Electrical circuits

Current electricity

Unlike static electricity, which can stay in one place, current electricity is always moving. All the electric devices we use rely on flowing electric current. Some, such as headphones and mobile phones, use only a small current, but appliances such as stoves and electric heaters use a much larger current.

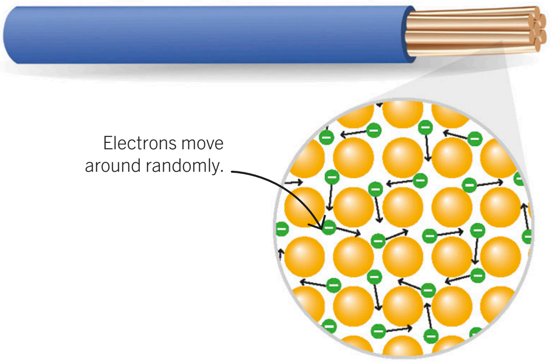
Key facts

- ✓ Current electricity depends on the movement of free electrons in materials such as metals.
- ✓ When pushed by an electrical voltage, free electrons move in one direction. This is an electric current.
- ✓ Materials that let electricity flow through them are called conductors.
- ✓ Materials that block the flow of electricity are called insulators.

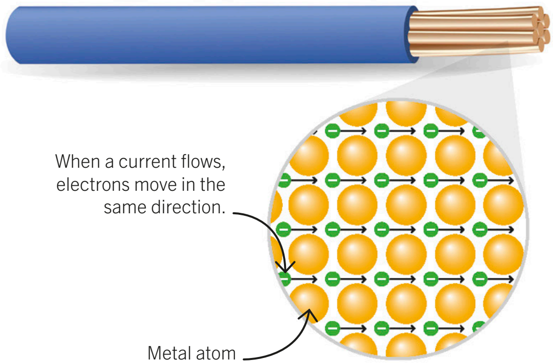
Moving electrons

Current electricity depends on the movement of electrons—the tiny, negatively charged particles that form the outer parts of atoms. In metals, some of the electrons are free to move around. These free electrons normally move around randomly, but when a circuit is switched on, they all move in the same direction. The electrons themselves move slowly, but all the electrons in a wire are affected at once, causing electromagnetic energy to flow through a circuit at close to the speed of light.

Current not flowing



Current flowing



Conductors and insulators

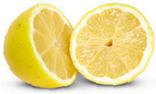
Materials that allow electricity to flow through them are called conductors. Metals are good conductors because their atoms have outer electrons that can separate from the atoms and move freely. Solutions containing dissolved ions (charged particles) can also conduct electricity. Materials with no free charged particles are called insulators because they block the flow of electricity.

Conductors


Copper


Gold


Silver


Lemon juice

Insulators


Ceramic


Wool


Rubber

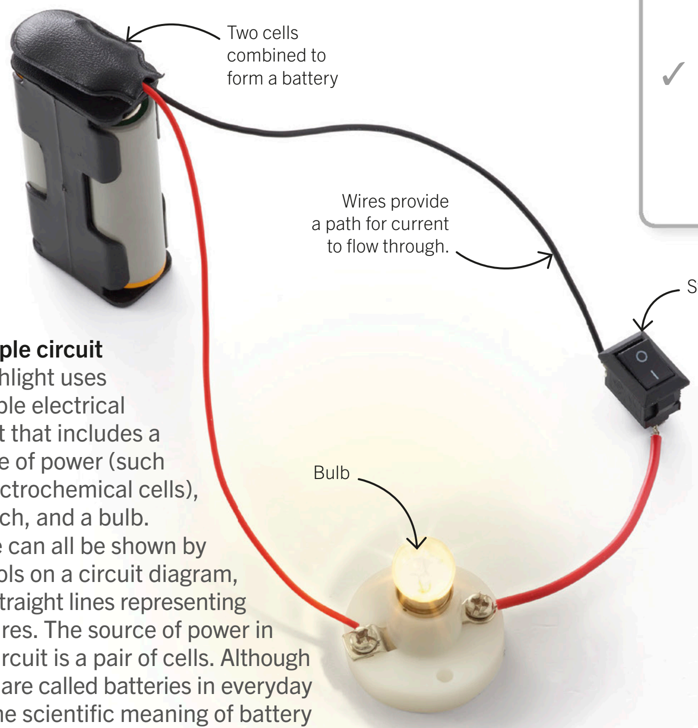

Wood

Electrical circuits

Much of modern life is dependent on electricity and electrical circuits. Some circuits are simple, like the one shown below. Others are much more complex, like those in mobile phones, computers, and many other gadgets.

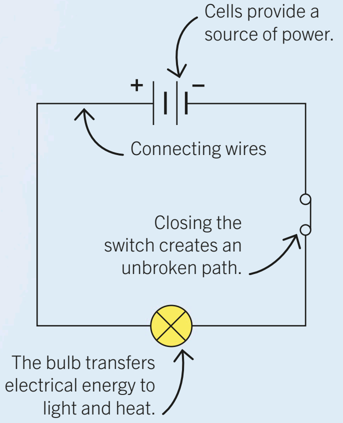
Key facts

- ✓ All electrical circuits need a source of energy, such as a cell.
- ✓ Two or more cells used together make up a battery.
- ✓ Electric current will only flow through a circuit if there is an unbroken conducting path.
- ✓ Many electrical circuits have components such as bulbs or motors, which transfer energy to do useful jobs.



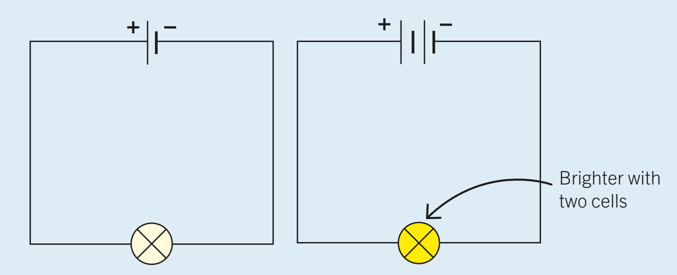
A simple circuit
A flashlight uses a simple electrical circuit that includes a source of power (such as electrochemical cells), a switch, and a bulb. These can all be shown by symbols on a circuit diagram, with straight lines representing the wires. The source of power in this circuit is a pair of cells. Although these are called batteries in everyday life, the scientific meaning of battery is a group of cells. An electric current can only flow in a circuit when the switch is closed, creating an unbroken path.

Circuit diagram



Voltage

The voltage of a cell is a measure of how powerfully it pushes current around a circuit. Adding an extra cell creates twice the voltage, making twice as much current flow. As a result, the bulb glows brighter.



Series and parallel circuits

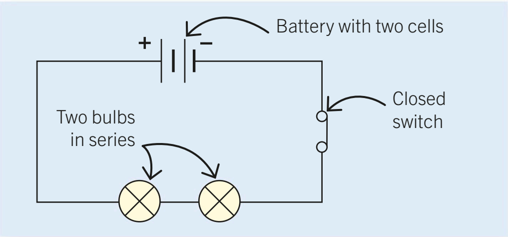
Circuits can be connected in two basic ways. If all the components are connected in a single loop, they are said to be connected in series. If the circuit splits into branches, they are said to be connected in parallel.

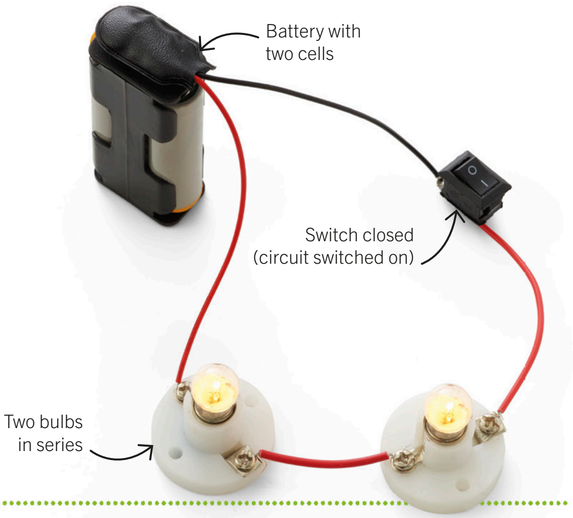
Key facts

- ✓ Electrical circuits can be connected in series or in parallel.
- ✓ In a series circuit, the components are connected in a single loop and can all be switched on or off together.
- ✓ In a parallel circuit, the circuit divides so that components are on different branches. If one branch breaks, the other can continue working.

Series circuit

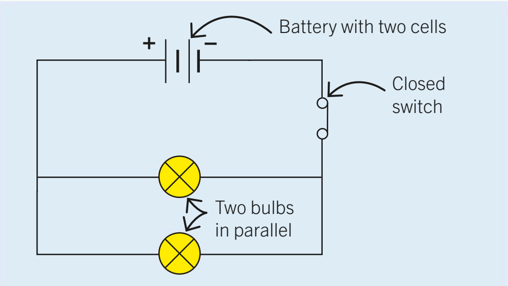
In a series circuit, the components are connected one after another in a single loop. The two bulbs here are connected in series. If one bulb breaks, the current cannot flow through and the other bulb stops working, too. If extra bulbs are added, they will all be dimmer because each bulb reduces the flow of current through the circuit.

