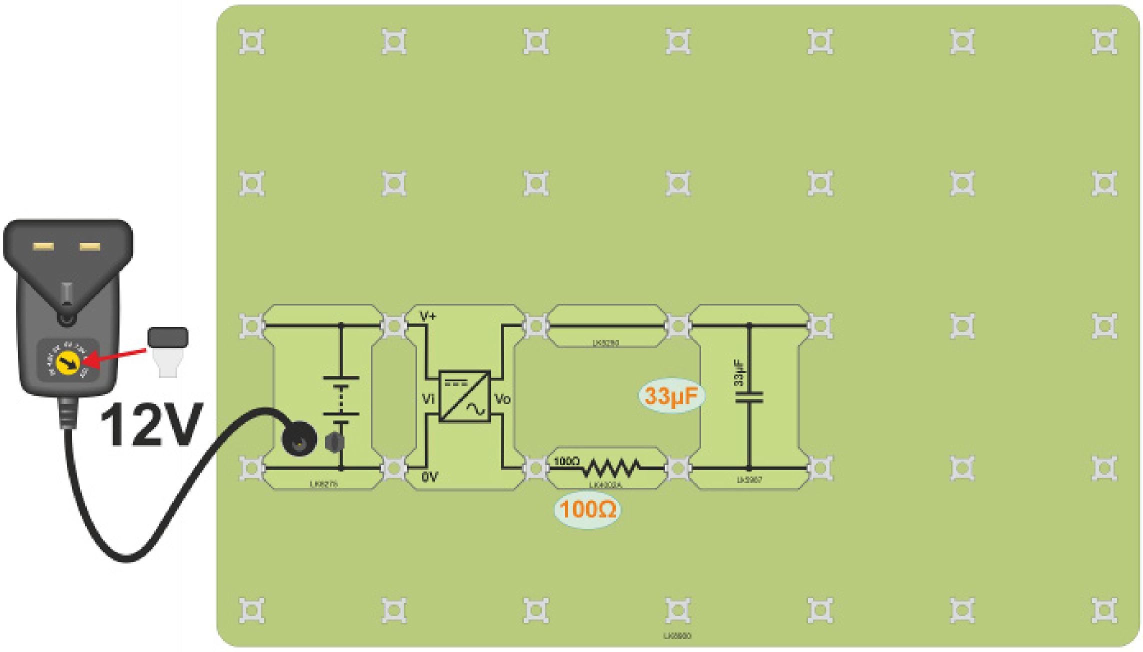
$X_c = 1/(2 \pi f C)$
X_c is the reactance in Ohms. f is the frequency in Hertz and C is the capacitance in Farads.

Look back at the measurements that you took in the first activity. Use the voltage and current measurements to calculate the reactance. Calculate the reactance using the formula above, does it agree with your result. Note that capacitors are manufactured to a tolerance and might not be exactly the value that they are marked as.

Worksheet 16 – Capacitor and Resistor in Series

In the previous worksheet, we applied an AC voltage to a capacitor and measured the current. We reasoned that the current and voltage must be out of phase with each other. However, voltage and current are still connected similarly to how they are in a resistive circuit so what difference does it make if they are out of phase?
In this worksheet we shall connect a resistor and a capacitor in series. We know from earlier work that this will create a voltage divider. We know how resistive voltage dividers work but having a phase difference in the capacitor will add another dimension to our analysis.





Activity

- Build the circuit as shown.
- Set the power supply to 12V and plug it in.
- Set the multimeter to AC voltage mode.
- Measure the voltage across the resistor and the voltage across the capacitor.
- Measure the total voltage at the output of the AC inverter.
- Set the multimeter to AC current mode.
- Measure the current in the circuit by removing the link and inserting the multimeter.

- Use your measurements to calculate the resistance of the resistor and the reactance of the capacitor.
- Use your measurement of the total voltage to calculate what value of resistor would draw as much current as the resistor and capacitor combined.
- Think back to what you know about Kirchhoff's laws and what you know about resistors in series. Do your measurements add up?
- Try replacing the capacitor with another resistor from your kit. Do the measurements add up now?

Analysis

At first glance our measurements look wrong. We would expect the voltages across the resistor and capacitor to add up to the total voltage supplied by the AC inverter. What is catching us out is the phase difference between the voltage and current in the capacitor.
The multimeter is only reporting the RMS value of each voltage. It tells us nothing about the phase of each measurement relative to each other. The same current flows through every component in a series circuit. In the resistor, the voltage across the resistor is in phase with the current. In the capacitor, the voltage is ninety degrees out of phase with the current. If we were to look at the sine waves of the two voltages, we would see that one is falling as the other is rising and vice-versa. This means that the RMS of total voltage is not simply the sum of the individual RMS measurements.
What can we do with these out-of-phase voltage measurements? One approach would be to plot two sine waves with the amplitudes that we measured but ninety degrees out of phase. We could then add up the voltages at each point and look at the amplitude of the resulting wave. The easier approach is to use Pythagoras' theorem. The voltages across the resistor and capacitor are ninety degrees out-of-phase so we can draw them as two sides of a right-angle triangle. The total voltage will be the hypothenuse of this triangle. It can be calculated:

$$V_{total}^2 = V_R^2 + V_C^2$$

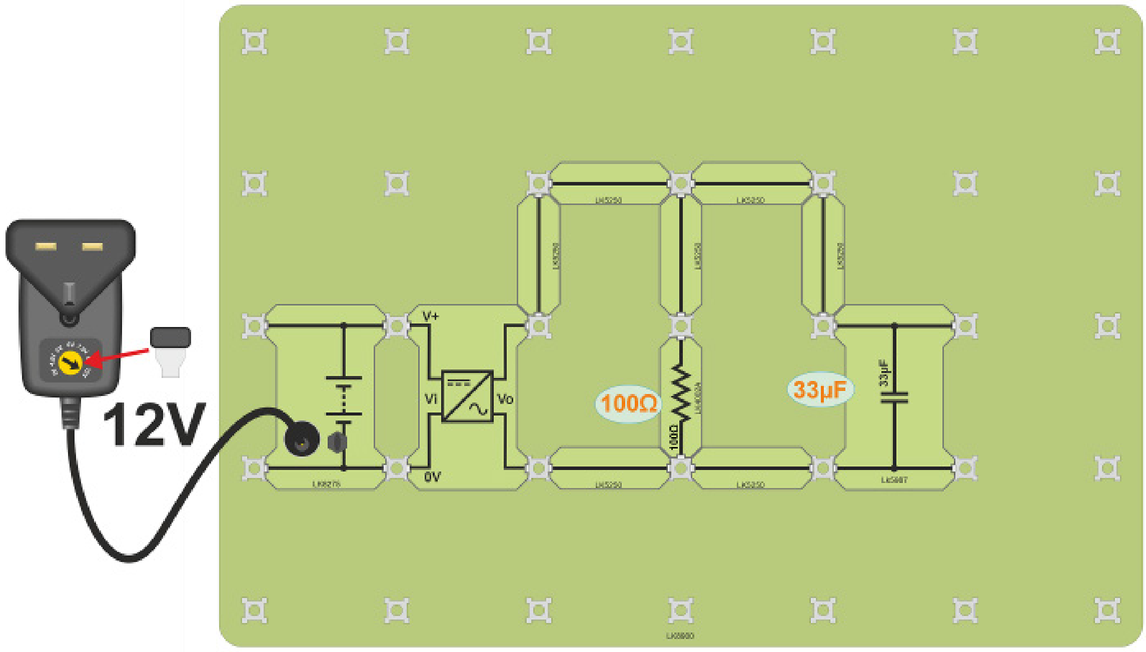
Check this against your measurements. Does it agree?
What about our calculations of capacitive reactance and resistance? What can we do with them? We already know that when we divide voltage by current to get the reactance of the capacitor, that they will be ninety degrees out of phase. This means that we can consider reactance to be ninety degrees out-of-phase with resistance. Since they are ninety degrees out of phase we can use Pythagoras in the same way. When we combine both resistance and reactance together, the quantity is called impedance. It is represented by the letter Z and the units are still ohm's.

$$Z^2 = R^2 + X_C^2$$

Check this against your measurements. Does it agree?

Worksheet 17 – Capacitor and Resistor in Parallel

When a capacitor and resistor are connected in series, they act as a voltage divider sharing the voltage between them.
When a capacitor and a resistor are connected in parallel, they act as a current divider, sharing the current.
In this worksheet, we shall study an AC circuit with a resistor and capacitor in parallel. We shall see how the circuit analysis rules that we have learned apply in this case.



Activity

- Build the circuit as shown.
- Set the power supply to 12V and plug it in.
- Set the multimeter to AC voltage mode.
- Measure the voltage output of the AC inverter.
- Set the multimeter to AC current mode.

- Remove the vertical links one by one and measure: -
  - The total current supplied by the AC inverter.
  - The current flowing in the resistor.
  - The current flowing in the capacitor.
- Look the three currents. Do they add up as Kirchhoff's law says they should? Look back at our analysis of the series circuit; can you explain the results for this circuit.
- Using you measurements, calculate the resistance of the resistor, the reactance of the capacitor and the combined impedance of the two components.

Analysis

Simply adding up the currents in the two components, we find that they do not add up to the total current in the circuit. We can analyse our results using the same logic that we applied to the series circuit. We know that the the voltage and current in the capacitor will be ninety degrees out of phase with each other. In a parallel circuit, the same voltage is applied to both components. Thus, the currents in the resistor and capacitor must be ninety degrees out of phase with each other. We applied pythagoras' theorum to the voltages in the series circuit. Similarly we can apply it to the currents in the parallel circuit.

$$I_{TOTAL}^2 = I_R^2 + I_C^2$$

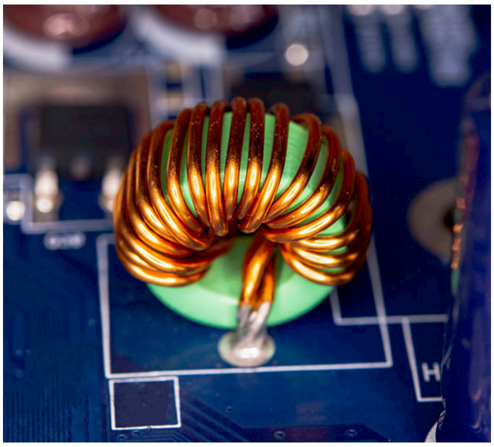
Check this against your measurements. Does it agree?
Look at the impedance, resistance and reactance derived from your measurements. How do they add up? In a series circuit, impedances are simply added up. We were able to apply Pythagoras' theorum. In a parallel circuit, it is the inverse of the impedances that add up. We can still use Pythagoras' theorum to take account of the ninety degree phase shift.

$$1 / Z_{TOTAL}^2 = 1 / R^2 + 1 / X_C^2$$

Check this against your measurements. Does it agree?

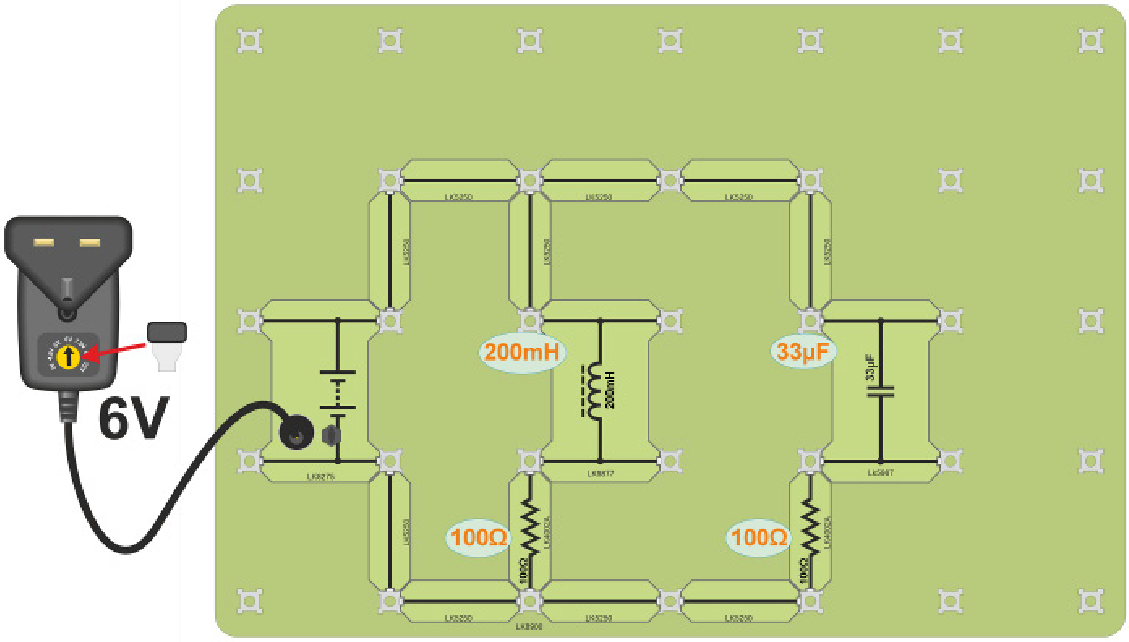
Worksheet 18 – Capacitors and Inductors

We have seen that capacitors store energy as an electric field. In this worksheet we will study another component that stores energy. In an inductor, the energy is stored not in an electric field but in a magnetic field. Like a capacitor, an inductor has the property of reactance. There is, however, a difference between capacitive reactance and inductive reactance. While there are similarities between inductors and capacitors there are many ways in which they are polar opposites. In this worksheet, we shall compare the two components.



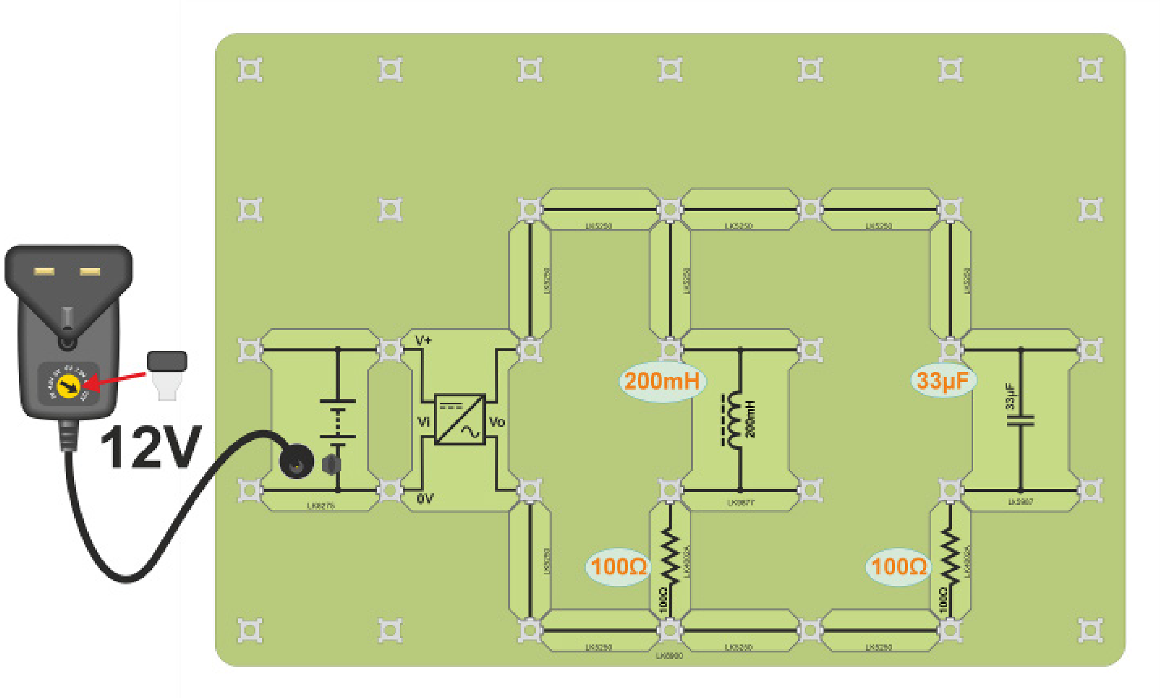
Activity

Find the 33μF capacitor and the 200mH inductor in the Locktronics kit.
Set the multimeter to resistance mode.
Try to measure the resistance of each component. The inductor will give a resistance reading but the capacitor will not. Record the resistance of the inductor.