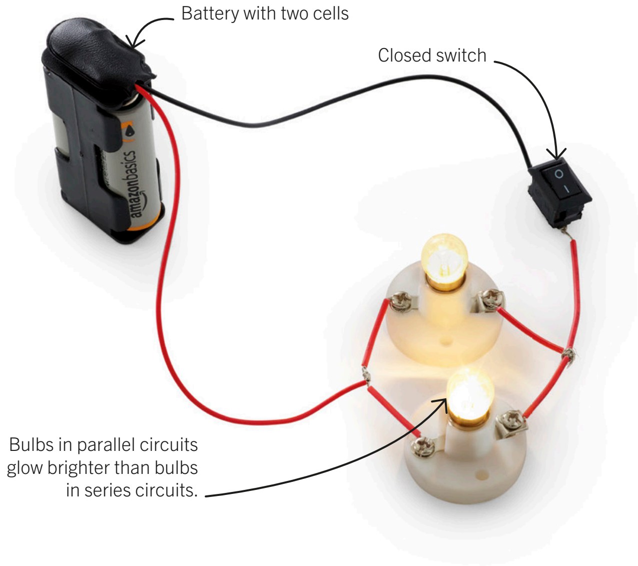




Parallel circuit

In a parallel circuit, the components are on separate branches. There's more than one path for the current to take, so if one bulb breaks, the other continues working. In each branch, the electric current only has to flow through a single bulb, which means more current can flow than in the series circuit. As a result, the bulbs are brighter. The wiring in homes is arranged as parallel circuits.



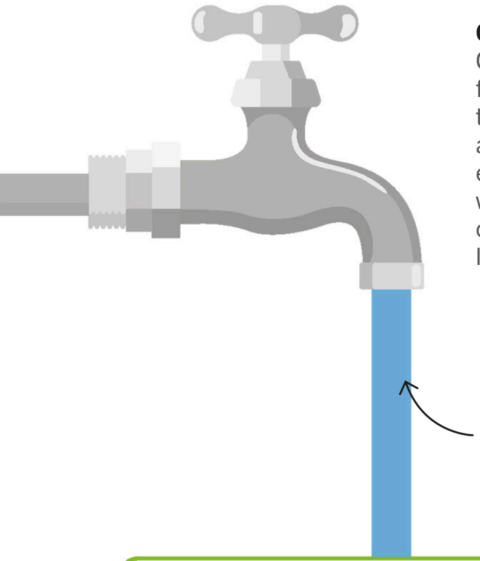


Measuring electricity

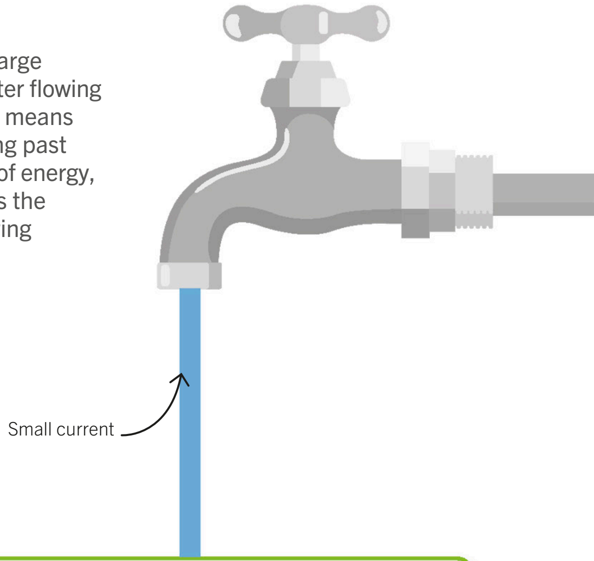
Measuring electricity is a bit like measuring the way water from a tank flows through pipes. The rate at which electric charge flows through a circuit is called current, and we measure it in units called amps. The size of the current depends on two main things: the strength of the driving force (called voltage or potential difference) that pushes electricity along, and how much resistance the electricity meets in the circuit.

Key facts

- ✓ Current is the rate of flow of electric charge. We measure it in units called amps (A).
- ✓ Current is measured by an ammeter, which is connected in series.
- ✓ Voltage (potential difference) is a measure of how strongly charge is pushed through a circuit. We measure it in volts (V).
- ✓ Voltage is measured by a voltmeter, which is connected in parallel.
- ✓ Resistance is anything that uses up electrical energy, reducing the flow of electric current. We measure resistance in ohms (Ω).



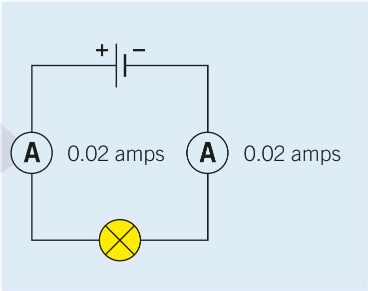
Current
Current is the rate at which charge flows through a circuit. Like water flowing through a pipe, a large current means a lot of electric charge is flowing past every second, transferring lots of energy, whereas a small current means the charge is trickling by, transferring less energy.



Measuring current

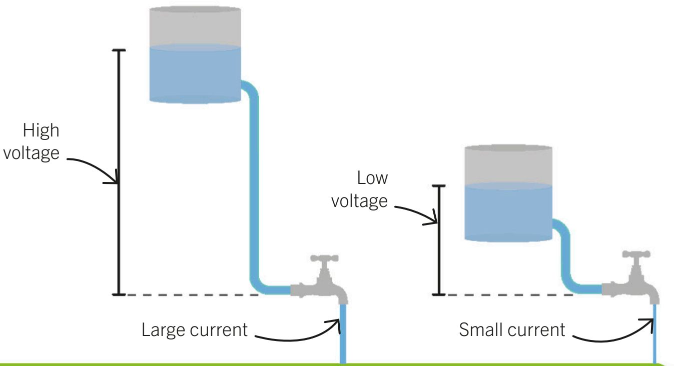
We measure current in units known as amps or amperes (A), using a device called an ammeter. An ammeter has to be connected in series wherever we want to measure the current. It doesn't matter where you put it in a series circuit, as the current is the same in every part of the circuit. The symbol for an ammeter on a circuit diagram is the letter A in a circle.

Ammeter



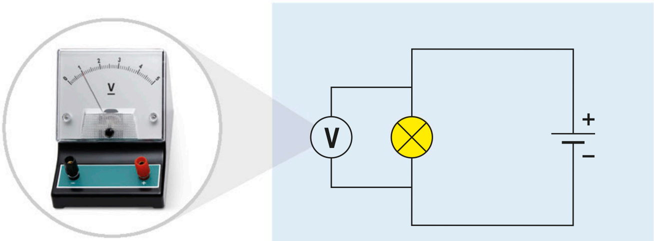
Voltage (potential difference)

A current can't flow unless something pushes it. The push comes from the difference in electric potential energy at the start and end of the circuit, which we call voltage or potential difference. It works a bit like water pressure. When a water storage tank is up high, the force of gravity creates a higher pressure, making the rate of flow of water through the tap bigger.



Measuring voltage

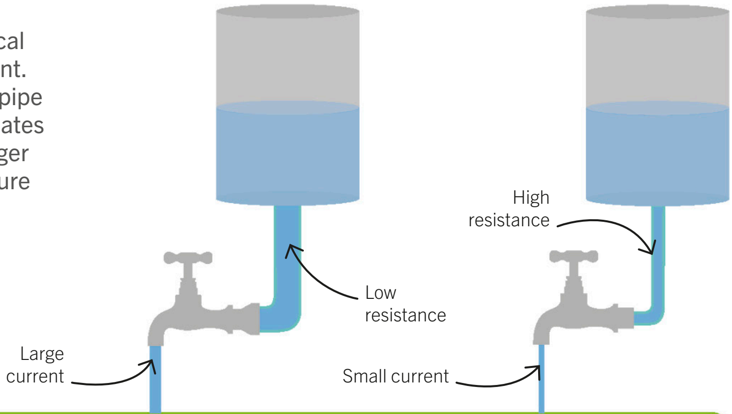
We measure voltage in units called volts (V), using a device called a voltmeter. The voltmeter must be connected in parallel with the component. The symbol for a voltmeter on a circuit diagram is the letter V in a circle.



Voltmeter

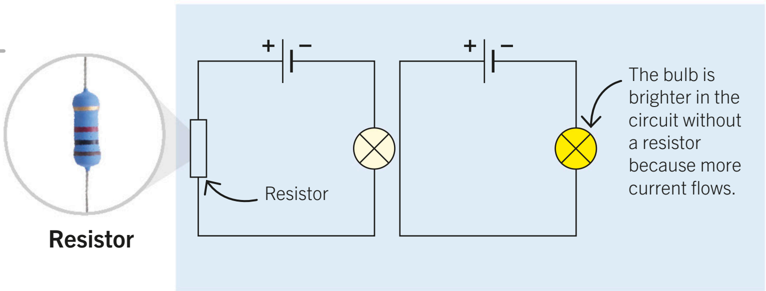
Resistance

Anything in a circuit that uses up electrical energy reduces the flow of electric current. We call this resistance. Just as a narrow pipe reduces the flow of water, a thin wire creates resistance and reduces the current. Longer wires also increase resistance. We measure resistance in units called ohms (Ω).