Set up the circuit shown.
Set the multimeter to DC voltage mode.
Measure the voltage across the inductor and the voltage across the capacitor.

Set the multimeter to DC current mode.
Remove the link above the inductor and measure the current flowing through it. Record the value.
Calculate the DC resistance of the inductor.
Try to measure the current flowing through the capacitor. Do you get any reading on the multimeter? Is it possible to calculate a DC resistance for the capacitor?



Set up the circuit shown above.
Set the multimeter to AC voltage mode.
Measure the voltage across the inductor and the voltage across the capacitor.
Set the multimeter to AC current mode.
Remove the link above the inductor and measure the current flowing through it. Record the value.
Remove the link above the capacitor and measure the current flowing through it. Record the value.
Calculate the AC impedance of the inductor.
Calculate the AC impedance of the capacitor.

Analysis

When an electric current flows in a conductor such as a wire, a small magnetic field is created around the wire. An inductor is constructed by winding wire into a coil. With every turn of the coil, the magnetic field is increased. When we have enough turns to create a significant magnetic field, it has an effect on our electric circuit. Many inductors have a ferrite core that concentrates the magnetic field increasing the inductance.

In a DC circuit, we observe that a steady state current is established in our inductor. The current is determined by the DC resistance that we can measure with a multimeter. A magnetic field surrounds the component but does not have any noticeable effect on the circuit. Later, when we study electromagnetic components, we shall see how that magnetic field can be put to use.

We know that the capacitor in our DC circuit will take some current to charge up. After it is charged up, no current will flow. The capacitor blocks DC current.

In an AC circuit, both the capacitor and the inductor will allow current to flow. The inductor impedes the flow of AC current more than it impedes the flow of DC current. This is because it takes time for the magnetic field to become established. As the magnetic field is growing it effectively generates an opposing electro-magnetic-force (e.m.f.). The strength of the e.m.f. depends on how quickly the magnetic field is changing, this has two important implications. The first is that the observed current will be reduced compared to what it would be without the e.m.f. giving the inductor a greater impedance. The second is that this extra impedance depends on the frequency of the AC supply. At DC (effectively zero frequency) the inductance provides no extra impedance. At higher frequencies, the inductor has increasing impedance and increasingly blocks high frequency AC.

Worksheet 18 – Capacitors and Inductors

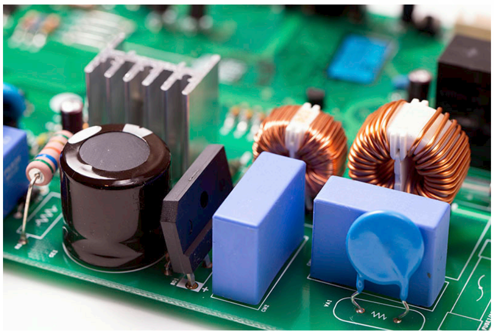
	Capacitors	**Inductors**
Construction	Parallel plates separated by an insulator	Turns of wire in a coil, often with a ferrite core.
DC resistance	Very high or infinite DC resistance.	Ideal inductors have zero resistance but practical components have resistance due to the length of fine wire used to make the coil.
DC behaviour	Blocks DC. Effectively behaves like an insulator.	Acts as a resistor. The resistance can be measured with a multimeter.
AC Reactance	Depends on capacitance value and frequency. $X_C = 1 / 2\pi \cdot f \cdot C$ Reactance decreases as frequency increases.	Depends on inductance value and frequency. $X_L = 2\pi \cdot f \cdot L$ Reactance increases as frequency increases.
AC Behaviour	Current leads voltage by ninety degrees	Voltage leads current by ninety degrees.

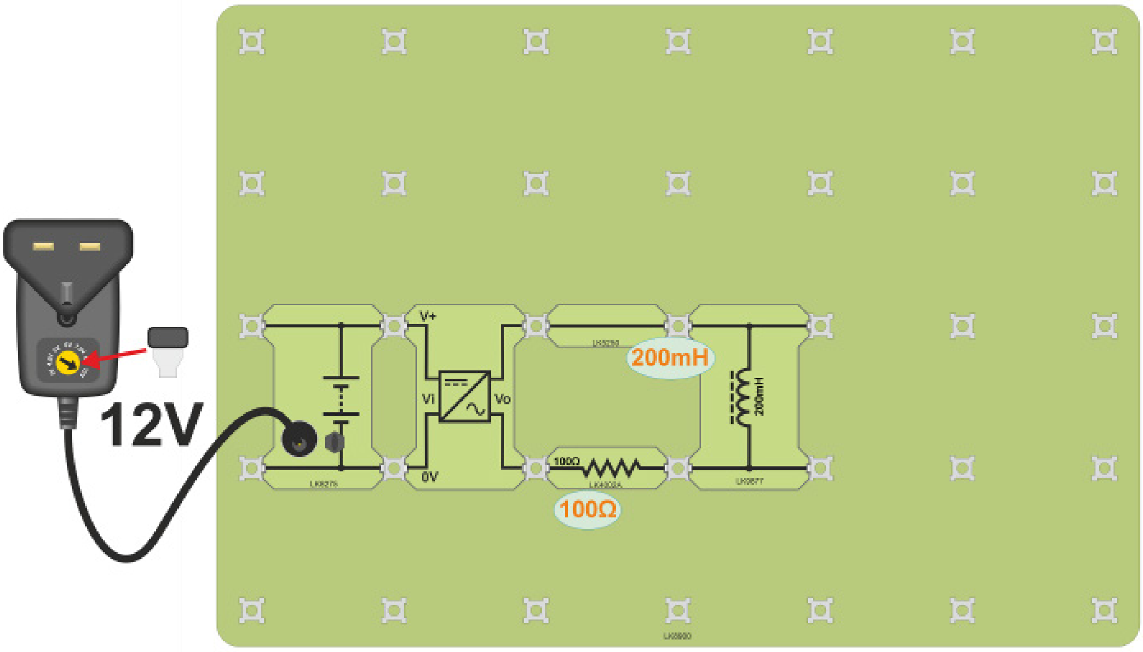
Worksheet 19 – Inductor and Resistor in Series

In the previous worksheet, we saw that an inductor has a reactance similar to that of a capacitor. In both components the AC voltage and current are ninety degrees out of phase with each other.

When we place an inductor and resistor in series with each other, we would expect the circuit to behave in a similar way to a capacitor and resistor in series.

In this worksheet we shall connect a resistor and inductor in series. We shall see how the phase difference between voltage and current in the inductor affect the behaviour of the voltage divider.





Activity

- Set the multimeter to resistance mode.
- Measure the DC resistance of the resistor and the inductor.
- Build the circuit as shown.
- Set the power supply to 12V and plug it in.
- Set the multimeter to AC voltage mode.
- Measure the voltage across the resistor and the voltage across the inductor.

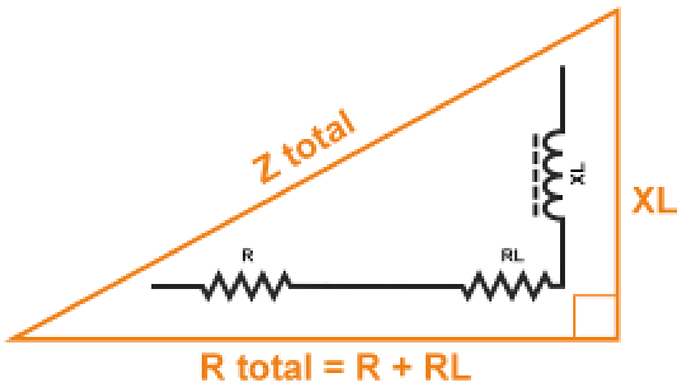
- Use your measurements to calculate the current flowing in the circuit.
- From the voltage across the inductor and the current, calculate the impedance of the inductor. How does it compare to the measured DC resistance?

Analysis

When we put a resistor and a reactive component in series, we find that the voltages and impedances do not add up simply as they do in a resistive circuit. With a resistor and capacitor, we found that the voltages across each of the components were ninety degrees out of phase and we could show that they did add up using Pythagoras' theorem.

$$V_{total}^2 = V_R^2 + V_C^2$$

Try applying this logic to your measurements of the resistor and inductor. Do they add up?
Something is still not right! We know that the voltage in the inductor is ninety degrees ahead of the current whereas it is ninety degrees behind in a capacitor but Pythagoras' theorem should still hold.
What we are missing is the resistance of the inductor. While the capacitor was entirely reactive, the inductor has both reactance and resistance. Both are part of our circuit. We deal with this by treating our real inductor component as if it were an ideal inductor in series with its DC resistance.
This means that there are two resistances in our circuit, the actual resistor that we deliberately put there and the internal DC resistance of the inductor. We know that the voltage across the ideal inductor will be ninety degrees out of phase with the voltage across the two resistances but we can not measure it directly. Can we work it out from what we already know?



We know the resistance of the inductor and we know the current. We can use Ohm's law to work out the in-phase part of the voltage. We know the voltage across the inductor and can thus use Pythagoras to work out the voltage across the ideal inductor.

$$V_L^2 = V_{RL}^2 + V_L^2$$

Having worked out the voltage across the ideal inductor and knowing the current, we can now work out its reactance.

$$X_L = V_L / I$$

The formula for inductive reactance is:

$$X_L = 2 \pi f L$$

X_L is the reactance in Ohms. f is the frequency in Hertz and **L** is the inductance in Henrys.

We can work out a total impedance for our circuit the same way as we did for the resistor and capacitor in series. This time, however, we must take into account both the component resistor that we put in the circuit and the internal resistance of the inductor.

$$R_{total} = R + R_L$$

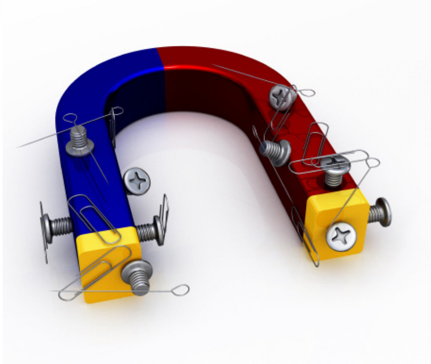
$$Z^2 = R_{total}^2 + X_L^2$$

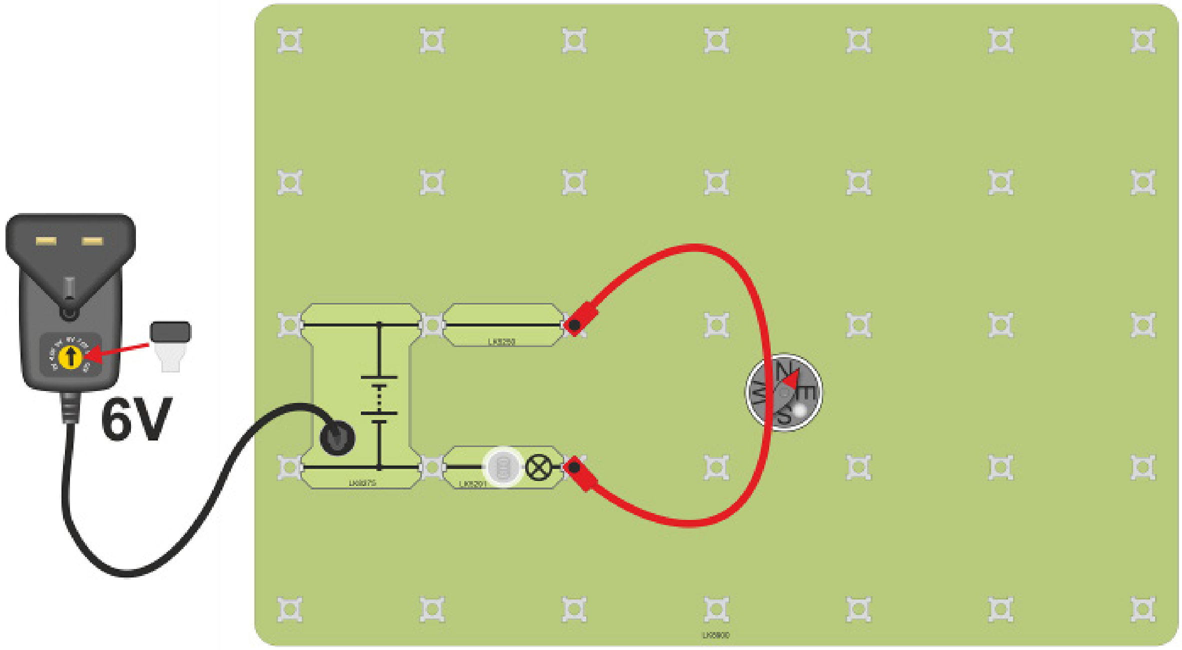
Check this against your measurements of the supply voltage and the current. Does it agree?

Worksheet 20 – Basic Principles of Electromagnetism

Inductors behave the way they do because of the magnetic field that is formed within them. The flow of electric current always creates a magnetic field. In the case of a small current in a single wire, the magnetic field is very small. There are ways to make the field stronger to the point where it can be useful for various tasks.

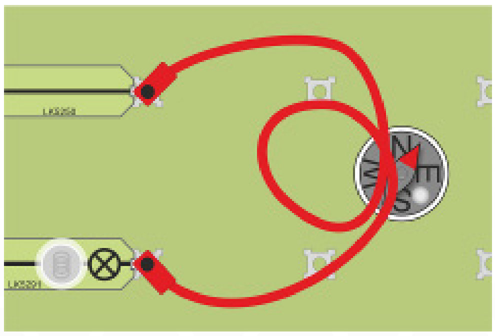
In this worksheet, we will look at electromagnetism in a little more detail. Later we shall see how it can be exploited in practical applications.





Over to You

- Build the circuit as shown.
- Rotate the Locktronics baseboard so that the top edge of the board is North and the plotting compass points straight up.
- Set the power supply to 6V and plug it in.
- Bring the wire close to the compass. What happens? How close does the wire need to be to affect the compass?
- Now loop the wire so that it passes the compass twice. Does this make the effect stronger? Add another loop so that it passes three times. What happens now?

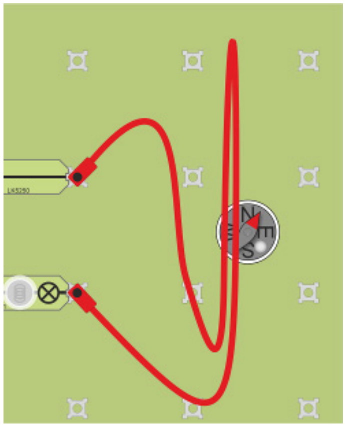


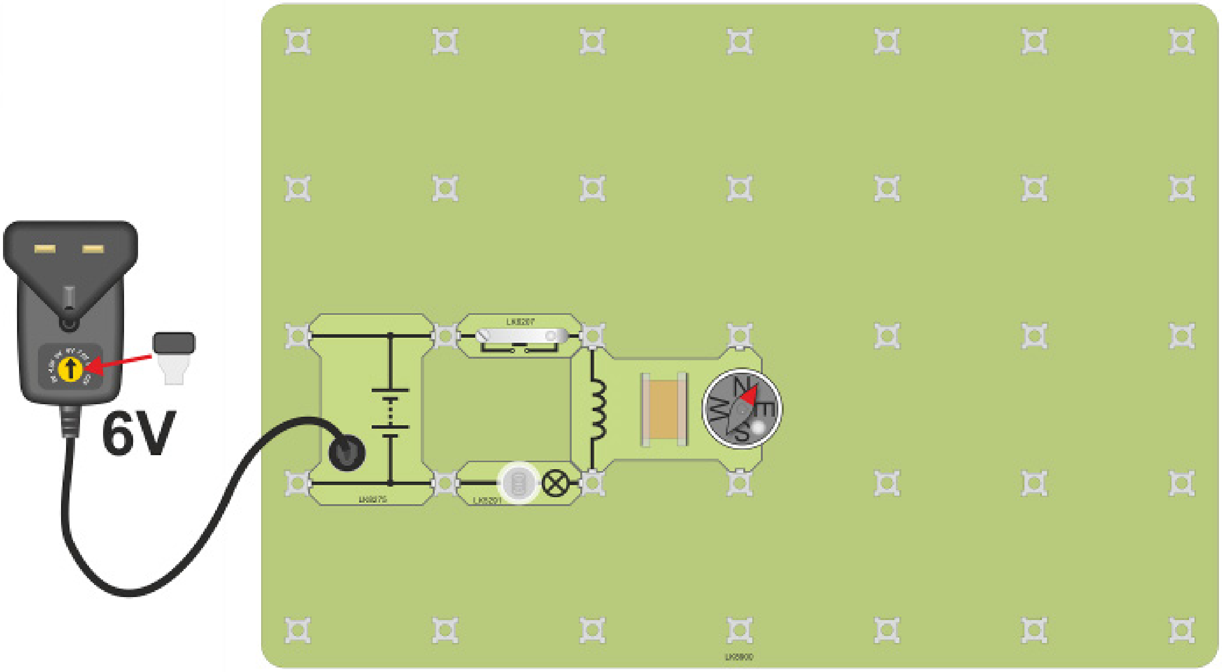
So What?

When a current flows in the wire a magnetic field is generated surrounding it. The field is pulling the compass away from the Earth's magnetic field. When we loop the wire so that the current passes the compass twice, the fields around the two loops reinforce each other. The more turns, the more the field is reinforced. If we could make many turns, we could make a really strong field.

Challenge

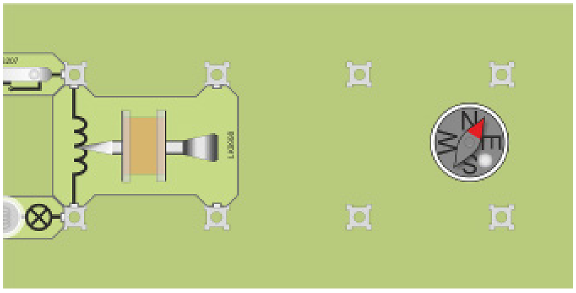
- Fold the wire over so that it is doubled.
- Hold the wire over the compass at the point where it is doubled.
- Does this have any effect on the compass?
- How does this compare to a single wire or a loop of two turns?
- Can you explain why doubling the wire in this way is different to making a loop?



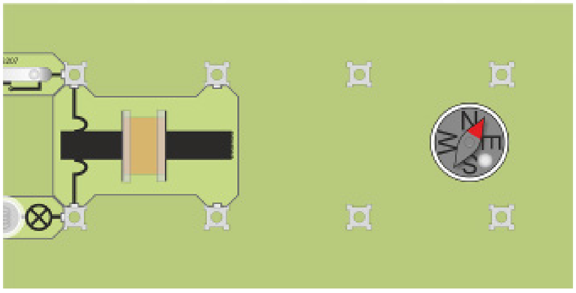


Over to You

- Build the circuit as shown.
- Set the power supply to 6VDC and plug it in.
- Push the switch and observe the effect on the compass.
- The coil has 400 turns of wire, how does its effect compare to that of the single wire?
- Move the compass away from the coil. How close to the coil does it have to be to detect the magnetic field.
- Slide a steel nail inside the coil.
- Switch on the power supply and watch the compass. Is the effect stronger than before?
- Place a paper clip on the carrier close to the nail. See if you can make the paper clip stick to the nail.



- Replace the nail with a ferrite rod. How does it compare to the nail?
- Long at what happens when the switch is released. Is there are difference between the nail and the ferrite rod?



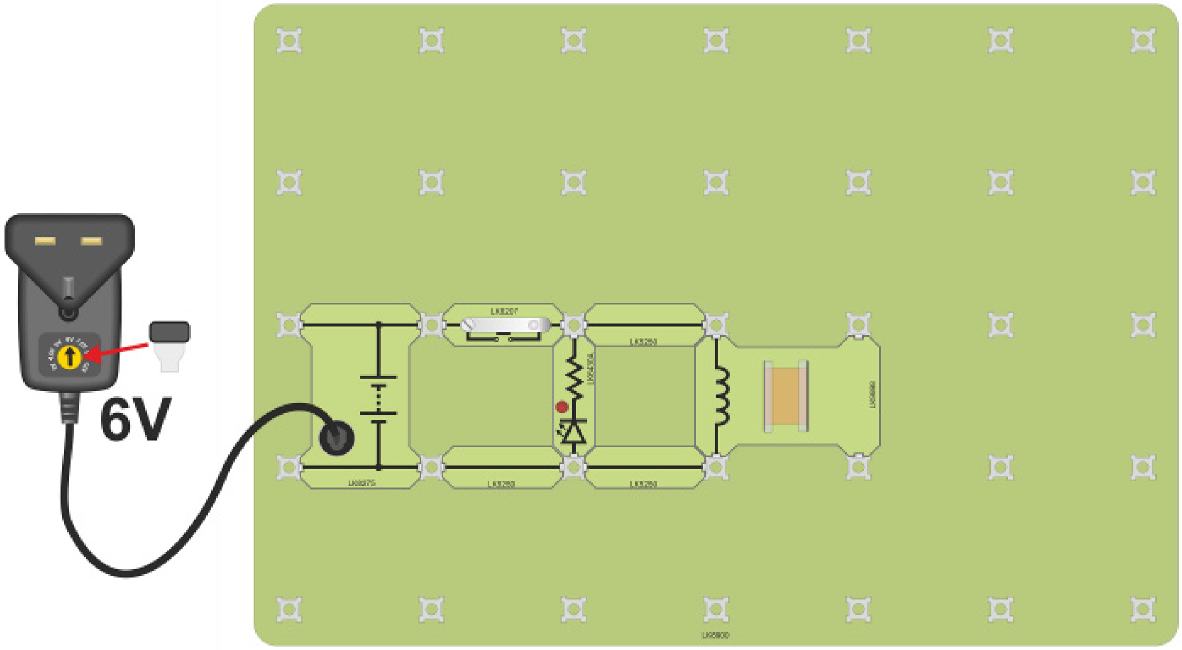
So What?

- An electric current flowing in a wire creates a small magnetic field.
- The magnetic field runs the whole length of the wire.
- If the wire is looped around then it reinforces the magnetic field.
- A coil with many turns of wire behaves the same as a magnet when an electric current flows through it.
- Adding a core to the coil concentrates the magnetic field making its effect stronger in the axis of the core.
- Small metallic objects such as paper clips are attracted to the core while the current is flowing. In our experiment, we were able to move a paper clip. If scaled up, this design can be used to create an electromagnet capable of lifting heavy loads.

Challenge

Which end of the compass is pointing towards the core? Can you think of a way to reverse it so that the opposite end points towards it?
We have powered our electromagnet with a DC current. If we used AC, what do you think the effect on the paper clip would be? What about the compass?
If we wanted to make a more powerful electromagnet, what changes might we make?

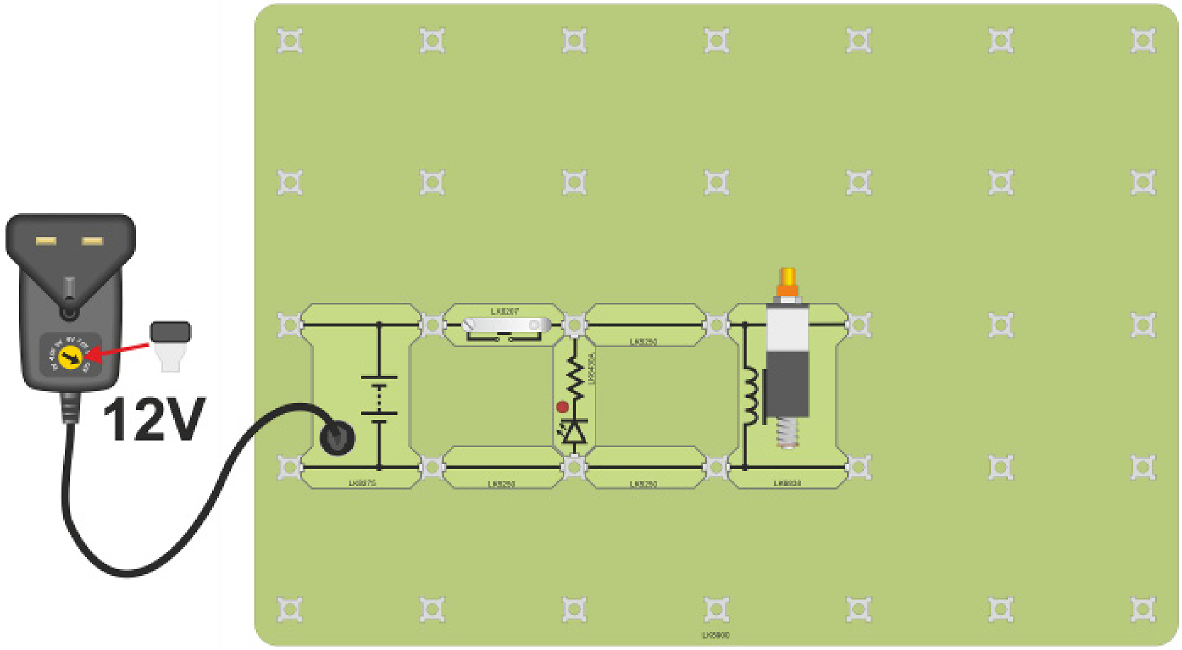
When an electric current flows through a conductor, it produces a magnetic field around that conductor.
The magnetic field can be concentrated by making the current flow through many turns in a coil of wire. It can also be concentrated by adding a core of magnetic material to the coil.
A solenoid is a powerful coil that is surrounded by a magnetic material. When energised, a core is pulled into the coil. This produces a repeatable, linear motion when a current is applied.
We will look at a small industrial solenoid and also address the question of where the magnetic field goes when the current is removed.



Over to You

- Build the circuit as shown.
- Set the power supply to 6VDC and plug it in.
- Push the switch, hold it for a moment and then release it.
- What happens to the LED as the switch is released?

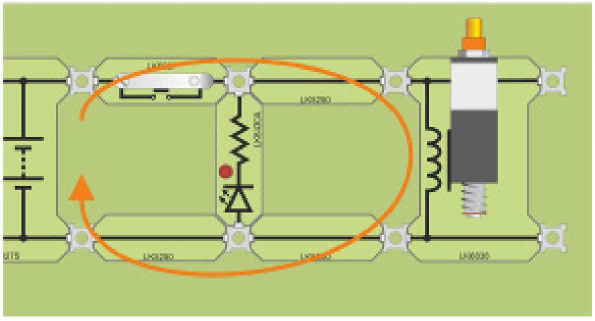
- Since the switch interrupts the current from the power supply; where does the current to light the LED come from?



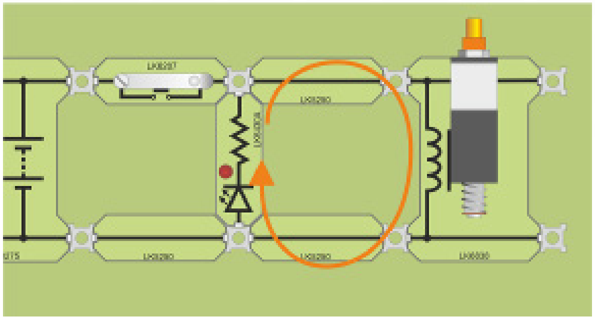
- Now replace the coil with the solenoid as shown.
- Set the power supply to 12VDC and plug it in.
- Press and release the switch. How does the appearance of the LED compare to the previous circuit?

So What?

When we compared capacitors and inductors, we noted that, in an inductor, the current lags behind the voltage. The inductor opposes a change in current. When the switch is released, the power to the solenoid is removed and the magnetic field collapses. As the field collapses, it induces a current in the wire in the same direction as the applied current. This is the current that we see illuminating the LED.
If this current has no where to go, it can generate high voltages which can damages switches and semiconductor devices. It is common practice to include a diode in parallel with a solenoid provide a safe path for this current. It is not usual for the diode to be a light-emitting diode (LED) as we have done here. The reason for the LED is that it allows us to see the effect of the induced current.
A term commonly used for the electrical energy that appears when an inductive component is switched off is “back e.m.f.” The acronym “e.m.f.” is short for “electro-motive force”.



Current path with switch closed.

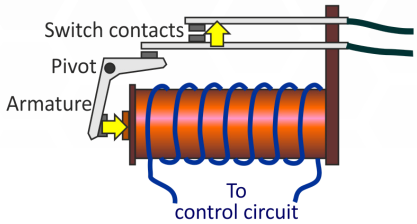


Current path when switch is opened.

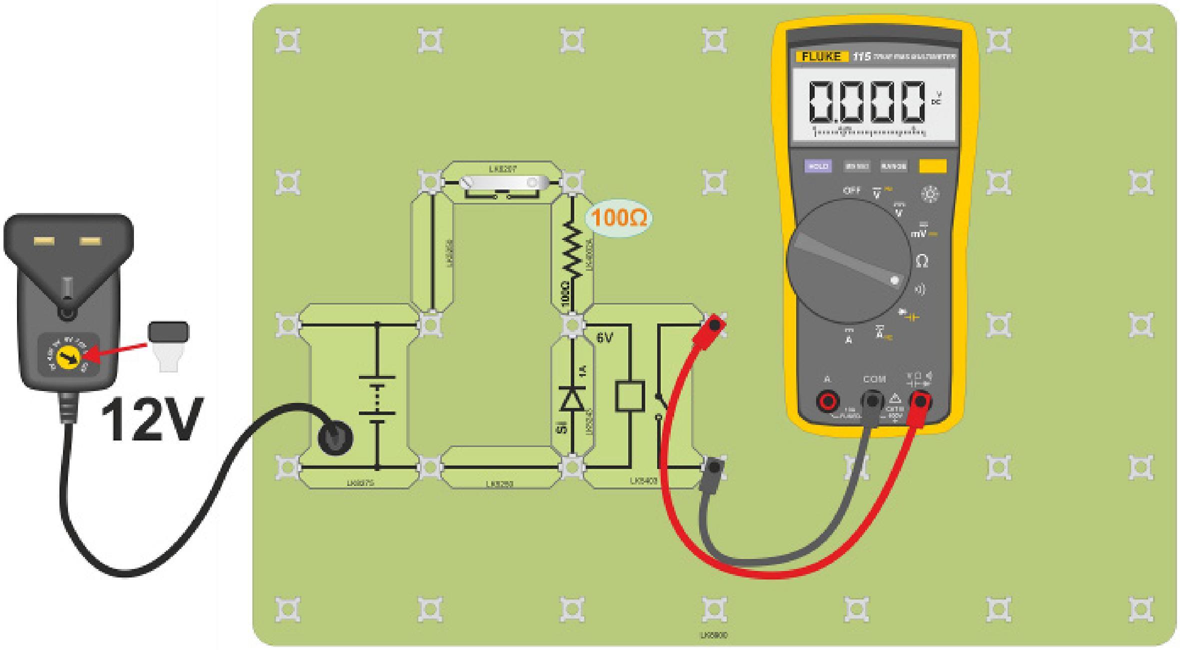
Challenge

Use the multimeter to measure the current in the solenoid as it operates. Calculate how much power the solenoid consumes.
Research some applications of solenoids. What properties of the solenoid make it suited to such applications?

The linear motion of the solenoid is well suited to operating a switch. A component containing a coil and a set of switch contacts mechanically linked together is known as a relay. When a current flows through the coil, a magnetic field is created which magnetises the core. This attracts a pivoted armature to it. As it moves towards the core, it rocks around the pivot and closes a pair of contacts in the process.



At first glance, this does not seem all that useful since we need a switch to operate the solenoid to begin with. However, this arrangement can have a number of advantages. One is that it is possible for the circuit that controls the coil and the circuit that is switched to be electrically isolated. The control circuit can operate at safe low voltages and low currents while the switched circuit could use high voltages or currents. Another is that one relay can operate multiple switch contacts, possibly with quite complex arrangements.