Resistors

In some circuits, a component called a resistor is added to ensure the current doesn't become high enough to damage other components. The symbol for a resistor in circuit diagrams is a rectangle.



Resistor

Series and parallel circuit rules

Here are the main rules that you need to know about currents and voltages in series and parallel circuits.

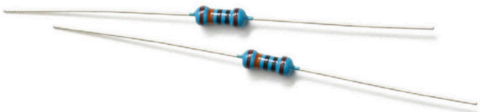
Key facts

- The sum of currents flowing toward any point in a circuit is equal to the sum of currents flowing away from it (current in equals current out).
- The voltages across components in series add up to the voltage of the power supply.
- Components connected in parallel have the same voltage across them.

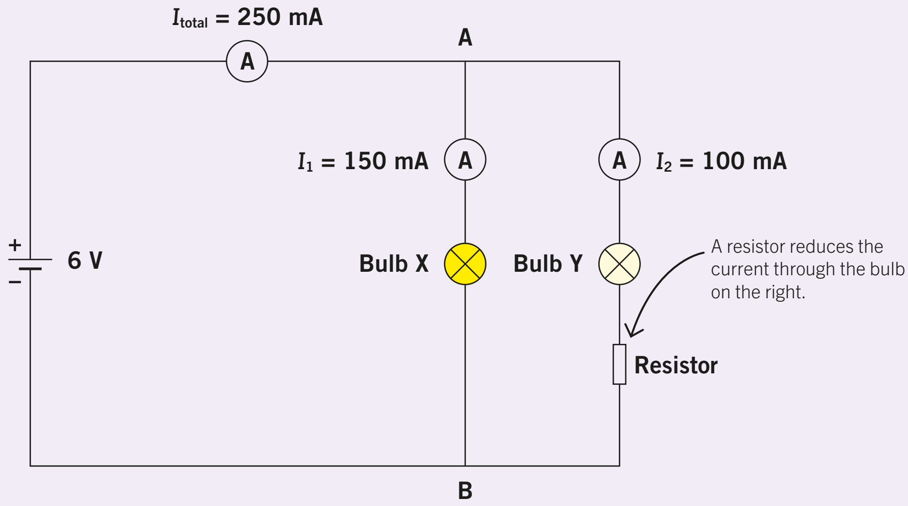
Rule 1: Current in equals current out
The sum of currents flowing toward any point in a circuit is always equal to the sum of currents flowing away from it. In the circuit below, a current of 250 mA (milliamps) flows toward A, where it splits into two. The two currents flowing away from A, 150 mA and 100 mA, add up to 250 mA.

$$I_{total} = I_1 + I_2$$

The symbol for current is the capital letter *I*.



Circuit 1



Calculating current

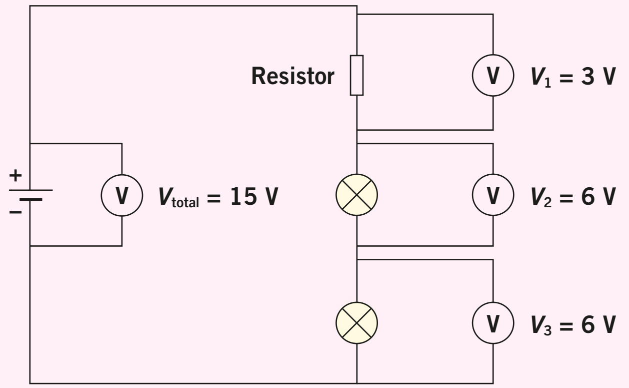
Question 1
In circuit 1, what's the size of the current flowing away from B?

Answer 1
Current in equals current out, so the answer is 250 mA.

Rule 2: Voltages in series add up
When components are connected in series, such as the two bulbs and the resistor shown here, the voltages across each component add up to the voltage of the power supply.

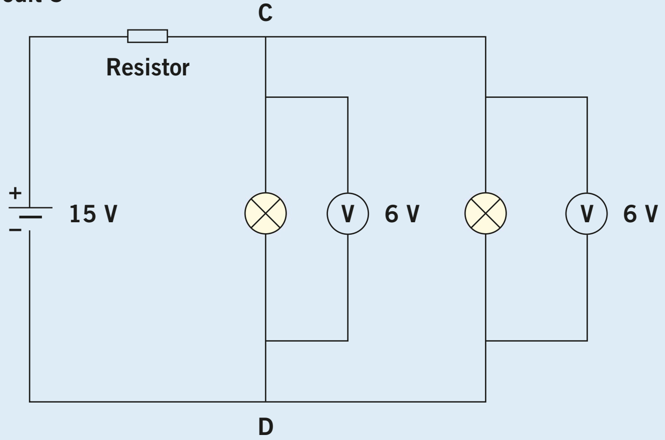
$$V_{total} = V_1 + V_2 + V_3$$

Circuit 2



Rule 3: Voltages in parallel are the same
In a parallel circuit, each parallel branch has the same voltage across it. In the example shown here, the two bulbs have the same voltage across them.

Circuit 3



Calculating voltage

Question 2
In circuit 3, what's the voltage across the resistor?

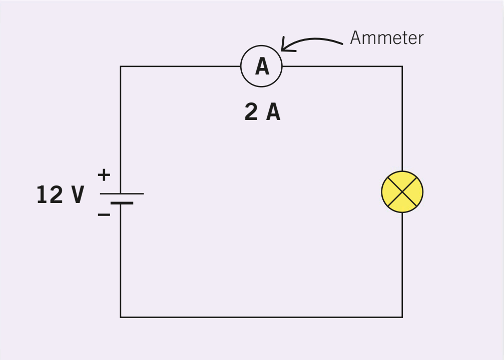
Answer 2
The circuit has a total voltage of 15 V, and the voltage between C and D is 6 V. The voltage across the resistor must therefore be 15 V – 6 V, which is 9 V.

Question 3
The voltage across the resistor in circuit 1 is 4 V. What is the voltage across bulb Y?

Answer 3
The voltage across each branch of the circuit is 6 V. In the right branch, 6 V is divided between bulb Y and the resistor, so the voltage across bulb Y is 6 V – 4 V = 2 V.

Charge

Electrons all have negative charge. When a circuit is switched on, the moving electrons cause an electric charge to flow through it. We measure charge in units called coulombs. Electric current is the rate of flow of charge: a current of 1 amp means 1 coulomb of charge flows past every second. The equations on this page show how charge, current, voltage, and energy are related.



Charge and current

The size of an electric current tells you how much charge moves past any point in a circuit each second. In this circuit, the reading of 2 amps on the ammeter shows that 2 coulombs of charge pass through the cell and the bulb every second. This relationship between charge, current, and time is summed up in the equation below.

$$\text{charge (C)} = \text{current (A)} \times \text{time (s)}$$

$$Q = I \times t$$

Charge and energy

Electrical devices do useful jobs by transferring energy. For instance, the circuit above transfers energy from the cell to light. If you know how much charge flows through a component and the size of the voltage (potential difference) pushing the charge, you can calculate how much energy the circuit transfers using the equation below.

$$\text{energy transferred (J)} = \text{charge (C)} \times \text{voltage (V)}$$

$$E = Q \times V$$

Key facts

- ✓ The unit of electric charge is the coulomb (C).
- ✓ A current of 1 amp means 1 coulomb of charge passes through a circuit each second.
- ✓ When 1 coulomb of charge moves through a potential difference of 1 volt, it transfers 1 joule of energy.

Calculating charge and energy

Questions

1. A flashlight bulb uses a 3 V battery and a current of 0.25 A flows through the bulb. The flashlight is turned on for 5 minutes. How much charge passes through the flashlight bulb?
2. How much energy is transferred from the battery to the bulb in that time?

Answers

1. First, work out the time in seconds:
   5 minutes = 300 seconds
   $Q = I \times t$
   $= 0.25\ \text{A} \times 300\ \text{s}$
   $= 75\ \text{C}$
2. Use the second equation to calculate energy transferred:
   $E = Q \times V$
   $= 75\ \text{C} \times 3\ \text{V}$
   $= 225\ \text{J}$

Changing resistance

Sometimes it's useful to change the resistance in a circuit to control how much current can flow. This makes it possible to change the brightness of a lamp, the speed of a motor, or the loudness of a radio.

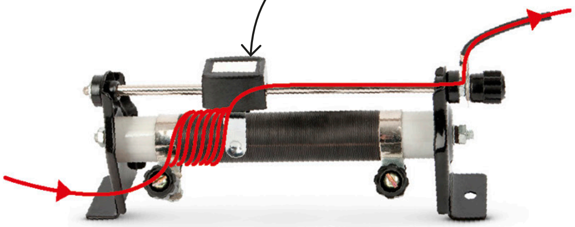
Key facts

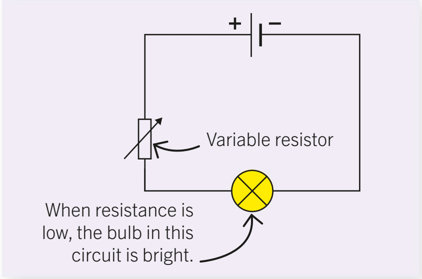
- ✓ A variable resistor consists of a resistance coil and a sliding contact.
- ✓ The current, voltage, and resistance of a circuit are linked by the equation voltage = current × resistance.