Over to You

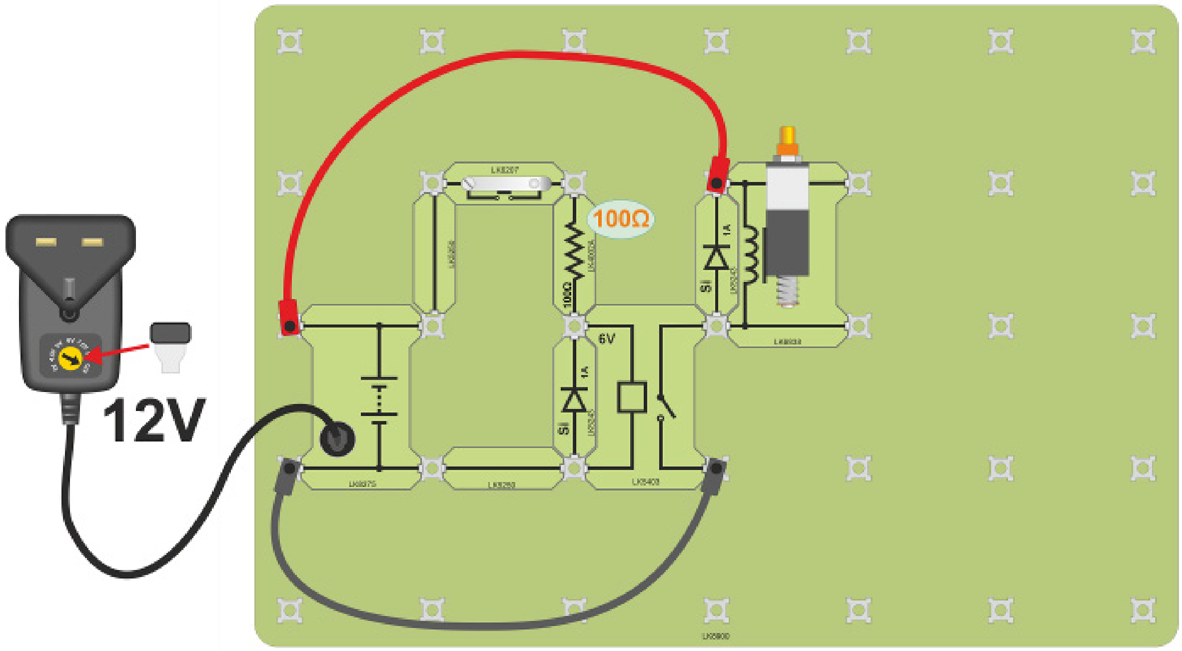
- Build the circuit shown.
- Set the power supply to 12V and plug it in.
- Set the multimeter to continuity (beeper) mode.
- What happens when you press the switch?
- How is this circuit different to simply connecting the multimeter to a switch?

So What?

In this circuit, the relay is simply acting as a switch. The difference here is that the multimeter is isolated from the power supply. The current through the switch contacts of the relay that causes the multimeter to beep is supplied by the internal battery of the multimeter.
The other components of note in this circuit are the 100Ω resistor that drops some of the voltage so that we do not have the full 12V across the 6V relay coil and the diode that re-circulates the back e.m.f. generated as the relay switches off.

Over to you

The next circuit illustrates how a solenoid actuator can be operated from a remote switch, using a relay. It demonstrates how a small current in the control circuit can switch a much larger current. The circuit includes two diodes, connected across the inductive components to prevent any damage to other components when the relay coil or solenoid de-energise.



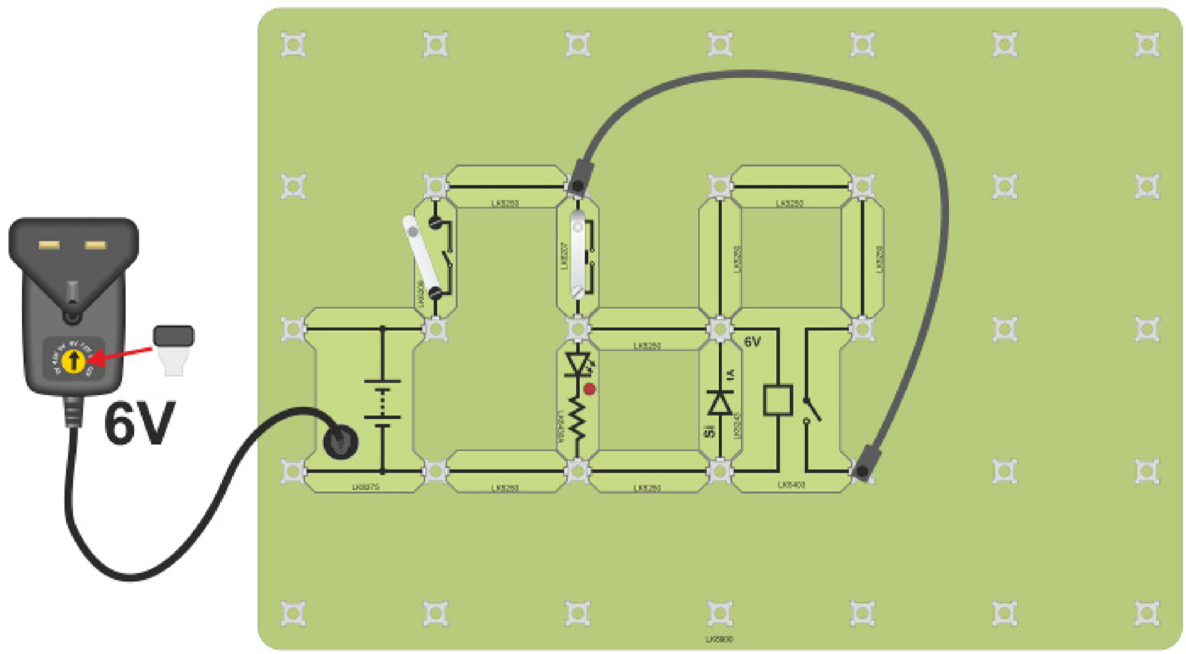
- Remove the multimeter from the circuit.
- Add the solenoid as shown.
- Check that the power supply is set to 12V and plug it in.
- What happens when you press the switch?

So What?

The push switch is not operating the solenoid in this circuit. It is only switching the small current in the relay coil. The switch contacts of the relay are switching the higher current in the solenoid. Note that there are two inductive components in this circuit so there are two diodes to provide paths for the back e.m.f.

Challenge

Use the multimeter to measure the voltage and current of the relay coil and that of the solenoid. Calculate the power in each component.



Over to You

- Build the circuit shown.
- Set the power supply to 6V and plug it in.
- Close the toggle switch and then press the push switch. What happens to the LED?
- Release the push switch. What happens to the LED now? Can you explain why?
- What do you have to do to put the circuit back into the state it was in when first switched on?

So What?

The circuit that we have constructed here is called a latching circuit. When the push button is pressed, the relay coil is energised. When the relay coil is energised, its switching contacts close. The switching contacts are wired in parallel with the push switch. This means that releasing the push switch has no effect, the relay contacts continue to conduct current. What we have created is an electrical memory; the circuit remembers that the switch has been pushed. The memory in a computer works in the same way. It uses very small semiconductor switches in integrated circuits and stores much more than one bit of information but the principle is the same.
Typically, if a relay is to be used as a latch then a relay with more than one set of contacts will be chosen. It is common to find 'Double Pole' relays which have two sets of switching contacts. There is no limit to the number of contacts that could be mechanically connected in a relay. Many different configurations are available.

Challenge

Have a look at the website of an electrical component supplier. How many different configurations of relay can you find?

Worksheet 23 – Transformers

We know that electric current flowing in a coil creates a magnetic field. When we studied solenoids, we saw that a changing magnetic field induces a back e.m.f. (electromotive force) in the coil. Imagine if we had two coils sharing the same space, the current in one coil would produce a magnetic field and that magnetic field would produce a current in the second coil.

Such a component is called a transformer. The coils can not physically occupy the same space but they can be positioned close together. A ferromagnetic core can concentrate the magnetic field and also direct it in a way that couples the two coils together.

The coil that we put energy into is called the primary coil. The coil that we take energy out of is called the secondary coil. Some transformers can have more than one secondary coil.

The power coming out of a transformer is always less than the power put in because there are losses within the transformer. In a very efficient transformer, the losses are small and most of the power is transferred. In a less efficient transformer, the losses can be significant.

If the coils are the same size then the voltage at the secondary coil will be the same as that at the primary. This is called an isolation transformer, it does not change the voltage but it does provide an isolation between the two circuits.

If the number of turns of the secondary coil is greater than the number of turns of the primary then the output voltage will be greater. This is called a step-up transformer. However, everything comes at a price; if the voltage is stepped up the current is stepped down. This means that more current must be supplied at the primary.

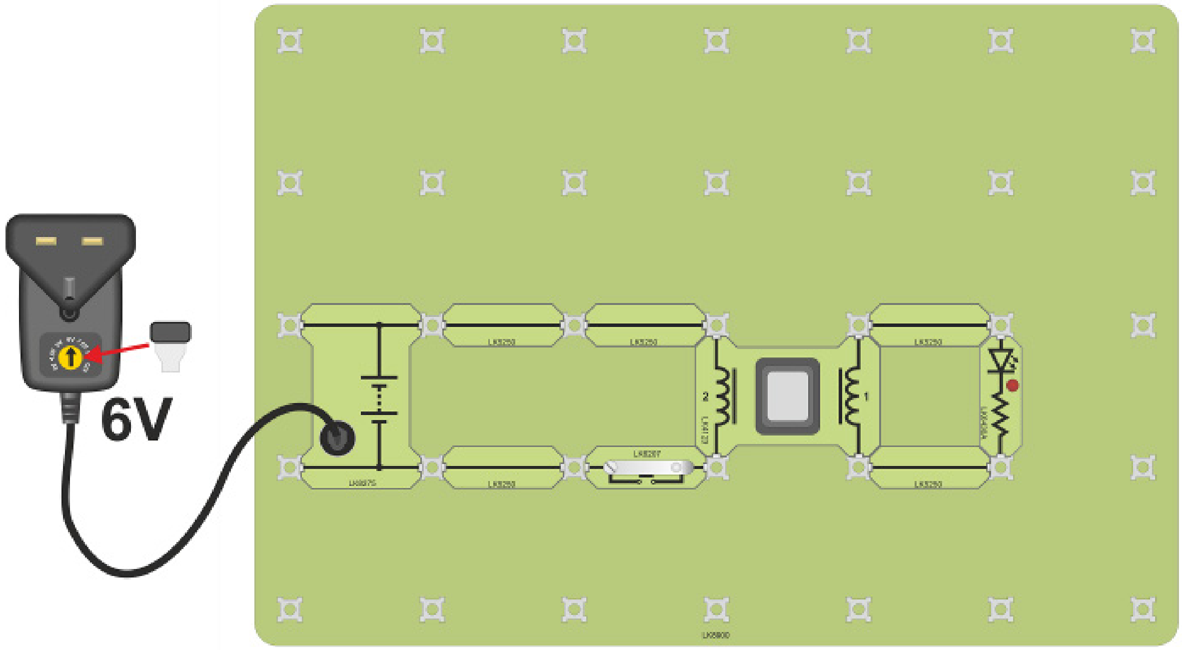
If the number of turns of the secondary is less than the primary then the output voltage will be smaller. This is called a step-down transformer. If the voltage is stepped down then the current is stepped up so less current is required at the primary.

A national electricity grid uses both step-up and step-down transformers. At a power station, the output voltage is stepped up (typically to 11kV or higher). By doing so, a smaller current is needed to transmit a given amount of electrical power and so less energy is wasted in the transmission cables. At the substation, a step-down transformer then lowers the voltage to the level used in homes and businesses, typically to 220 V or 110 V.

In the home, step-down transformers are commonly, used as battery eliminators for electronic devices such as computers, televisions, and mobile phones. The Matrix Locktronics power supply also uses a step-down transformer. The step-down transformer outputs an AC voltage which then needs rectification to DC and smoothing before being used as a power supply.

Over to you

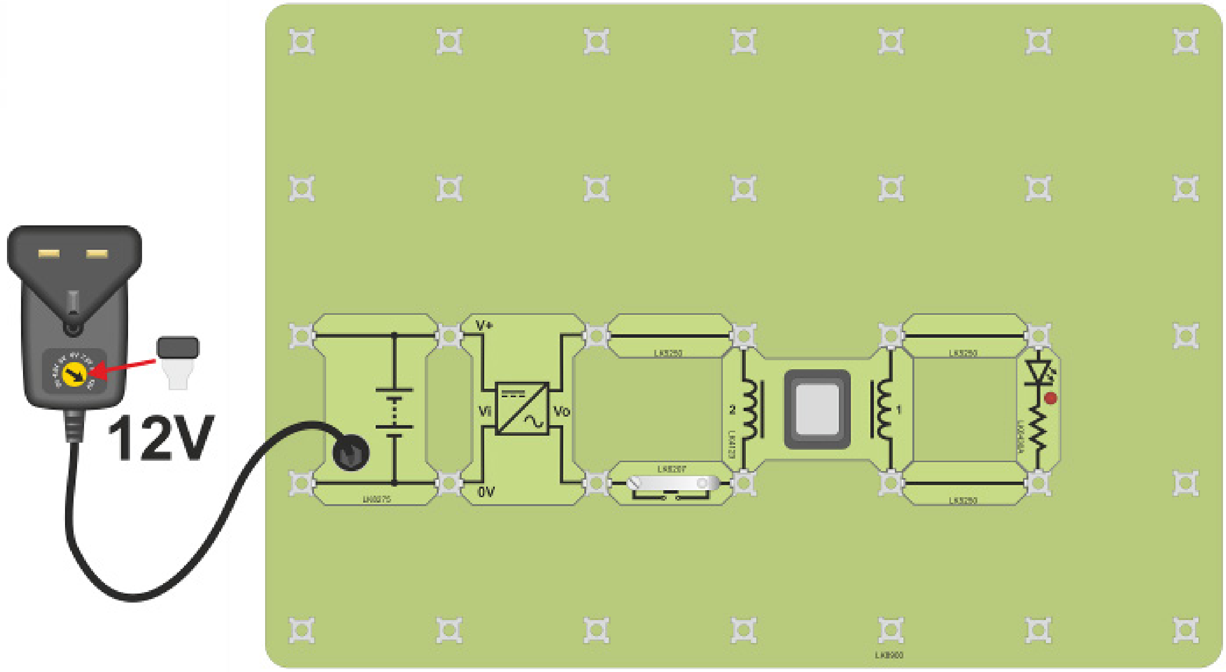
In this activity, we use a small transformer that is not very efficient, with a turns ratio of 2:1, meaning that one coil has twice as many turns as the other. The primary will be the '2' coil, and the secondary the '1' coil. The numbers refer to the turns ratio so the primary has twice as many turns as the secondary.



- Build the circuit as shown.
- Set the power supply to 6V and plug it in.
- Press the switch a few times and watch what happens to the LED. What does this tell you about the operation of a transformer?

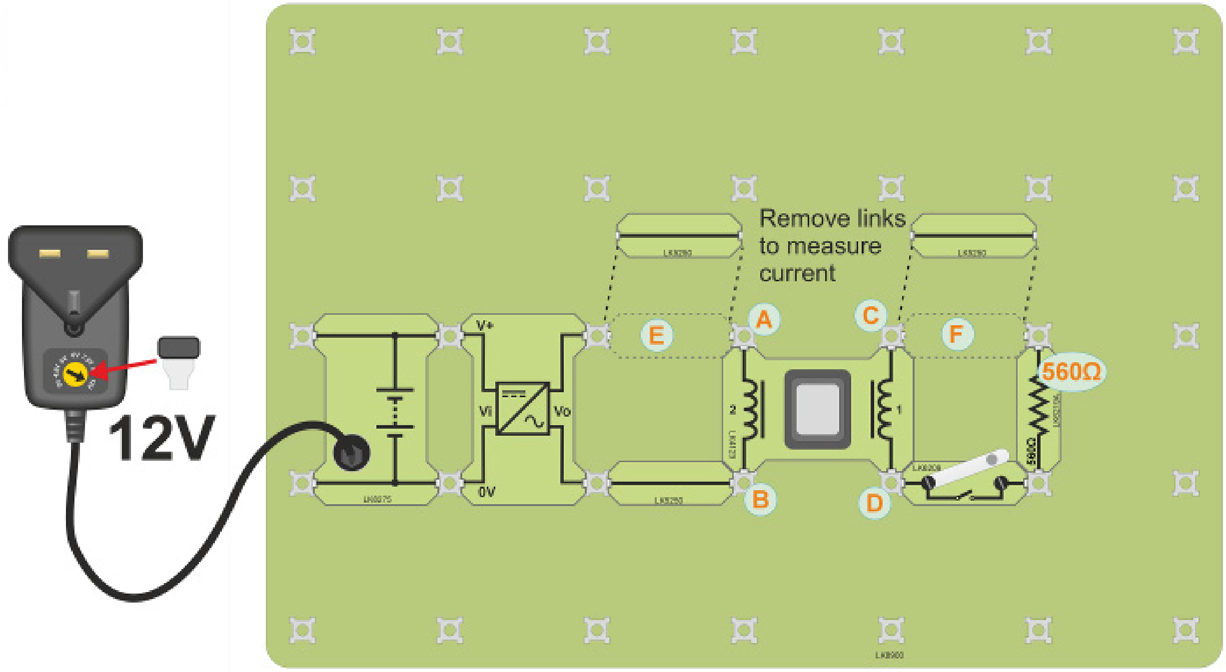
So What?