Variable resistor

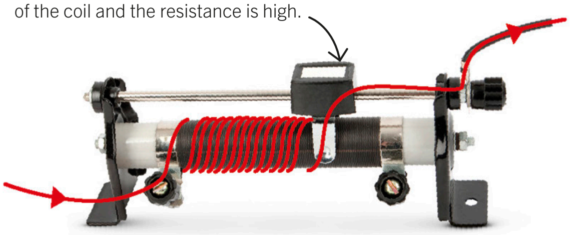
The component used to change resistance is called a variable resistor. It consists of a long, coiled wire that creates resistance and a sliding contact that can be moved to vary how much coil the current flows through.

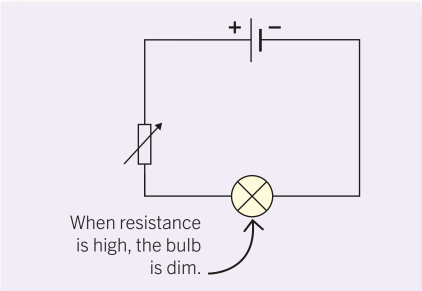
With the slider near the left end of the coil, the current does not have to pass through many turns of wire and the resistance is low.





With the slider near the right end, the current has to pass through most of the coil and the resistance is high.





Calculating current, voltage, and resistance

The current, voltage, and resistance in a circuit or component are linked by the equation below, which is known as Ohm's law.

voltage (V) = current (A) × resistance (Ω)

$$V = I \times R$$

Question

A current of 0.5 A flows through a bulb when there is a voltage of 6 V across it. Calculate the resistance of the bulb.

Answer

Rearrange the equation to make resistance the subject:

$$R = \frac{V}{I}$$

$$R = \frac{6\ \text{V}}{0.5\ \text{A}}$$

$$R = 12\ \Omega$$

Investigating resistance in wires

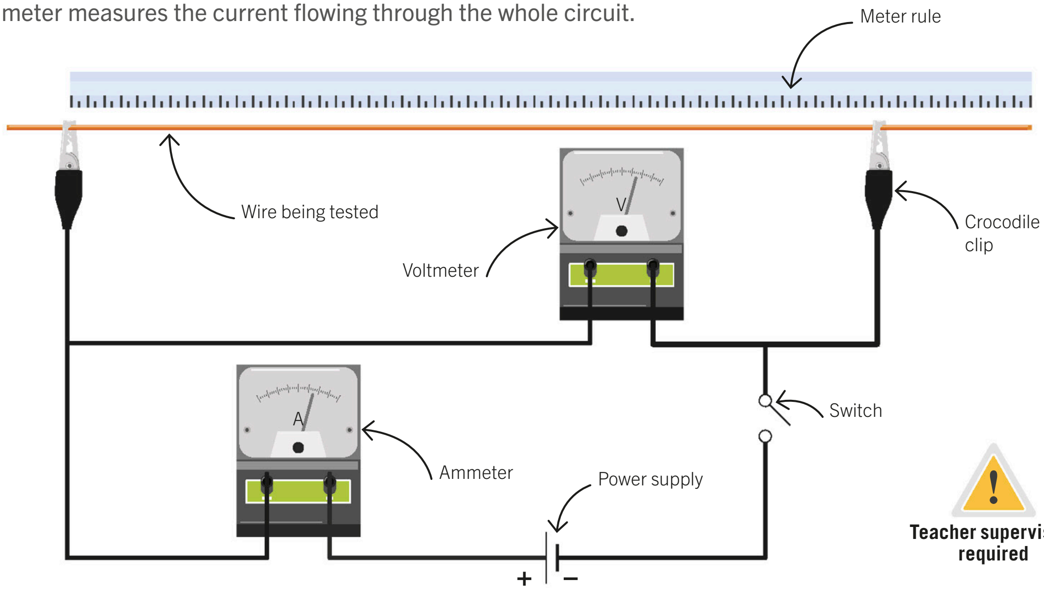
The resistance of a component depends on many factors. This experiment investigates how the resistance of a wire varies with the wire's length.

Key facts

- ✓ The resistance of a wire increases with the wire's length.
- ✓ Resistance can be calculated by dividing voltage by current.

The circuit

The two crocodile clips in this circuit allow you to vary the length of a piece of wire through which the current flows. The voltmeter measures the voltage (potential difference) across this wire, and the ammeter measures the current flowing through the whole circuit.



Method

1. With help from a teacher, set up a circuit as shown above.
2. Fasten one crocodile clip to the wire at the zero mark on the ruler. Fasten the other crocodile clip at 30 cm.
3. Set the power supply to a low voltage (3–4 V) or use a cell.
4. Turn on and note the readings on the ammeter and voltmeter. Turn off again as soon as you've done this to stop the wire from becoming hot.
5. Write your results in a table with column headings for wire length, current, and voltage.
6. Move the crocodile clip to 40 cm and repeat steps 4 and 5.
7. Repeat every 10 cm up to 100 cm.

Warning
Your teacher will provide a special kind of wire (Constantan or Eureka wire with a diameter of about 0.5 mm) that is safe to be used as a resistor in this experiment. Do not use ordinary wire. The wire should either be raised or supported on a heat-resistant mat made of a material that does not conduct electricity. Take readings quickly and then disconnect the power to prevent the wire from heating up. Do not touch the naked wire when the circuit is turned on.

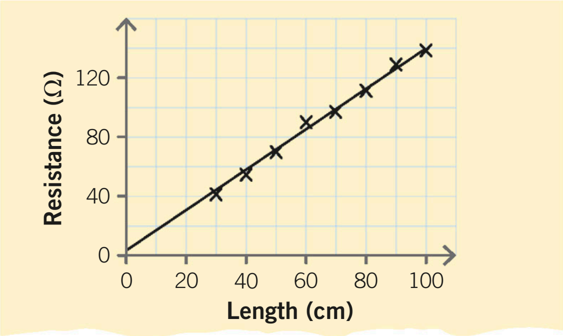
Results

1. Use Ohm's law (below) to calculate the resistance for each length of wire, and record the answers in a new table.

$$\text{resistance } (\Omega) = \frac{\text{voltage (V)}}{\text{current (A)}}$$

Wire length (cm)	30	40	50	60	70	80	90	100
Calculated resistance (Ω)	44	53	71	88	95	112	127	138

2. Draw a graph of resistance against length of wire, and join the points with a line of best fit. The points should be on a straight line that passes through the origin (0, 0). This shows that the resistance of the wire is proportional to its length. In other words, if its length doubles, its resistance doubles.



3. You may find that the straight line on your graph doesn't pass through the origin. This is caused by what's known as a systematic error—an error that affects all your readings. In this case, it could be that one crocodile clip was not exactly at the zero point on the ruler, so all your measurements of length are incorrect by the same amount. Another possible cause of systematic error is resistance from the other wires in the circuit, especially if they are long.

Resistance is useful

Resistance is caused by collisions between the free electrons in a wire and the lattice of fixed metal ions. The collisions transfer energy to the ions, increasing their store of thermal energy. Electric heaters and electric light bulbs exploit this process to generate heat and light. The filament in a light bulb gets so hot that it glows white hot, flooding its surroundings with light.

Resistance in wires

Why do some substances make it difficult for electricity to pass through them? Insulators have huge resistance because there are no free electrons to carry charge, but metals have lots of free electrons. However, electricity flows more easily through some wires than others.

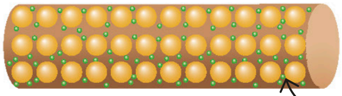
Key facts

- ✓ Resistance in metals happens because free electrons collide with metal ions as they move through the wire.
- ✓ Short wires have less resistance than long wires.
- ✓ Thick wires have less resistance than thin wires.
- ✓ Some metals conduct better than others.

Wire length

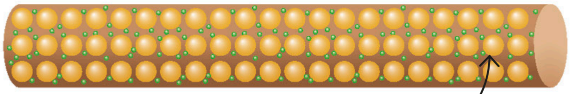
Wires create resistance because the free electrons bump into the fixed metal ions as they move, transferring some of their energy to the ions. The longer the wire, the greater the resistance. Resistance is proportional to the length of the wire.

Short wire



Collisions between electrons and metal ions cause resistance.

Long wire

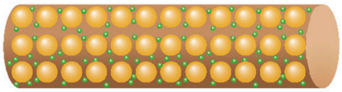


Longer wires cause greater resistance (like placing resistors in series; see page 165).

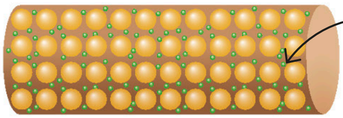
Wire thickness

In thicker wires, there are more electrons to flow, allowing a greater current and therefore lower resistance. Resistance is inversely proportional to the cross-sectional area of a wire. If the cross-sectional area doubles, the resistance halves. If the diameter of the wire doubles, the resistance goes down by a factor of four.