For current to be induced in the secondary coil, the magnetic field must be changing. This only happens when the current in the primary is changing. When we supply our circuit with DC, a small amount of energy is transferred at the instant that we push the switch. In a DC circuit, the transformer is not a very useful component.

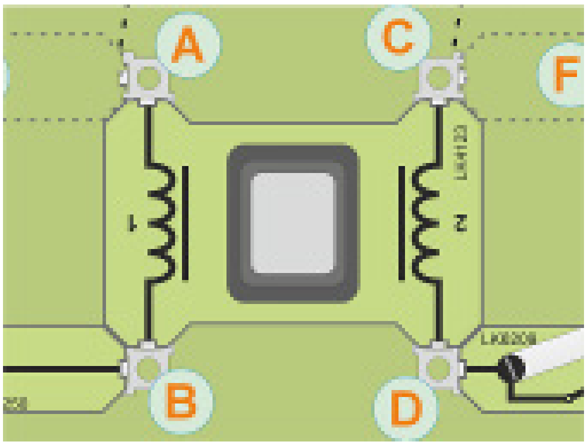


Over to You

- Build the layout shown above.
- Set the power supply to 12V and plug it in.
- Press the switch and observe what happens to the LED now?
- Build the next layout shown with a 560Ω resistor in place of the LED. Note that this circuit has a toggle switch on the secondary side.
- Set the multimeter to AC voltage mode.
- With the switch open, measure the primary voltage between points A and B. Measure the secondary voltage between points C and D.
- Set the multimeter to AC current mode.
- With the switch still open, remove the link at point E and measure the current in the primary coil.
- Close the switch and measure the primary current again.
- Replace the link at point E. Remove the link at point F and measure the current in the secondary coil.
- With the switch still closed, measure the primary and secondary voltages again.
- Record all your measurements in the student handout.



- After recording all the measurements, rotate the transformer through 180 degrees. This means that the coil labelled “1” will be the primary. Record the voltages and primary current with the switch open.
- Close the switch and record both currents and voltages. What do you notice?
- For each set of measurements, calculate the power into the primary side and out of the secondary side. What do you notice? Calculate the efficiency of the transformer in each case.



So What?

When we built the circuit with the “2” on the primary side, the transformer functioned as a 2:1 step down transformer. The voltage was roughly halved and the current doubled. There were some losses observed in the system . When we rotated the transformer so that the “1” was on the primary side, it functioned as a 1:2 step up transformer. The voltage was roughly doubled and the current was roughly halved.

The ratio $V_P : V_S$ for both types of transformer is related to the turns ratio.
The transformer relation says that for an ideal transformer:

$$V_P / V_S = N_P / N_S$$

where N_P is the number of turns on the primary coil;
and N_S is the number of turns on the secondary coil.

In general terms:

- a step-up transformer 'steps up' the voltage (here, virtually doubles it,) but 'steps down' the current - the primary current is much greater than the secondary.
- a step-down transformer 'steps down' the voltage, but it delivers the same secondary current as before for a much smaller primary current.
- For an ideal transformer (100% efficient):
-

$$P_{IN} = P_{OUT}$$

where P_{IN} is the power delivered to the primary,
and P_{OUT} is the power delivered by the secondary;

and $I_S / I_P = N_P / N_S$

A transformer changes the 'format' of the electricity supply, but at a cost in terms of energy wasted.

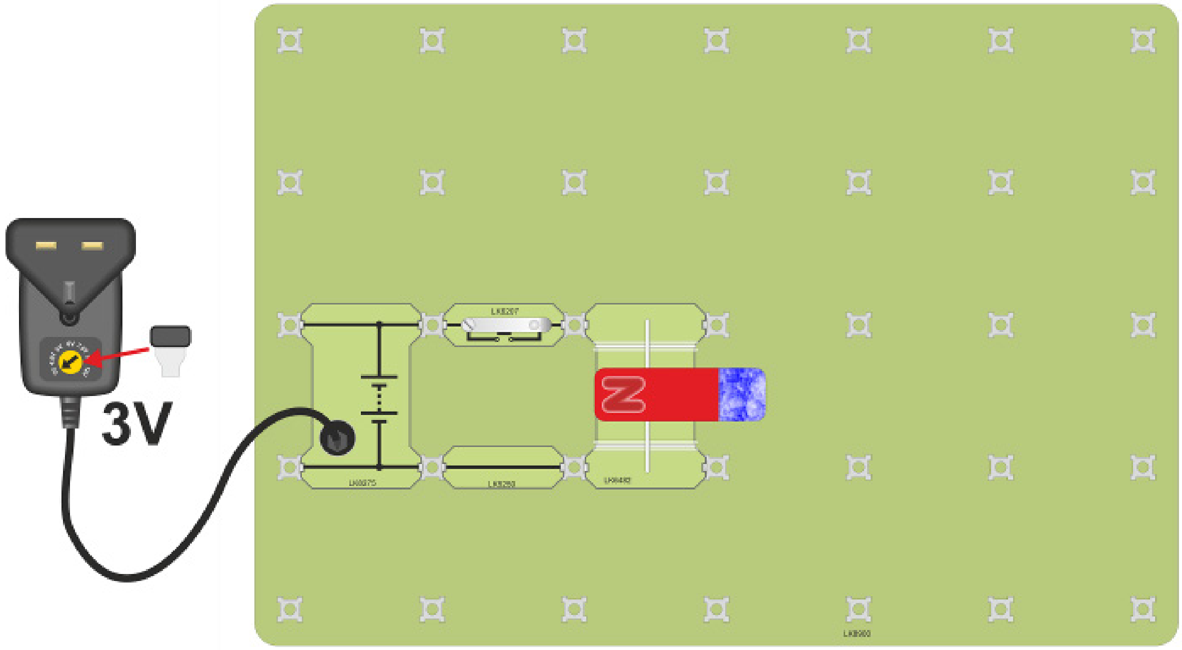
Worksheet 24 – Motor Principles

We have seen that electromechanical components can produce small mechanical movements. There are many applications where larger movements are useful and particularly the continuous rotary movement of an electric motor.

Electric motors come in all shapes and sizes. Some run on DC power, others need AC. Approximately 40% of all electricity used worldwide is consumed by electric motors of various types.

Motors drive pumps, fans, compressors, conveyors, winches, vehicles and much more.

Within a vehicle, motors operate windows, windscreen wipers, fans and pumps. They may start an internal combustion engine or they may be the main motive power of the vehicle.



Over to you

This investigation uses the motor-effect carrier, shown opposite. It has two fixed conductors, with a moveable metal rod resting on top, across them.

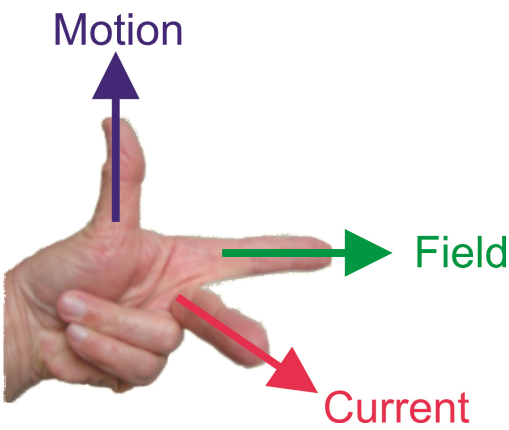
- Build the system shown in the diagram. The magnetic yoke is positioned so that one magnet is below the Locktronics carrier and one is above it. Position it so that the moveable rod is in the middle of the magnetic field.
- Set the power supply to 3V and plug it in.

- Press the push switch, and notice what happens.
- Next, flip the magnet over so that the South pole is on top.
- Press the push switch again. What is the difference?
- Reverse the current direction by rotating the power supply carrier so that the negative end (short line on the symbol) is at the top.
- What happens now when you press the push switch?
- Change the power supply voltage to 6V. This should increase the current flowing through the rod.
- Can you see any difference when you close the push switch?

So What?

Here's the underlying theory: -
When an electric current flows, a magnetic field is created. Thus, any conductor becomes an electromagnet.
Magnets interact with each other with opposite poles attracting and like poles repelling.
When a current flows within an existing magnetic field, the two fields interact causing a force that can move the conductor.

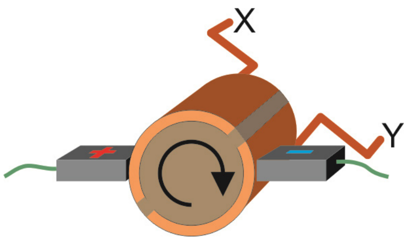
Fleming's Left-hand Rule:
John Ambrose Fleming devised a way to work out the direction a conductor will move (also known as the motor rule): -
Clamp your left-hand to the corner of an imaginary box, so that thumb, fore finger and centre finger are all at right-angles to each other.
Then, line up the Fore finger points along the magnetic Field (from North pole to South pole,) and line up the Centre finger with the Current (from positive battery terminal to negative.)
The thuMb now points in the direction of the resulting Motion.



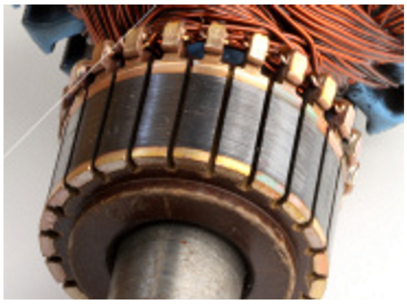
Rotating Motors
Electric motors usually consist of a coil rotating inside the magnetic field of either a permanent magnet or an electromagnet. From what we have just learned, we can see how the motor effect could give a half turn. We also saw that reversing the direction of the current reverses the direction of movement. In a practical electric motor, the coil must rotate in one direction for part of the rotation and then the opposite direction on the opposite side of the rotation. They rotate because the current reverses at just the right time.

So What?

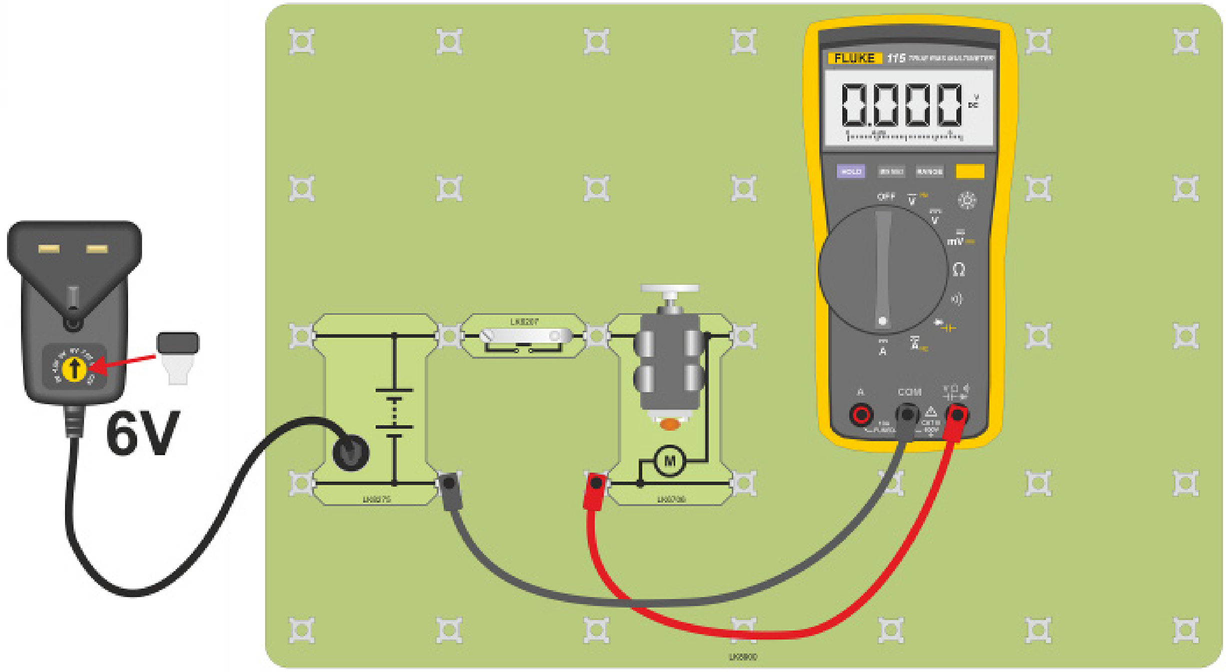
There are two ways to reverse the current:
use ***slip-rings*** with brushes:
The picture shows one form of slip-ring.
Each end of the coil is connected to its own full brass ring.
Electrical contact is made to each ring with a carbon brush, which moulds itself to the shape of the ring, reducing contact resistance.
The coil is supplied with AC, and so the current automatically changes direction in step with the mains supply.



DC motors use a ***commutator*** with brushes:
The diagram shows the design of a simple commutator, a brass drum, split into two halves, separated by an insulator.
Electrical contact is made by carbon brushes.
The coil is connected to the two halves at X and Y.
As the coil rotates, X is connected to the positive supply for roughly half of the time, and then to the negative supply. At all times, Y is connected to the opposite supply to X.



The maximum force is created as the coil is at ninety degrees to the magnetic field. Many more powerful motors have multiple coils. This requires a commutator split into many segments as pictured here.



Over to You

This investigation uses the Locktronics DC motors. It has a commutator and carbon brushes.

- Build the system as shown.
- Set the power supply to 6V and plug it in.
- Press the push switch, and watch the ammeter reading.
- Next, keep the push-switch closed, and press gently on the motor shaft, or against the plastic wheel attached to it, to slow down the motor. Watch the ammeter reading as you do so.
- Record your measurements.

So What?

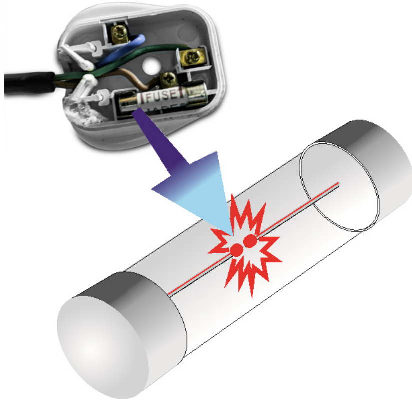
When a coil spins round inside a magnetic field, it generates a voltage. The faster it spins, the greater the voltage and this voltage opposes the external voltage producing the motion.

As a result, at full speed, the overall voltage, and so the current, is reduced. Putting it another way, when we ask the motor to do more work, spinning against the extra friction of us pressing on the axis, it needs more current.

WORKSHEETS

Worksheet 25 – The Fuse

The power supply that we have used so far gives a safe low voltage and can provide only a limited current. Mistakes or faults in our circuits do not have serious consequences. Electrical installations using higher voltages can be dangerous; particularly if they are capable of providing high currents. If something were wrong with a circuit, wires or components could overheat. This could lead to serious damage or even fire.
In all practical systems, safety must be considered.
Fuses are designed to be a weak link. In the event of a fault, the fuse breaks in a safe manner before any other part of the circuit can dangerously overheat.



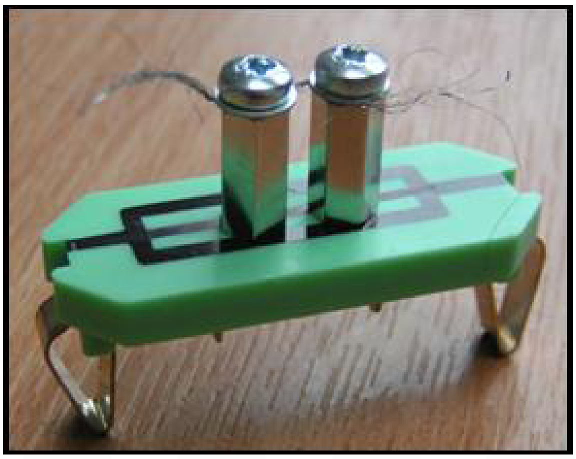
When we design an electrical system, we arrange for the current that powers the circuit to flow through a fuse. We look at each component in the circuit and check that it is sufficiently rated that it can handle the demands placed up on it. Components may be rated by voltage current or power. We ensure that any cables used are rated to carry more than the required current without overheating. When it comes to the fuse, we specify it to handle more current than the circuit uses in normal conditions but less than the rating of the rest of the components.

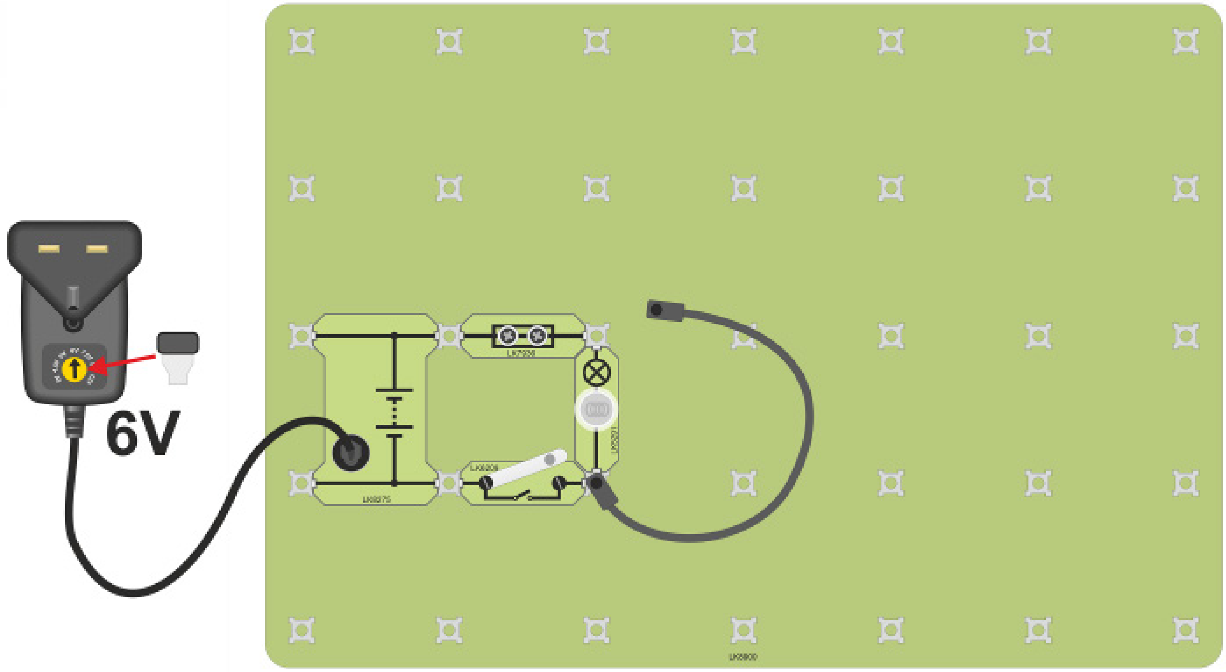
Normal Conditions < Fuse Rating < Component ratings

For example, if we expect a circuit to consume two amps, we might specify a three-amp fuse and a five-amp cable. If there is any fault that causes the circuit to draw more current than it should, the fuse would 'blow' and this would protect the cable and other components from overheating.

Over to You

- Find the fuse carrier component shown in the illustration.
- Loosen off the screws but do not remove them.
- Take the pack of steel wool and tease out a few strands.
- Clamp the strands of steel wool between the terminal pillars of the fuse carrier.
- Examine the undersides of the Locktronics links and other components. How do they compare to the strands of steel wool?
- Use the multimeter in resistance mode to measure the resistance of your fuse.



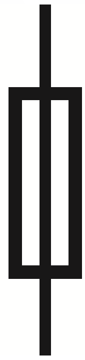


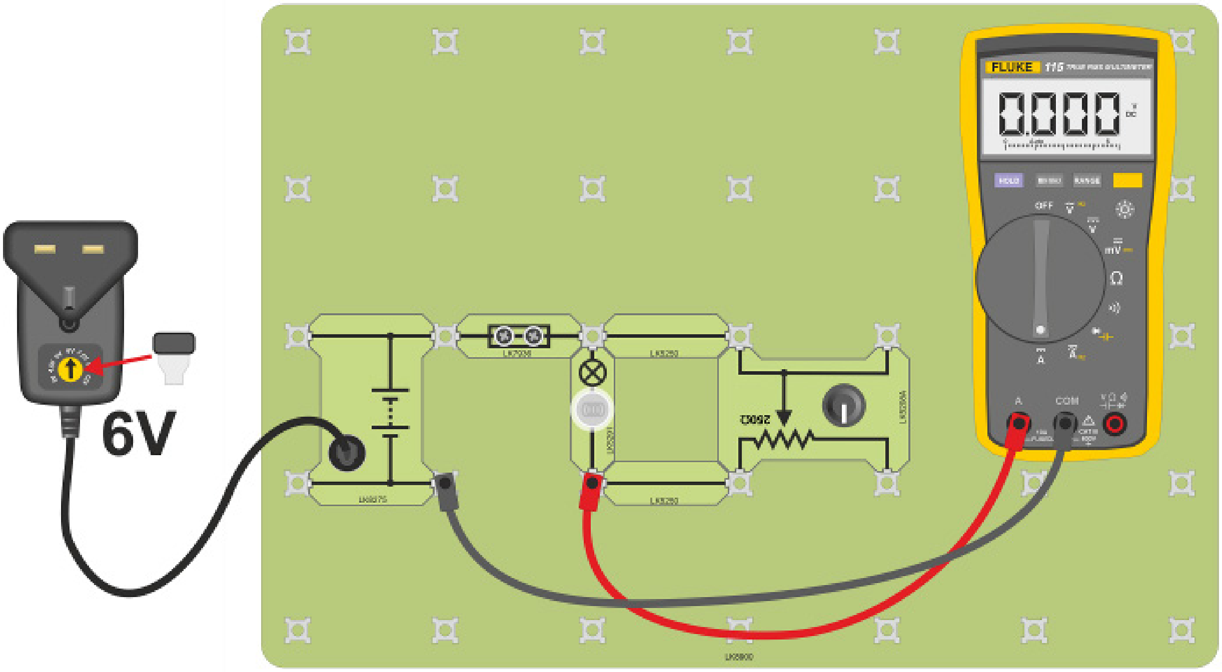
- Build the circuit shown in the diagram.
- Leave one end of the black lead loose. Make sure that it does not touch any part of your circuit.
- Set the power supply to 6V and plug it in.
- Close the switch and make sure that the lamp lights.
- Now create a fault in the circuit: Touch the loose end of the wire lead onto the pillar above the bulb. Watch the fuse carefully as you do this. What happens to the fuse?
- Remove the black lead. What happens in the circuit now?

So What?

When the circuit is working normally, the lamp sets the current. When you touched the black lead to the pillar, you short-circuited the lamp. The current can flow through the lead, bypassing the bulb. The power supply lead, connector, Locktronics pillars, and switch all have very little resistance. This means that a large current can flow.
The fuse had a small resistance and this caused it to heat up. Recall that P = I2R, this power was converted to heat. In a very short time, the fuse heated up until it glowed and then melted. After the fuse melted, there was an air gap and no path for the current to flow.
Look up the melting point of steel. How hot did the fuse get?
Feel the other parts of the circuit. Did anything else get warm?

This diagram opposite shows the symbol used for a fuse.
Our fuse was exposed so that we could see it in operation. In a practical system, fuses are protected so that hot metal and live parts are not accessible.
Fuses are a one-use item. After our fuse has blown, we must rebuild it. In the past, it was common for electrical installations to have re-wireable fuses. Wire of the required rating was installed in a fuse body. If it melted then the fault would be fixed and then the wire in the fuse replaced. In modern systems, fuses come in cartridges that plug in to fuse-holders in the installation.





Challenge

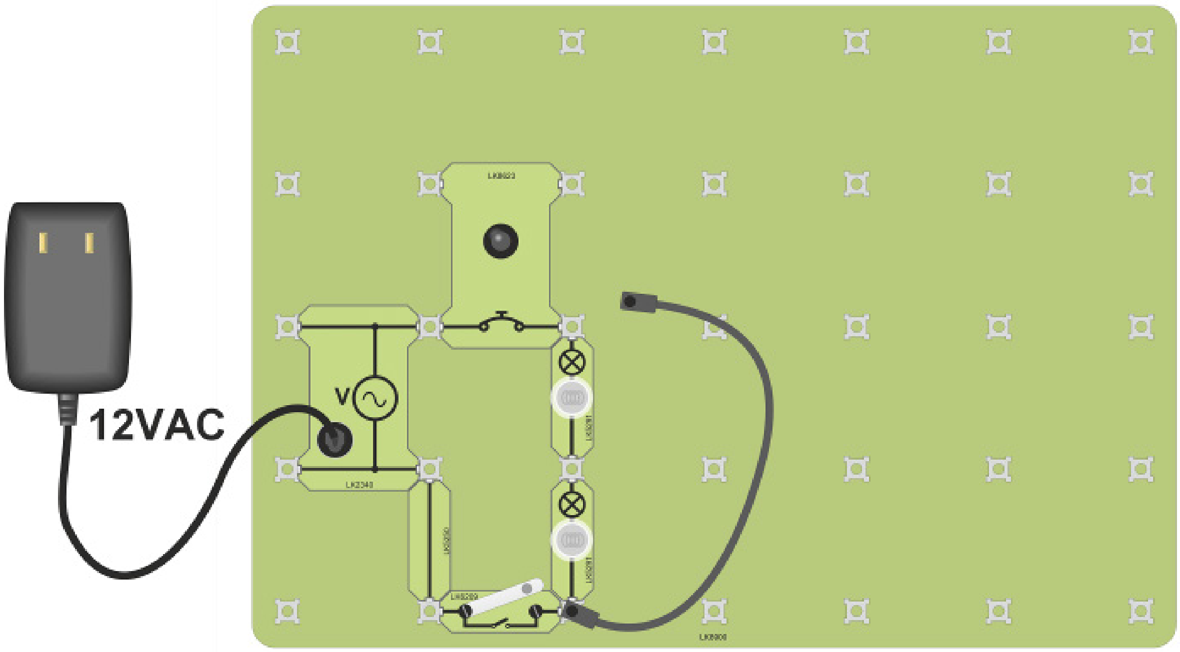
In this challenge, we will test our fuse to see what current it takes for it to blow.

- Build the circuit shown above.
- Turn the potentiometer fully anti-clockwise so that it provides the maximum resistance.
- Set the multimeter to DC current mode and connect it into the circuit.
- Set the power supply to 6V and plug it in.
- Check the current reading on the multimeter.
- Slowly turn the potentiometer clockwise to increase the current. At what current does the fuse blow?

Worksheet 26 – Circuit Breaker and RCD

The fuse is a very simple device for protecting circuits. Its disadvantage is that it works once and then needs to be replaced. We have seen that electromechanical components such as relays can be made to operate switches. This principle can be applied to creating resettable circuit protection devices.
In a modern distribution box, protection devices 'trip' when a fault occurs. The devices outwardly appear to be similar to toggle switches and can be switched on and off. When some fault occurs, an electromagnetic mechanism inside the device pushes the switch to the off position.

After the fault has been fixed, the device can be reset by manually by switching it back to the on position. Such a device can be used many times without the need for repair or replacement.



Over to You

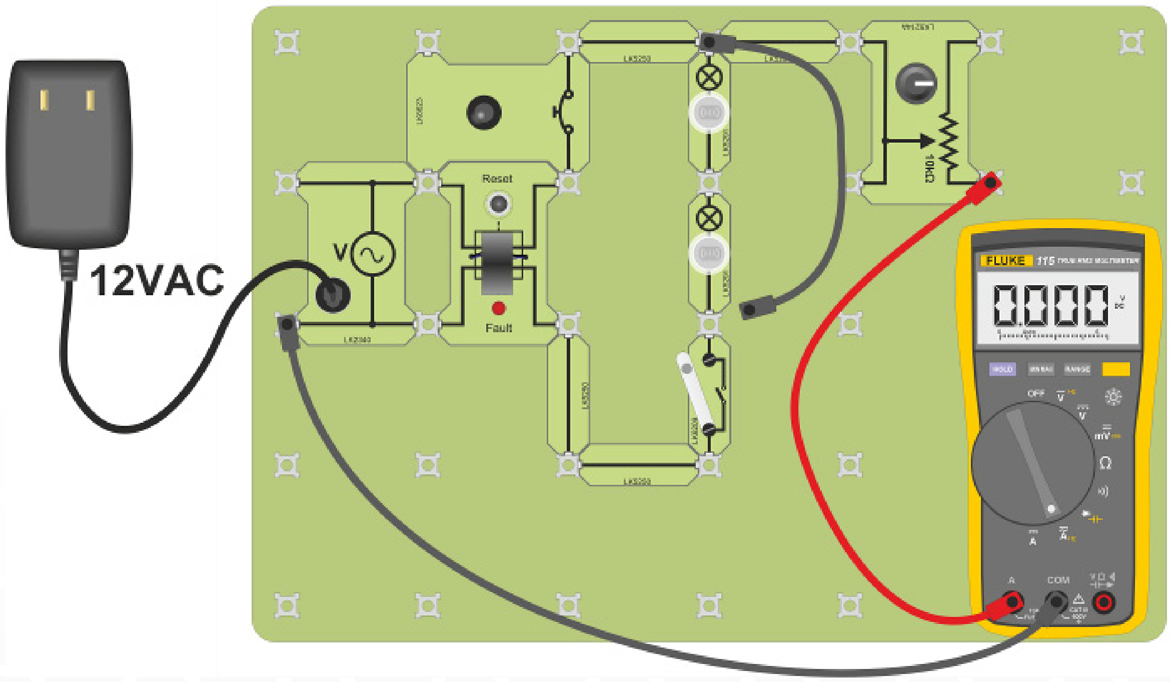
- Build the circuit shown in the diagram.
- Leave one end of the black lead loose. Make sure that it does not touch any part of your circuit.
- Note that this circuit uses the AC power supply which provides 12VAC. Plug in the power supply.
- Push the button on top of the circuit breaker to ensure that it is set.
- Close the switch and make sure that the lamps light.
- Now create a fault in the circuit: Touch the loose end of the lead to the pillar above the bulb. What happens to the circuit?
- Remove the black lead. What happens in the circuit now?
- Push the button on top of the circuit breaker and try again.

So What?

The circuit breaker contains two elements; a switch and an actuator. When the button is pushed in, the switch closes and allows the device to pass current. The rated current has little effect on the actuator and the rest of the circuit functions as normal.
When we made the short-circuit, a large current flowed. This large current very quickly caused the actuator to open the switch. This breaks the circuit and stops the current from flowing.
Once the fault is removed, pressing the button will reset the circuit breaker. The circuit is now restored and will work as before.
A circuit breaker is a more complex device than a fuse and is generally more expensive. It has the advantage over a fuse that it can be reset and continue to work.
Many electrical installations include circuit breakers. In a domestic setting, a modern consumer unit contains devices known as miniature circuit breakers, (MCBs). Each MCB protects one circuit such as a ring of sockets or the lighting on one floor.

The circuit breaker protects against the large currents that can flow in the case of an overload or short circuit. Not all faults will result in large currents. At the voltages that are used in domestic settings, even relatively small currents are enough to cause severe injury or death. The next device that we will study protects against small 'leakage' currents. These are currents that are smaller than the normal operating currents of the circuit but are flowing somewhere they should not be. This could be the current delivering an electric shock when a person touches a faulty appliance.