Thin wire



Thick wire

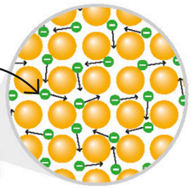


Thicker wires allow more electrons to flow (like placing resistors in parallel; see page 166).

Free electrons

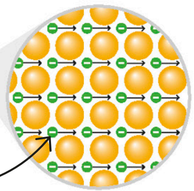
Atoms in a metal are held together in a regular lattice. The atoms' outermost electrons can easily separate to become free electrons, leaving behind positively charged ions. These free electrons normally move randomly in all directions inside the metal, but when a voltage (potential difference) is applied, the electrons all flow in the same direction. Some metals (such as copper and silver) are better conductors than others because their atoms lose the outer electrons more easily.

Free electrons normally move randomly in all directions between the ions.



No current flowing

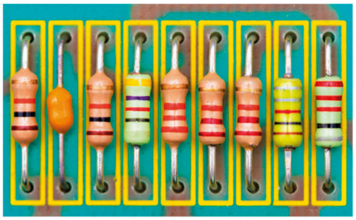
Current flowing



A potential difference makes electrons move in the same direction.

Investigating resistors in series and parallel

We use resistors to control the amount of current flowing through a circuit. This experiment investigates how much resistance they create when multiple resistors are connected in series or parallel.

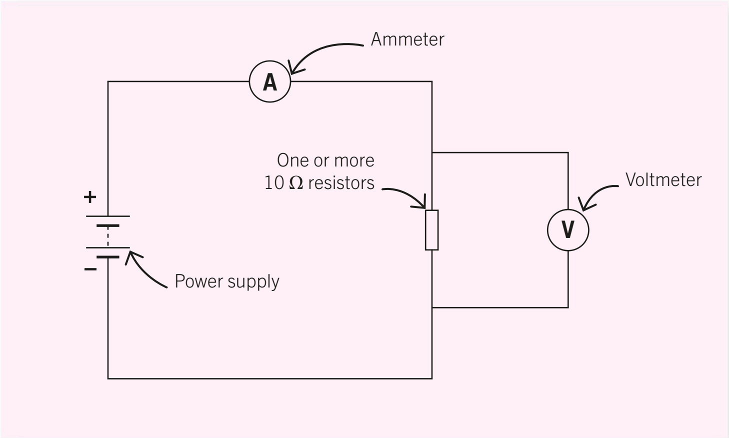


Resistors on a circuit board

Resistors in series

Use a circuit like the one below to find out what happens when you add resistors in series. This experiment shows that when resistors are added in series, the total resistance in the circuit increases.

Teacher supervision required



Method

1. Set up the circuit shown, with just one 10 Ω resistor held between two crocodile clips.
2. Turn on the power supply and record the voltage across the resistor and the current.
3. Turn off and add another 10 Ω resistor in series with the first. Turn on and record the current and voltage again.
4. Repeat step 3 until you've tested the circuit with four resistors in it.
5. Use the following equation to calculate the total resistance of the circuit for each test:

$$\text{resistance} = \frac{\text{voltage}}{\text{current}}$$

Results

Record your readings in a table like the one shown here. The results show that the resistance of the circuit increases by 10 Ω every time a 10 Ω resistor is added in series. The total resistance is the sum of the resistors in the chain. This is shown by the equation below.

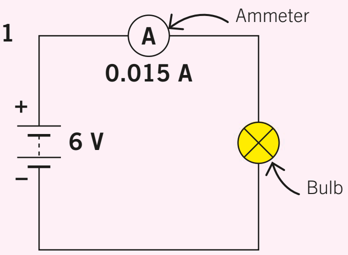
$$R_{total} = R_1 + R_2 + \dots$$

Number of 10 Ω resistors	Voltage (V)	Current (A)	Calculated resistance (Ω)
1	2.0	0.200	10
2	2.0	0.100	20
3	2.0	0.067	30
4	2.0	0.050	40

Resistors in parallel

We can investigate the effect of resistors in parallel using the circuits below. The bulbs serve as resistors here, but we would get similar results using actual resistors. This experiment shows that when resistors are added in parallel, the overall resistance of the circuit falls and the current in the main part of the circuit increases.

Circuit 1



Teacher supervision required

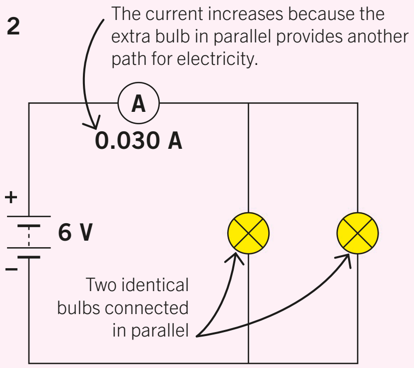
Method

1. Set up the circuit with a single bulb and note the current on the ammeter.

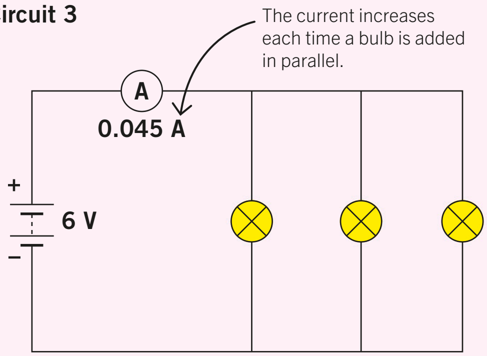
2. Turn off the power and add a second bulb in parallel. Turn on the power and note the new reading. The current will have doubled because the new path allows more electricity to flow through the circuit.

3. Add a third bulb in parallel and take another reading. The current will have tripled.

Circuit 2



Circuit 3



Calculating resistance for components in parallel

The total resistance of components in parallel can be calculated using this equation:

$$\frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots$$

Question

Each bulb in the circuits above has a resistance of 400 Ω. What is the total resistance of the circuit with two bulbs?

Answer

$$\frac{1}{R_{\text{total}}} = \frac{1}{400\ \Omega} + \frac{1}{400\ \Omega}$$

$$= \frac{2}{400\ \Omega}$$

$$R_{\text{total}} = \frac{400\ \Omega}{2}$$

$$= 200\ \Omega$$

Note that this is half the resistance of one resistor by itself.

Check the answer using the equation $V = I \times R$ (voltage = current × resistance). For this circuit, $I = 0.030$ A and $V = 6$ V.

$V = 0.030\ \text{A} \times 200\ \Omega$
$= 6\ \text{V}$

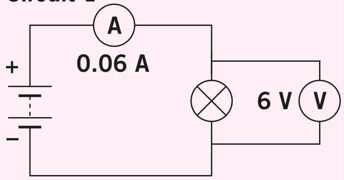
Current and voltage calculations

Previous pages in this chapter have introduced lots of ideas about series and parallel circuits, and some equations. The calculations here show you some ways in which these ideas can be used. The first three questions feature series circuits. The rest are about parallel circuits.

Series circuits key facts

- ✓ Resistances of components in series add up to the total resistance: $R_{total} = R_1 + R_2$.
- ✓ Voltage = current × resistance: $V = I \times R$. This is known as Ohm's law.
- ✓ Ohm's law works everywhere in the circuit, whether we're looking at individual components, a part of the circuit, or the whole circuit.

Circuit 1



Question
What's the resistance of the bulb in circuit 1?

Answer
You know the voltage across the bulb and the current flowing through it, so rearrange the equation $V = I \times R$ (Ohm's law) to calculate the resistance.

$$R = \frac{V}{I}$$
$$= \frac{6\ \text{V}}{0.06\ \text{A}}$$
$$= 100\ \Omega$$

Circuit 2

Question
What's the total resistance in this circuit? Use the answer to calculate the current that flows through the circuit.

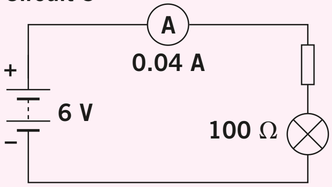
Answer
The resistances of components connected in series add up.

$$R_{total} = R_1 + R_2$$
$$= 100\ \Omega + 50\ \Omega$$
$$= 150\ \Omega$$

You know the resistance and voltage, so rearrange $V = I \times R$ to calculate the current.

$$I = \frac{V}{R}$$
$$= \frac{9\ \text{V}}{150\ \Omega}$$
$$= 0.06\ \text{A}$$

Circuit 3



Question
The bulb in this circuit has a resistance of 100 Ω. What's the resistance of the resistor?

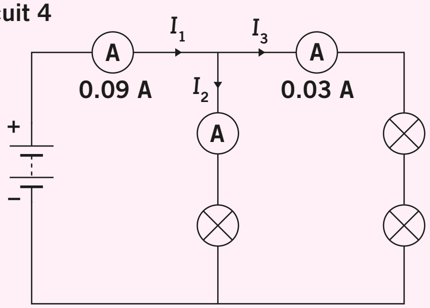
Answer
Start by working out the total resistance of the circuit, using the voltage of the battery and the current.

$$R = \frac{V}{I}$$
$$= \frac{6\ \text{V}}{0.04\ \text{A}}$$
$$= 150\ \Omega$$

The resistances of the bulb and resistor add up to 150 Ω, so:

$$R_{resistor} = 150\ \Omega - 100\ \Omega$$
$$= 50\ \Omega$$

Circuit 4



Parallel circuits key facts

- ✓ Current flowing into a junction equals current flowing out: $I_1 = I_2 + I_3$.
- ✓ The total resistance of components in parallel is smaller than the resistance of either of the components.
- ✓ Each branch of a parallel circuit has the same voltage across it.

Question

All the bulbs in this circuit are the same. What's the current I_2? Explain why I_2 is greater than I_3.

Answer

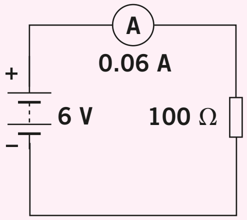
The current going into a junction equals the total current coming out of the junction.

$0.09\text{ A} = I_2 + 0.03\text{ A}$

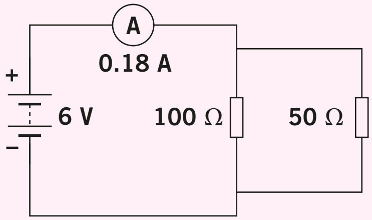
$I_2 = 0.06\text{ A}$

I_2 is flowing through one bulb, but I_3 flows through two. The two parallel branches have the same voltage, but two bulbs create twice as much resistance, so the current through I_3 is half the size.

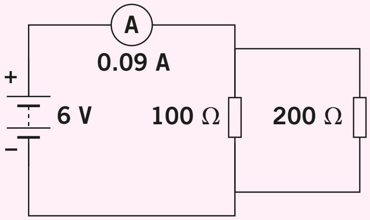
Circuit 5



Circuit 6



Circuit 7



Questions

1. Which of the three circuits above has the smallest total resistance?
2. Which resistor has the highest voltage across it?
3. Explain why the current is highest in circuit 6.

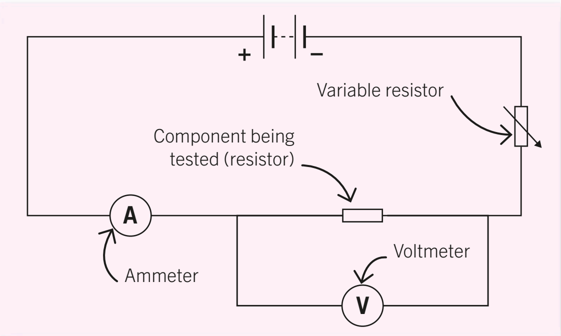
Answers

1. Circuit 6. All the circuits have the same voltage supplied by the battery, and the current is biggest in circuit 6.
2. They all have 6 V across them. In the parallel circuits, each branch of the circuit has the same voltage across it.
3. The current through the 100 Ω resistor is the same in all three circuits. In circuits 6 and 7, more current can flow through the extra resistors. A higher current will flow through the 50 Ω resistor in circuit 6 than through the 200 Ω resistor in circuit 7, so the total current in circuit 6 is highest.

Current and voltage graphs

Resistors and wires are called ohmic conductors because they obey Ohm's law ($V = I \times R$). In other words, a resistor or a wire has constant resistance, and the current flowing through it is proportional to the voltage across it. Not all components obey this law, however. You can investigate the resistance of different components using the circuit below.

Teacher supervision required



Key facts

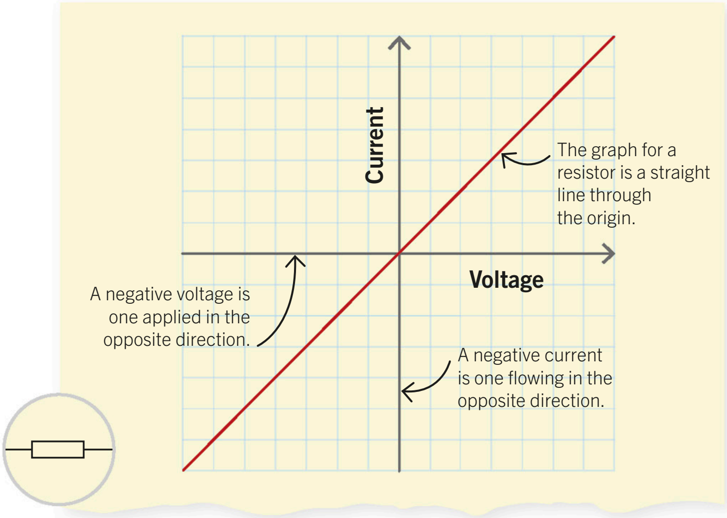
- ✓ The graph of current against voltage for an ohmic conductor is a straight line passing through the origin (0, 0).
- ✓ Filament bulbs and diodes are examples of nonohmic conductors.
- ✓ The resistance of metals increases with temperature.
- ✓ Diodes only allow current to pass through in one direction.

Method

1. Set up the circuit shown in the diagram.
2. Use the variable resistor to change the current to 10 different values. Make a note of the voltage for each different current. Write down your results in a table.
3. Swap the connections to the battery over, and repeat step 2. Your current and voltage readings will now have negative values.
4. Repeat steps 2 and 3 with a filament bulb instead of the resistor, and then with a diode.
5. Plot a graph of current against voltage for each component.

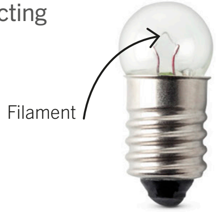
Results for a resistor

A graph of current and voltage for a resistor forms a straight line that passes through the origin (0, 0). As resistance can be calculated from voltage divided by current, this shows that the resistance is constant and doesn't change when the direction of the voltage and current changes. A resistor is an ohmic conductor.

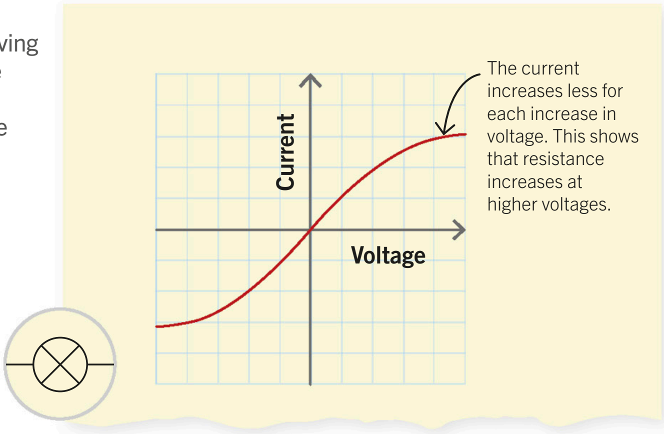


Results for a filament bulb

The graph for a filament bulb shows the line curving at higher voltages. This indicates that resistance is increasing, so a filament bulb is not an ohmic conductor. The filament in a light bulb gets white hot when current passes through, transferring electrical energy to light. Resistance increases because the metal atoms vibrate more as they get hotter, obstructing the flow of free electrons.



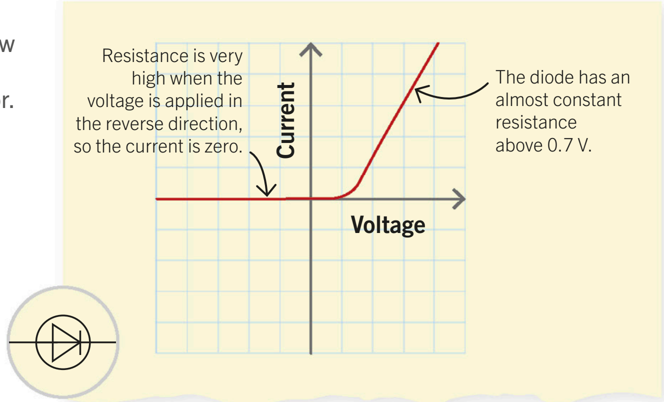
Bulb



Results for a diode

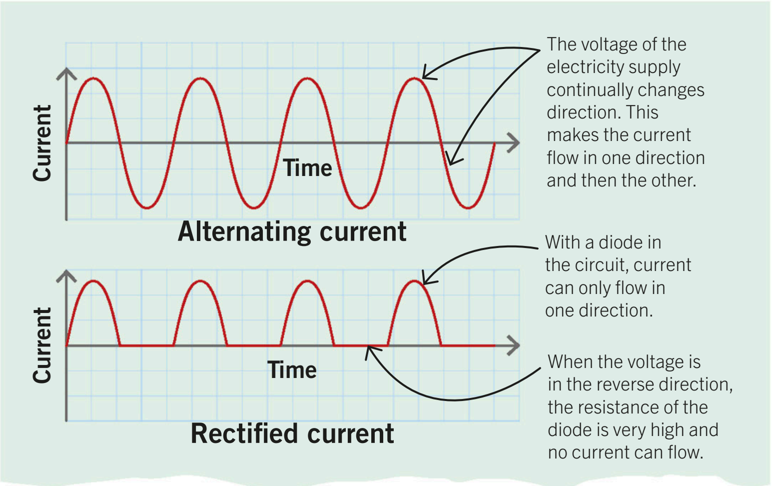
A diode is like a one-way street: current can flow freely in one direction but not the other. As the graph shows, a diode is not an ohmic conductor.