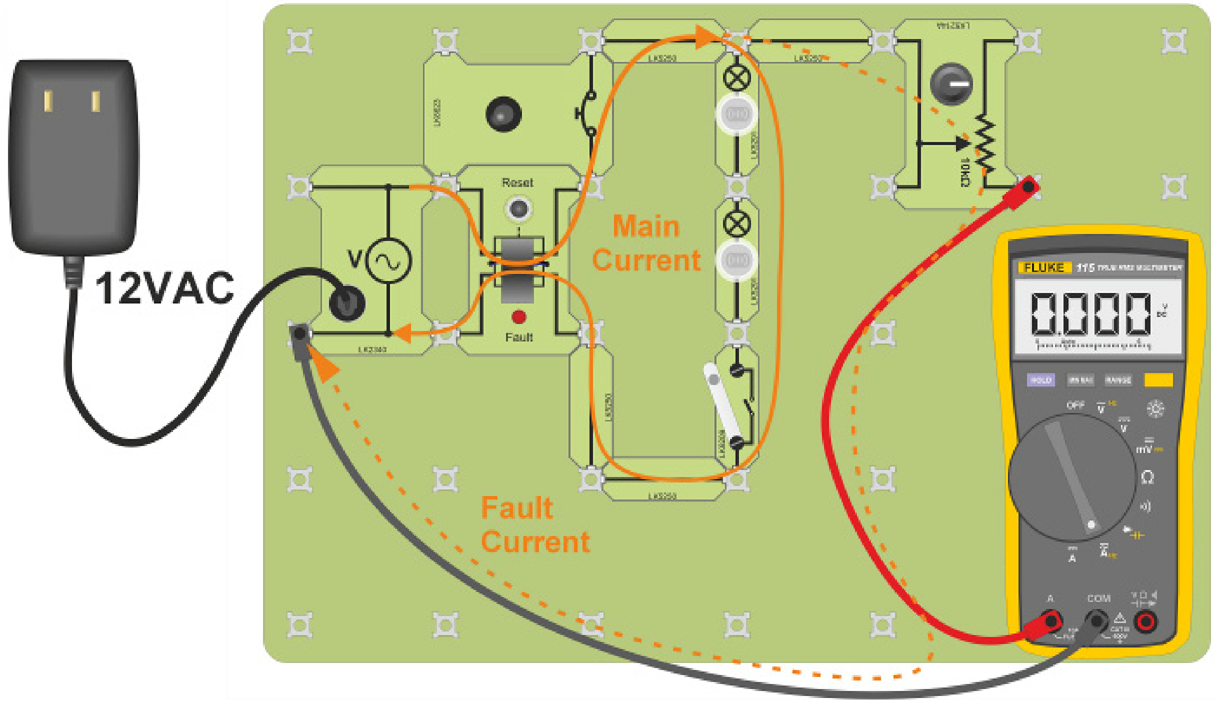
Over to You



- Build the layout shown.
- Turn the potentiometer fully anti-clockwise so that it gives its maximum resistance.
- Set the multimeter to AC current mode and connect it as shown.
- Connect the AC 12V power supply and switch on.
- If the red 'Fault' indicator on the RCD component shows, press the 'Reset' button.
- Check that the lamps can now be controlled using the toggle switch. This is the normal operation of our circuit.
- Connect the lead to short-circuit the lamps. Which device trips?
- Remove the short-circuit and reset the device that tripped.
- Slowly rotate the potentiometer clockwise, noting the reading on the multimeter as you do.
- Make a note of the reading that you get just before the circuit trips. Which device tripped this time?
- Turn the potentiometer anti-clockwise and reset the device that tripped?
- Repeat the test with the lamps switched on and with them switched off. Does it make a difference whether the lamps are on?

So What?

Our circuit has two protection devices that both do very different jobs. We have already seen that the circuit breaker protects against the large currents of an overload or short circuit. The residual current device (RCD) has a much more subtle operation.
On the top of the RCD is a current transformer (CT). The core of this transformer is the shape of a toroid ring. The secondary coil is wound around the core and is encapsulated in the plastic casing. The primary coil of the current transformer is a single wire passing through the centre of the core. This makes it a one-turn coil. The current in this wire induces a smaller current in the secondary that is detected by a measurement circuit.
Look closely at the RCD, you will see that there is not one but two wires going through the centre of the current transformer. One of these wires is carrying current out to the circuit, this is equivalent to the live wire in an electrical installation. The other wire is carrying the same current back from the circuit, this is equivalent to the return or neutral wire in an installation. Since the two wires are carrying current in opposite directions, they are producing magnetic fields in opposite directions. These magnetic fields cancel each other out. In normal operation, the current supplied to a circuit is exactly equal to the current returned. Whether the current is large or small, no current is induced in the secondary coil of the current transformer. The RCD never detects the normal current in the circuit.

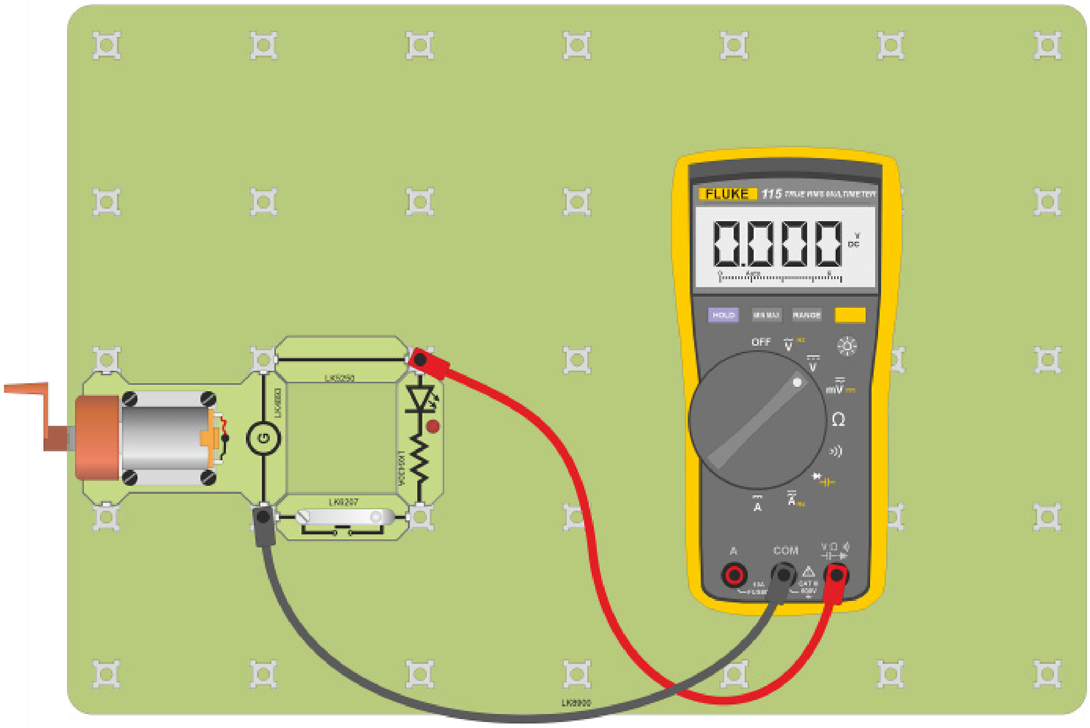


If there is a fault that causes some current to run to earth then there will be in imbalance between the two wires. The RCD detects the difference in currents between the two wires. This difference is equal to the fault current. When the fault current reaches some preset value the RCD ‘trips’, shutting off the electricity supply. In a typical domestic installation there may be several circuit breakers (MCBs) with trip levels from a few amps to tens of amps depending on the circuit that they are protecting. There is usually one or two RCDs. The RCD supplies current to several MCBs and trips when it detects a fault current. The RCD in a domestic installation is typically rated at 30mA but most will trip well below this level.

Appliances that have metal cases should have an earth connection to the case. This way, if fault were to occur inside, the fault current would be conducted to earth by the cable and not by the user who inadvertently touched the case. Either way, if a current flows to ground, there will be an imbalance and the RCD will trip. Appliances that have plastic cases do not need an earth connection but the case should be strong enough to prevent a user from touching live parts.

Worksheet 27 – Generating Electricity

Where does electricity come from? Electricity can come from electrochemical processes in batteries or from photovoltaic effects in solar panels. A lot of electricity is derived from mechanical energy. Windmills, steam turbines, hydroelectric and diesel generators are all sources of rotating mechanical energy that is converted to electricity using an electric generator.
In this worksheet will look at a small, hand-cranked generator. We shall see how the generator produces electricity and how the electrical load affects it.



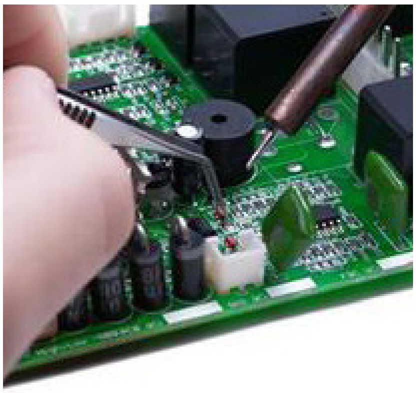
Over to You

- Build the layout as shown.
- Set the multimeter to DC voltage mode and connect as shown.
- Gently, turn the handle on the generator. Note the voltage displayed. Is the voltage positive or negative? What happens when you turn the handle the opposite way?

- Turn the handle so that the meter displays a positive voltage. While still turning the handle press the push switch. (You might find it easier to have a friend push the switch while you continue turning the handle.) The LED bulb should light. If it does not, turn the handle in the opposite direction. (The generator outputs DC. The current must flow in the right direction to make the LED light.) What happens to the voltage when the switch is pushed? What do you feel while turning the handle?
- Replace the LED carrier with a lamp. Turn the handle again. How does this compare to the LED?

So What?

We have already seen that an electric current flowing in a magnetic field creates a force that can produce physical movement. Now we look a complimentary effect: when a conductor moves in a magnetic field, an electric current is induced.
This is similar to the way that we saw current induced in the secondary coil of a transformer. The difference is that, in the transformer, the coil was stationary and the magnetic field was moving. Here we shall have a stationary magnetic field and a moving coil.
This arrangement sounds very similar to an electric motor an in fact it is. Physically, our generator is constructed in the same way as a motor. The only difference is that the generator has a crank so that we can put mechanical energy in and get electrical energy out.
When we pushed the switch, we suddenly felt more resistance. Where did that come from? The simple answer is that the LED and lamp were consuming energy. If more energy is taken out, more energy must be put in. This is complimentary to an effect that we have already seen when we studied the electric motor.
The motor spinning freely consumed a smaller amount of current because the spinning coil generated a voltage that opposed the applied voltage thus reducing the current. Loading the motor slowed down the rotation, this reduced the opposing voltage and lead to a higher current. More mechanical energy out, requiring more electrical energy in.
In the generator, adding an electric load draws current from the generator. This electric current creates a force that opposes the movement driving the generator. More electrical energy out requires more mechanical energy in. Nothing comes for free!



Designing an electronic system is only the start. Making a reliable system that can be manufactured repeatably and reliably is another discipline. Troubleshooting when it goes wrong is another thing again. All stages are challenging, rewarding and require a solid understanding of the underlying electronics theory. Although engineers will often specialise in or prefer one particular stage, it is important to understand the whole life-cycle of a product. Successful fault finding calls for a particular skill set, including the ability to plan, think logically, use test equipment and keep detailed records.

In this field, nothing is more valuable than experience. The exercises you will be working through aim to start off the process of building that experience.

Five Steps to Fault Finding

- **Step 1 - Prepare**
  - Are there any safety issues? If any part of the system uses unsafe voltages, make sure that they are isolated. If working on site, make sure that your working area is safe.
  - What information can be learned from the failure report whether written or verbal? Bear in mind that the report may not be entirely accurate. Operators will often tell you, "I was nowhere near it and it just stopped working!"
  - Gather the test equipment, tools and spare parts that you intend to use.
  - Document what you are doing!
- **Step 2 - Observe**
  - How is the system supposed to work? Is a manual available? Sometimes, what is reported as fault is simply someone not understanding the operation of the system.
  - Is there a working example of the same product that can be used as a comparison?
  - Are there signs of damage - overheated components, melted insulation, frayed wire, bad solder joints?
  - Can you smell burning or overheating?
  - What parts of the system are accessible and could be used for testing or measurement.
  - Document your findings!
- **Step 3 - Identify the problem subsystem**
  - Which subsystems are operating correctly?
  - Where does the problem seem to lie?
  - Is a schematic or any design documentation available for that part?
  - Document your findings!

- **Step 4 - Suggest possible causes**
  - Look at the connections and components in the faulty subsystems. Try to imagine what could go wrong with each, would that cause the observed fault.
  - Check connections: -
    - look for faulty connections or loose contacts which may offer high resistance.
    - look for stray connections that can short-circuit.
    - look for breaks that create open-circuit conditions.
  - Check likely components: -
    - Switches, fuses and bulbs tend to wear out or burn out.
    - Electrolytic capacitors have a finite lifetime.
    - Some components can be damaged by overload such as an incorrect power supply.
  - Document your findings!

- **Step 5 - Test and repair**
  - Be safe! Remember -
    - capacitors can store electrical charge and give electric shocks;
    - inductors can store energy in a magnetic field and give electric shocks.
  - Take measurements around the circuit, but mentally predict what they should be.
  - In this way, home in on the problem components, and replace them, observing all safety procedures.
  - Next, re-test the system to ensure that no other faults exist.
  - Document your findings!

Why Document Your Findings?
Do you remember what you had for breakfast the day before yesterday? Some people have better memories than others. When fault finding, it is common to overestimate your memory. Often things that are very clear in your short-term memory will not make it to your long-term memory.
Every fault-finding task is a learning opportunity that contributes to your increasing experience. Writing things down helps to reinforce that learning and gives you a resource to refer back to.
Many faults re-occur, sometimes years later and keeping records means that you will find the fault quicker the next time and save yourself a lot of hassle. Even if the fault is caused by a different component the next time, the things that you have already observed about the system will come in useful.
The next time the machine goes wrong, it might not be you that fixes it. Your documentation can be of great help to the person that takes over.

Time is of the Essence

In fault finding, time is of the essence, for a number of reasons:

- The electronic system may play a part in keeping people safe. While it is faulty, their safety must not be compromised.
- In a commercial setting, the system may be filling a valuable role. All the time that it is offline, its value is missed. For example, while a piece of a production line is broken, no product can be made.
- A company may have to pay for staff and premises even though the faulty system is not generating any value.
- If you are being paid to repair the system, then your time is part of the repair cost. The longer it takes, the more expensive the repair.

Remember: -

- Your time has a value and the system that you are repairing has a value. At a certain point, your time becomes more expensive than the cost of scrapping and replacing the faulty machine.
- “Short cuts make long delays.” (J.R.R. Tolkien) Even when the pressure is on, a logical, methodical approach may prove to be the fastest means to solve the problem.

Comparisons

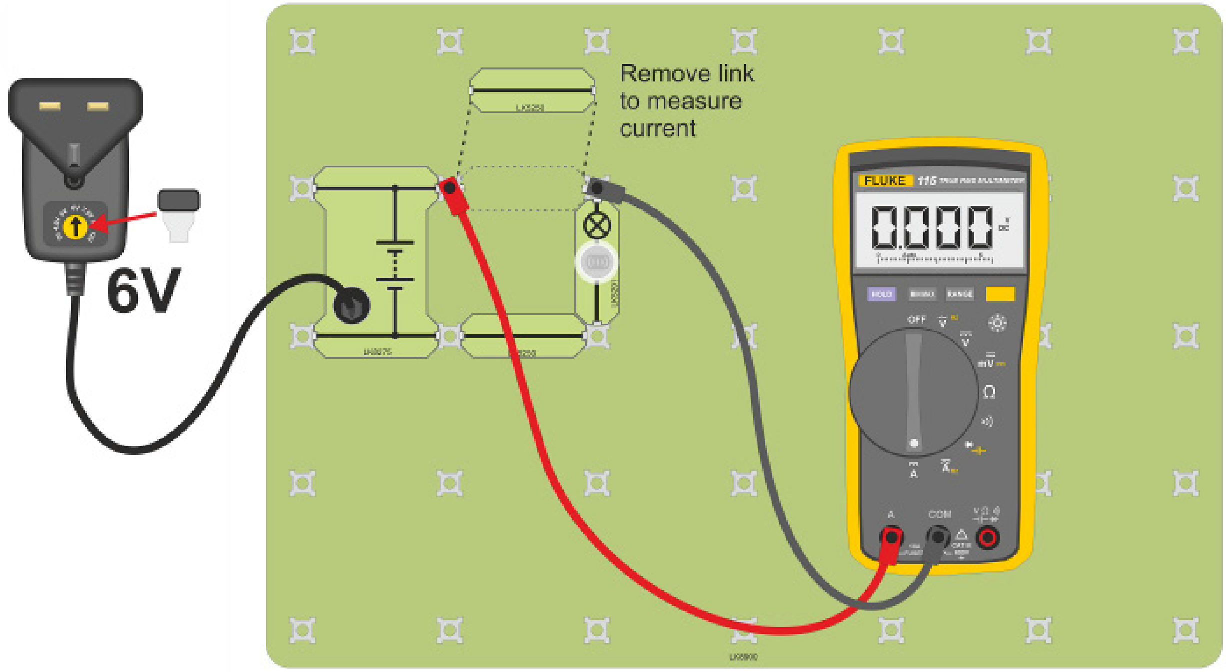
If a working example of a product is available, then comparing the faulty product with the working product can often be a very effective means of homing in on a fault.