Diode



Rectification

Diodes are used in rectifier circuits, which convert alternating current (a.c.) from electricity supplies to direct current (d.c.) for electronic devices.



Power in circuits

Electrical devices transfer energy from a power supply such as a battery to components such as lamps, heaters, and motors. Electrical power is the amount of energy transferred each second. We measure it in watts (W).

Key facts

- ✓ Power is measured in watts (W).
- ✓ One watt means that one joule of energy is transferred in each second. 1 W = 1 J/s.
- ✓ Electrical power can be calculated using three equations:
  power = current × voltage
  power = $(\text{current})^2$ × resistance
  power = $(\text{voltage})^2$ ÷ resistance.

Power equations

The energy transferred by an electrical device depends on the current and voltage. We can calculate power—the amount of energy transferred each second—using the equation below. The equation doesn't need to include a term for time, as current is a measure of flow of the charge passing each second.

$$\text{power (W)} = \text{current (A)} \times \text{voltage (V)}$$
$$P = I \times V$$

If we combine the equation above with Ohm's law (voltage = current × resistance), we can derive two new equations for power. One, shown below, calculates power from current and resistance. The other calculates power from voltage and resistance: power = $(\text{voltage})^2$ ÷ resistance.

$$\text{voltage} = \text{current} \times \text{resistance} \qquad \text{power} = \text{current} \times \text{voltage}$$

$$\text{power (W)} = \text{current}^2\ (\text{A})^2 \times \text{resistance } (\Omega)$$
$$P = I^2 \times R$$

Calculating power

Question
A flashlight uses a 6 V battery, and the current through the lamp is 300 mA. What's the power of the flashlight? What's the resistance of the lamp?

Answer
Use the first equation to calculate power. Remember that 300 mA is 0.3 A.

$$P = I \times V$$
$$= 0.3\text{ A} \times 6\text{ V}$$
$$= 1.8\text{ W}$$

To find resistance, rearrange either $V = I \times R$ or $P = I^2 \times R$ to make R the subject.

$$R = \frac{P}{I^2}$$
$$= \frac{1.8\text{ W}}{(0.3\text{ A})^2}$$
$$= 20\ \Omega$$

Calculating energy

From flashlights and phones to electric cars and high-speed trains, all electrical devices transfer energy. The amount of energy transferred can be calculated using several related equations.

Key facts

- ✓ Energy transferred by a device equals power multiplied by the time the device is used for: $E = P \times t$.
- ✓ Energy transferred by a device equals the charge that has passed through it multiplied by the voltage across it: $E = Q \times V$.
- ✓ Energy transferred by a device equals current × voltage × time: $E = I \times V \times t$.

Equation 1

The power of a device is the energy used per second, so if you multiply the power by the number of seconds it is turned on, you can find the energy transferred.

$$\text{energy (J)} = \text{power (W)} \times \text{time (s)}$$

$$E = P \times t$$

Equation 2

The voltage of an electricity supply is the energy it transfers for each coulomb of charge, so you can work out the energy transferred by multiplying charge by voltage.

$$\text{energy (J)} = \text{charge (C)} \times \text{voltage (V)}$$

$$E = Q \times V$$

Equation 3

The power of an electrical device can be found by multiplying the current and the voltage. Combine this with energy = power × time and you get the following equation.

$$\text{energy (J)} = \text{current (A)} \times \text{voltage (V)} \times \text{time (s)}$$

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

Calculating energy, charge, and current

Question
This 3 kW oven took 30 minutes to cook an apple pie. The voltage is 230 V. Calculate the energy transferred, the total amount of charge that flowed during this time, and the current used.

Answer
There's a lot to work out here! Start by writing down what you know, but convert the information into the correct units:

power = 3 kW = 3000 W
time = 30 minutes = 1800 s
voltage = 230 V

Use the first equation to calculate the energy transferred.

$E = P \times t$
$= 3000\text{ W} \times 1800\text{ s}$
$= 5\,400\,000\text{ J (5.4 MJ)}$

Now that you know the energy, you can use the second equation to calculate charge.

$E = Q \times V$

$Q = \dfrac{E}{V}$

$= \dfrac{5\,400\,000\text{ J}}{230\text{ V}}$

$= 23\,478\text{ C} = 23\,000\text{ C}$

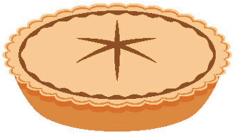
Use the last equation (or just $P = I \times V$) to calculate the current:

$E = I \times V \times t$

$I = \dfrac{E}{V \times t}$

$= \dfrac{5\,400\,000\text{ J}}{230\text{ V} \times 1800\text{ s}}$

$= 13\text{ A}$



Electrified railway
High-speed trains, such as France's TGV (*Train à Grande Vitesse*), are powered by electricity supplied by overhead cables, giving the locomotive at the front of the train a power of 9.3 megawatts (9.3 million watts).

Light-dependent resistors

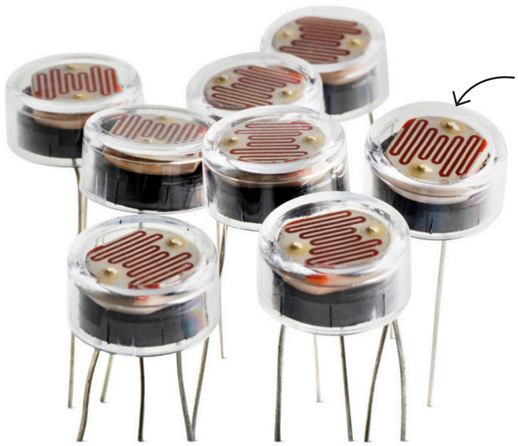
Light-dependent resistors (LDRs) are resistors that sense the brightness of light falling on them: as the light gets brighter, an LDR's resistance falls. LDRs have many applications. They are used in night lights, streetlights, burglar alarms, and smartphone screen dimmers.

Key facts

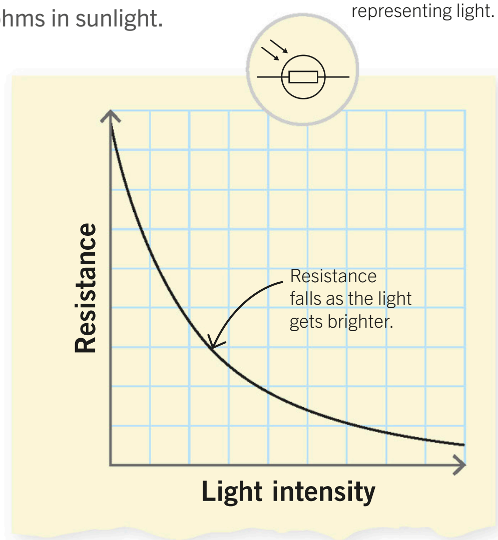
- ✓ **The resistance of LDRs falls as the brightness of the light increases.**
- ✓ **LDRs are used in night lights, streetlights, burglar alarms, and smartphone screen dimmers.**

How LDRs work

Also known as photoresistors, LDRs are small circuit components made of a semiconductor material. When light shines on the semiconductor, electrons are released from atoms, allowing a larger current to flow and so reducing resistance. The higher the light intensity (brightness), the lower the resistance, as the graph here shows. In darkness, a typical LDR has a resistance of over 1 000 000 Ω, but this falls to a few hundred ohms in sunlight.

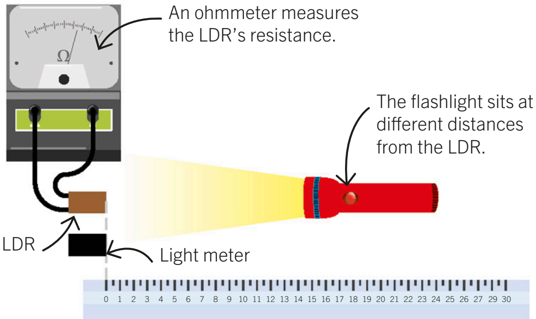


The circuit symbol for an LDR is a rectangle in a circle with arrows representing light.



Investigating LDRs

You can investigate how the resistance of an LDR changes using the apparatus shown here. Carry out the experiment in a darkened room so the only light falling on the LDR comes from the flashlight. Place the flashlight at different distances from the LDR and use an ohmmeter connected to the LDR to measure resistance. Place a light meter next to the LDR to measure light intensity. Use your data to plot a graph of resistance against light intensity.



Thermistors

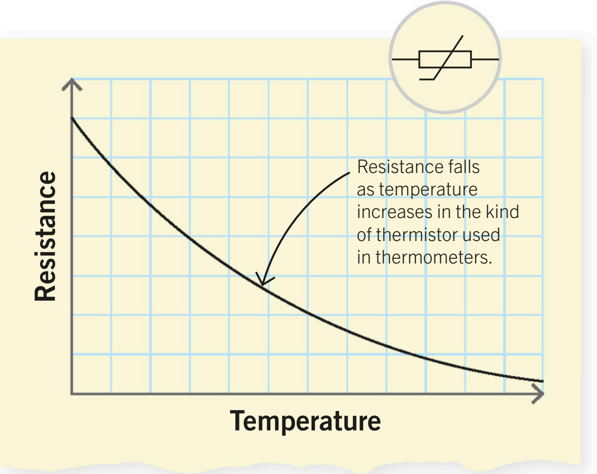
Thermistors are resistors that react to a change in temperature. When the temperature rises, a thermistor's resistance may either rise or fall, depending on the type of thermistor. Thermistors are used as temperature sensors in many kinds of device, from digital thermometers to refrigerators, ovens, and thermostats.