On the **working** circuit: -

- Measure the power supply voltage, and notice the orientation.
- If possible, measure the supply current and note how it changes in different situations.
- Think about the role of each component in the circuit;
- Trace signal paths through the circuit;
- Measure and record the DC voltage levels at the input and output of significant components.

On the faulty circuit: -

- Compare the components to the good circuit. Have any been replaced incorrectly?
- Measure voltages and currents and compare to measurements of the working circuit. Are any differences significant or are they due to component tolerances?
- If there are switches or relays that may be faulty. Could they be bypassed to check?

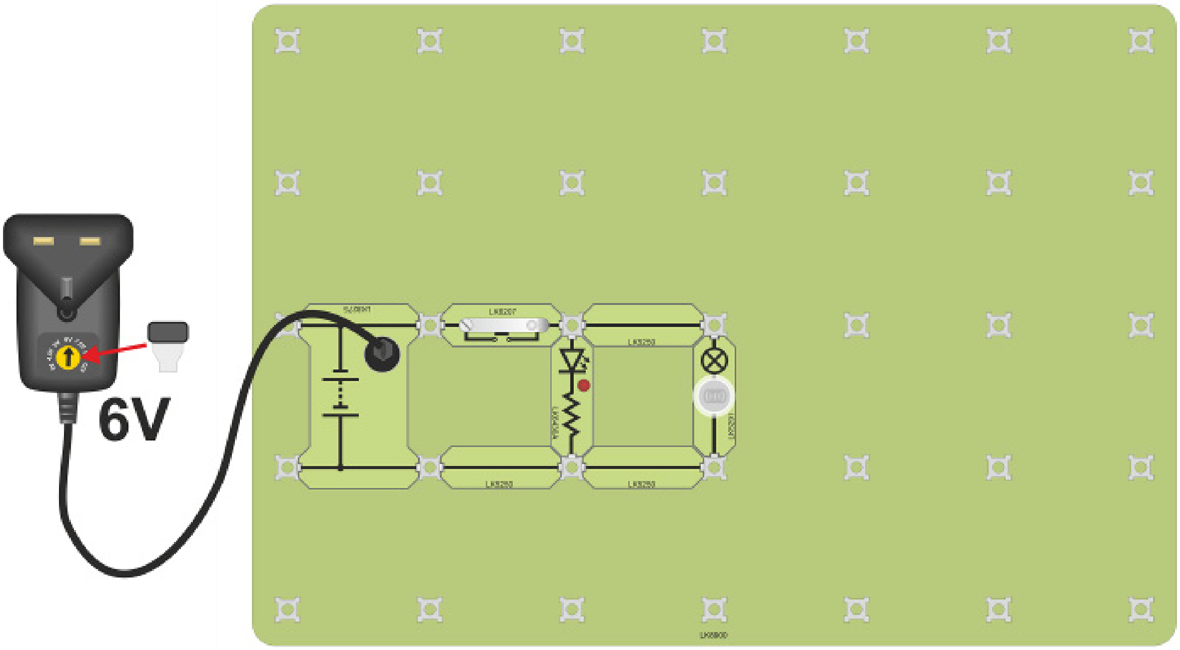


Over to You

- Set up the circuit shown.
- Set the multimeter to DC current mode and connect it as shown.
- Set the power supply to 6V and plug it in.
- Measure the current flowing in the circuit.
- Remove the multimeter and replace the link.
- Set the multimeter to DC voltage mode and connect it across the lamp.
- Given the voltage and current readings, calculate the resistance of the lamp.
- Remove the power supply from the circuit.
- Set the multimeter to resistance mode.
- Measure the resistance of the bulb.
- Does the measured resistance match the calculated value? Can you explain any difference.
- Replace the lamp with the LED and repeat the experiment. It might be difficult to get the multimeter to give any reading for the LED. If your multimeter is not auto-ranging, use the highest range possible. Also remember that the polarity of the LED may affect the measurement. Do not worry if the meter does not give a reading; just make a note of the fact.

So What?

The lamp and the LED are both non-ohmic components. A simple resistance measurement does not necessarily indicate what the component will do in a circuit. Nevertheless, these measurements are useful. Make a note of these measurements as they will be useful in the later activities.

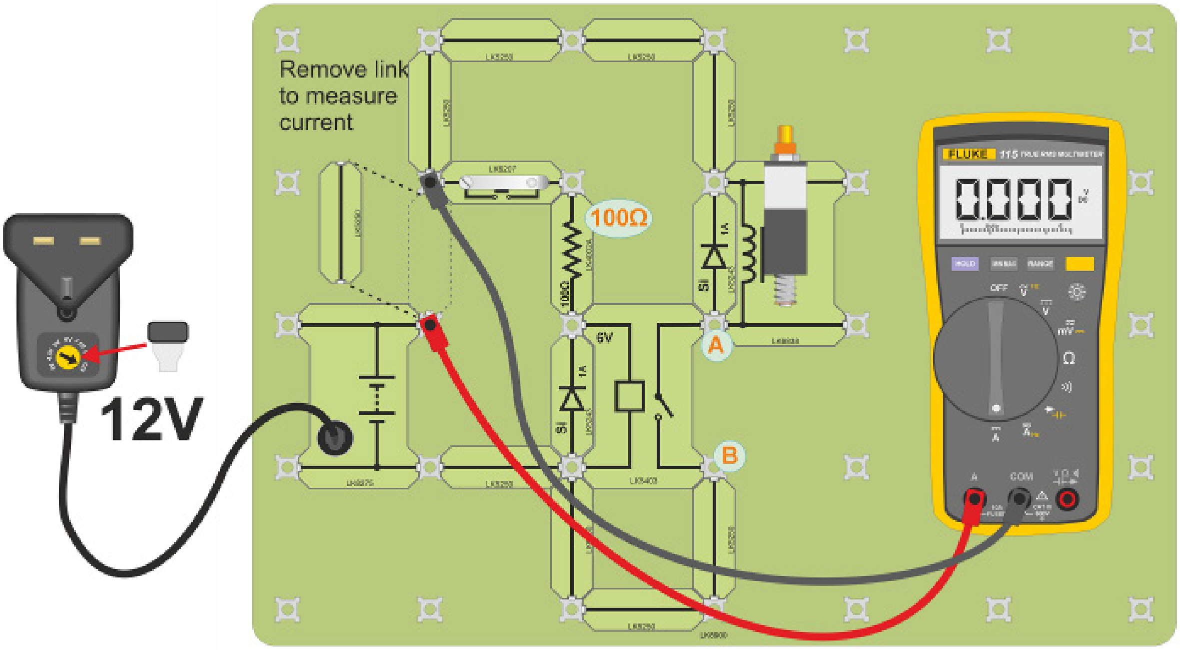


Over to you

- Set up the circuit shown. (Note the orientation of the power supply)
- Imagine that these components are part of a machine that has been striped down and reassembled during routine maintenance. “It’s not working!” you are told. What are you next moves? Think back to the five steps of fault finding described at the beginning of this worksheet.
- After more questioning, you are told: “The LED and lamp are both supposed to come on when the switch is pressed but only the lamp is coming on. It worked yesterday.”
- Examine the circuit again. Can you see why the LED is not coming on?
- Can you suggest a change that would cause the LED to come on with the lamp? There are two possible answers here.
- If you found two answers, test them both. How do you decide which one to implement?

So What?

In the absence of the original schematic for the machine it is not possible to say which solution is the correct one. Perhaps you answer was influenced by the fact that most of the Locktronics circuits that you have seen in this series of worksheets have the positive side of the power supply towards the top of the diagram. Following conventions can be helpful, especially where more than one person is involved in design and maintenance. On the other hand, you may have noted that the LED is one single component and the rest of the machine has no reported faults. On this basis, maybe the logical thing is to leave the power supply as it is and change the LED. Both approaches seem good and both would leave the machine working. The important thing in this situation is to make sure that you document what you have done. Your documentation will either yourself or the next person when the machine is services again next year.



Over to you

- Build the circuit shown.
- Set the multimeter to DC current mode and check that it is on its highest range.
- Set the power supply to 12V and plug it in.
- Imagine that this circuit is a spare of a controller that your company uses in multiple locations. Having the opportunity to study a good circuit now may help you in the future.

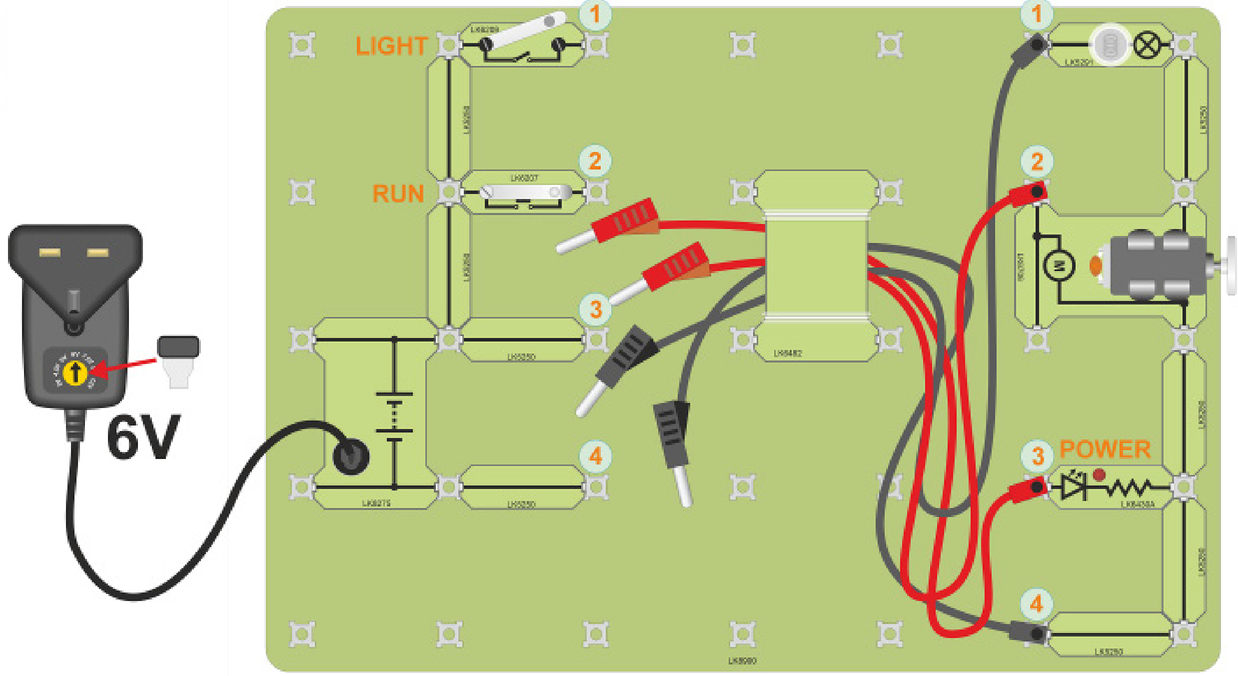
- Carefully examine the circuit. If it looks familiar from an earlier worksheet, you may want to refer back to your notes. Make a list of the components in the circuit. What are their functions and what would happen if they were to fail?
- Look at the reading on the multimeter. Is any current flowing in the circuit?
- Press the switch and check that the solenoid operates. What is the current now?
- Remove the solenoid from the circuit and then press the switch. What current flows now? Is there a way of telling whether the relay is operating without looking at the meter?
- Take a spare cable or link and connect it between points A and B in the circuit. What is the current reading now?
- Look at your notes. You should now have a detailed description of the circuit including the individual currents of both the relay and the solenoid.
- Imagine that it is 4:50 pm on a Friday afternoon and you are looking forward to the weekend. You get a call from the site furthest from your office; a machine has stopped working and needs to be fixed immediately. The technician at the site says that she has a multimeter and could replace components if she knew which ones to replace. What would you instruct her to do?
- The technician reports that the machine draws 0.07A when the switch is pressed. She can hear a clicking sound but it is very quiet. When the machine is working correctly, there is a loud ‘clunk’ as the switch is pressed. Which component would you advise her to replace?

Over to you

Having examined the circuit in the comfort of your office, you gained enough knowledge to diagnose a problem over the phone. This saved you a lengthy drive in rush hour traffic and means that you can now enjoy your weekend in peace.
You will not always have the opportunity to examine a circuit in detail like this but documenting your observations every time you attend a repair can enable you to build up a picture over time. You may also find that a circuit used multiple times may have variations. Perhaps the machines on one particular site use a more powerful solenoid. Maybe machines built after a certain date use a different design of relay. These are all things that you should document as you find them.

Challenge

The machine is now working and the technician is grateful for you help. She mentions that the relay needed replacing three times over the last month but before that, the old relay lasted for years. Can you think of a reason that the relays are suddenly not lasting as long? What would you advise?



Over to You

- Build the circuit shown. The motor effect carrier in the middle represents a length of trunking between the control room on the left and the plant on the right.
- Set the power supply to 6V but do not switch on yet.
- Imagine that you have just arrived at a new site that is under construction. You have told your team over and over that they should use different coloured cables and label each core. However, the installers have used two red and two black wires and no labels. You can not even trust the colours as they might have joined two shorter lengths in the trunking. The installers have finished their shift and gone home leaving you with the job of wiring up the controls.
- Look back at the first activity in this worksheet. You know what reading the multimeter will give you when you measure the resistance of either a lamp or an LED. You have not tried measuring a motor and you do not really want to walk all the way to the plant to try it.
- Set your multimeter to resistance mode.
- Label the four wires A, B, C and D.

	D	C	B
A			
B			
C			

- A table like the one above has been drawn for you in the student record book. Use the multimeter to measure the resistance between each pair of wires. With four wires there are six possible pairs.
- Looking at your measurements and given what you know about the LED, can you work out which wire should be connected to the post labelled ‘3’?
- Which pair gives the resistance reading that you would expect for the lamp? One of these wires should be connected to post ‘1’ and the other to ‘4’ but we are still not sure which is which.
- Look at the other measurements and think back to what you know about resistances in series. What do you think the resistance of the motor is?
- If you know the resistance of the motor then you can identify a pair of wires that should be connected to posts ‘2’ and ‘4’. Since you already know that one of these two wires is also a member of the pair that gave the resistance expected for the lamp, you know which one should connect to ‘4’.
- Connect the remaining wires to their correct posts.
- Plug in the power supply and test the circuit. If it is working correctly, the LED should be on all the time, the lamp should come on when the ‘Light’ switch is on and the motor should spin when the ‘Run’ switch is pressed.

Over to you

In fault finding it is common to start with incomplete information. You did not know how the wires were connected at the plant end and you did not know the resistance of the motor windings. By a process of logical deduction, you were able to fill in the blanks. Since you already knew how to measure resistance and a single component connected to a switch is a rather trivial circuit; this activity was really more of a ‘logic exercise’ than an ’electronics lesson’. Fault finding is often like this. If you were documenting your process and findings then you now know the resistance of the motor winding and can use this knowledge next time you are called to this installation.

Challenge

Go back to the start of this activity. Imagine that there is an operator in the plant room. He does not have a multimeter but he is able move wires around and can speak to you by phone while doing so. How might you have been able to complete the wiring with his help?

ELECTRICAL ESSENTIALS

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