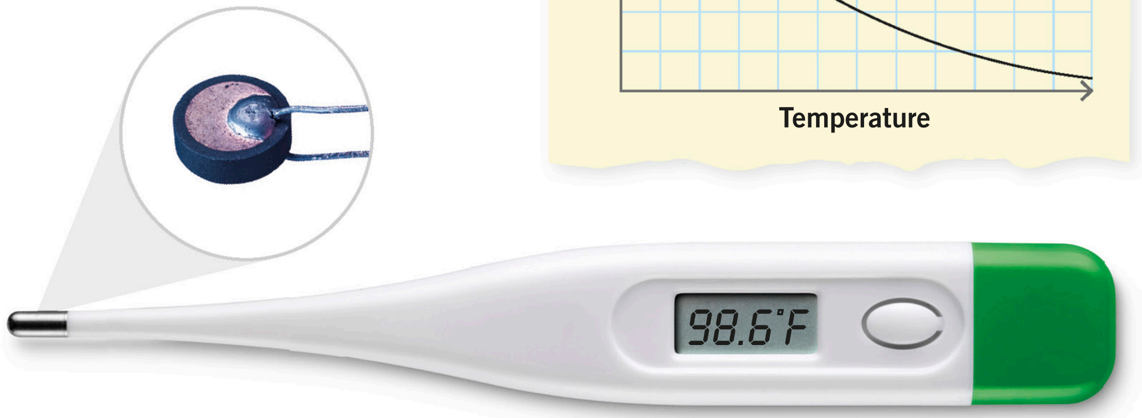
Key facts

- ✓ In thermistors, the resistance changes as temperature increases.
- ✓ Thermistors are used in devices that measure or control temperature.

How thermistors work

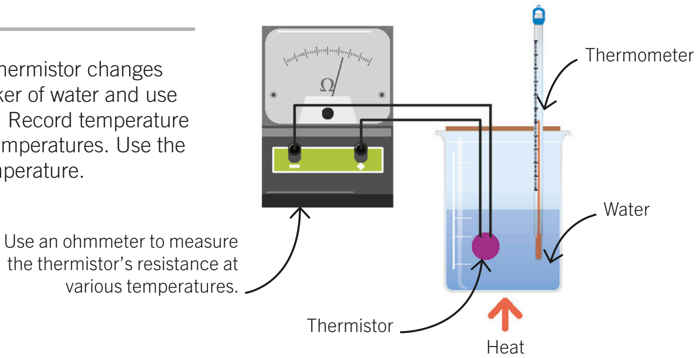
Thermistors are found in the tips of digital thermometers. These thermistors are made from a semiconductor material that releases more free electrons as it gets hotter, allowing more current to flow. The higher the temperature, the lower the resistance, as the graph shows.





Investigating thermistors

You can investigate how the resistance of a thermistor changes using this setup. Place a thermistor in a beaker of water and use a heat source to raise the water temperature. Record temperature and resistance at the same time at various temperatures. Use the data to plot a graph of resistance against temperature.



Teacher supervision required

Sensor circuits

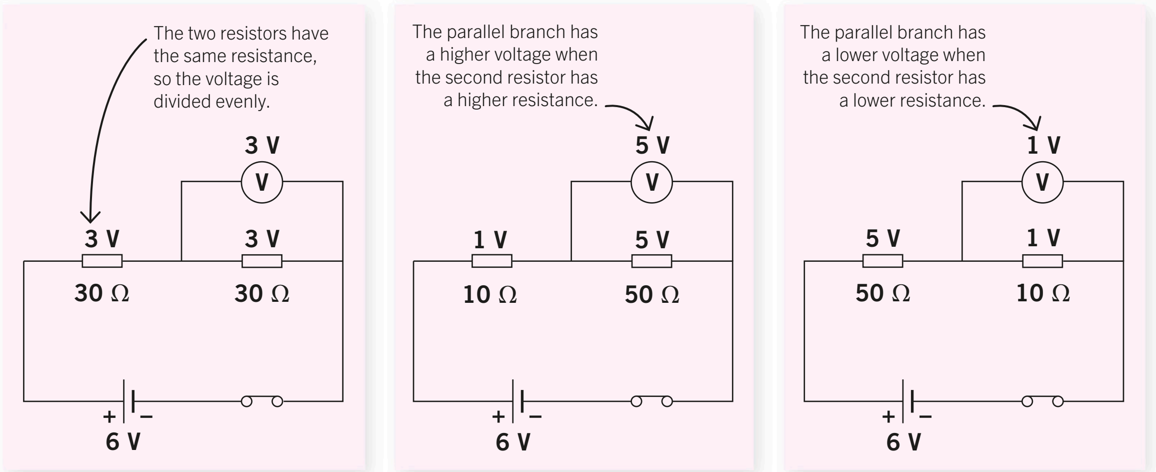
Sensor circuits are used to control electric devices automatically, such as streetlights that turn on when it gets dark and heating or cooling systems that keep the temperature in buildings comfortable all year round.

Key facts

- ✓ LDRs and thermistors can be used as sensors to control lights, heaters, and other devices.
- ✓ The LDR or thermistor is connected in series with another resistor, forming a potential divider.
- ✓ A potential divider is a circuit that uses resistors in series to control the voltage supplied to a different part of the circuit.

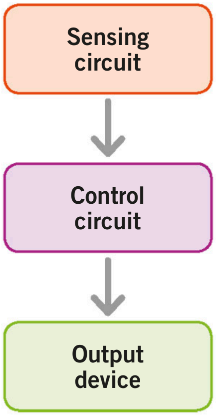
Potential dividers

Sensor circuits often use potential dividers. A potential divider is a circuit that uses resistors in series to control how much voltage is supplied to a parallel branch of the circuit. It works because voltage is divided between components in series but is equal across parallel branches. Changing the combination of resistors changes the voltage in the parallel branch.



Control circuits

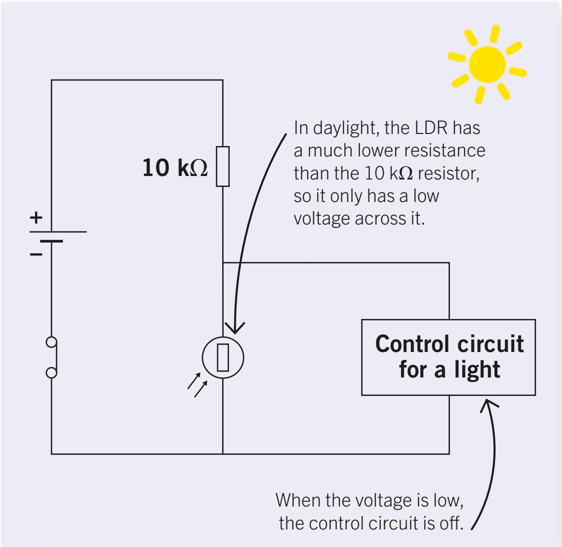
When a light-dependent resistor or thermistor is used as one of the resistors in a potential divider, the voltage in the parallel branch varies depending on the light level or temperature. This varying voltage can then be used to activate a control circuit that switches on when the voltage rises above (or falls below) a chosen level. The control circuit does not draw current from the sensing circuit—it has a different power supply and provides the much larger current needed to power a device such as a streetlight, heater, or fan.

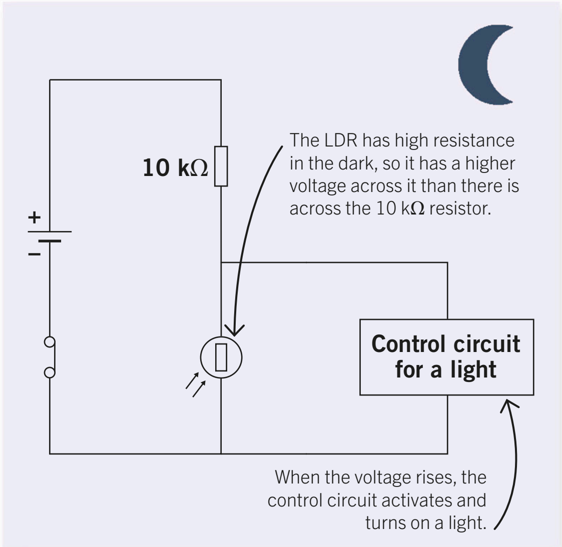


Controlling lights

The circuit below uses an LDR (light-dependent resistor) and a potential divider to send a signal to a control circuit that turns on a light at night as it gets darker.

Light-dependent resistor (LDR)





Controlling temperature

The circuit below uses a thermistor and a potential divider to send a voltage signal to a control circuit that controls a fan. A similar circuit could be used to control an air-conditioning unit or a refrigerator.

Thermistor