●●●○○ Level 3 · Science S3.9

Light, colour and sound

Light bounces, bends and splits into colours, and sound is a wave that needs something to travel through.

Draw rays bouncing off a mirror, see why a coin appears in a cup of water, find how the eye and glasses make an image, split light into colours, predict the colour of things in coloured light, and follow sound as a wave: how fast it goes, what makes it high or loud, and how to protect your hearing.

YOU ARE READY FOR THIS BOOK IF

You can explain how a shadow is made.

One step up	S4.9 Energy, work and power
This book	**S3.9 Light, colour and sound**
One step down	S2.7 Sound

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S3.9.1 Reflection

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S3.9.5 Why things have colour

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S3.9.7 The speed of sound

S3.9.8 Pitch, loudness and hearing

Key words, A to Z

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S3.9.1 CHAPTER 1

Reflection

When light hits a mirror, which way does it go?

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- ☐ **A** Away at the same slant it came in, on the other side of the upright line.
- ☐ **B** Straight back the way it came, whatever the slant.
- ☐ **C** In any direction. It changes every time.

IF THIS FEELS HARD, READ THIS FIRST

- Level 2, Light and shadows, S2.6.7. A smooth mirror bounces light one way.
- Level 2, Light and shadows, S2.6.2. Light travels in straight lines.

BY THE END YOU CAN

- Show that light leaves a mirror at the same angle it arrives
- Draw rays reflecting from a flat mirror with a ruler

Mei holds a small mirror. Her friend Ravi stands to one side. Mei sees Ravi in the mirror. The light from Ravi has bounced off the mirror into her eyes.

When light bounces off a surface, we call it **reflection**. A flat mirror is very smooth, so it reflects light in a neat and certain way.

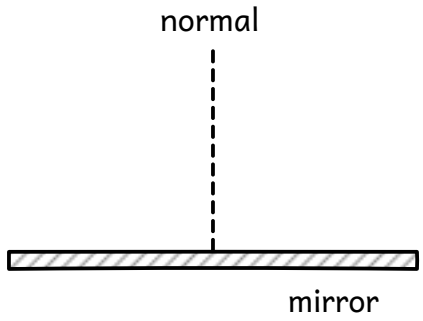
To say which way a ray goes, we need a line to measure from. Draw a dashed line at right angles to the mirror. This line is called the **normal**.

The ray that comes in makes an angle with the normal. This is the **angle of incidence**. The ray that leaves makes an angle with the normal too. This is the **angle of reflection**.

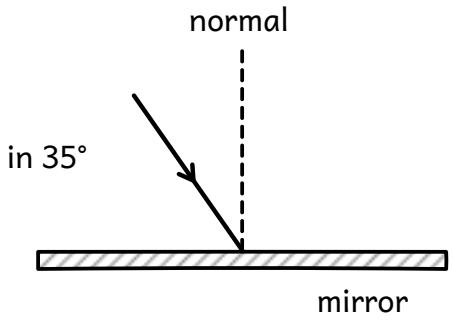
Here is the rule. The angle of reflection always equals the angle of incidence. A ray that comes in at 35° leaves at 35°, on the other side of the normal.

DRAW IT FIRST

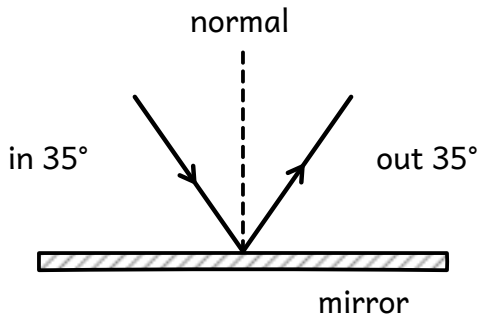
Draw a reflection



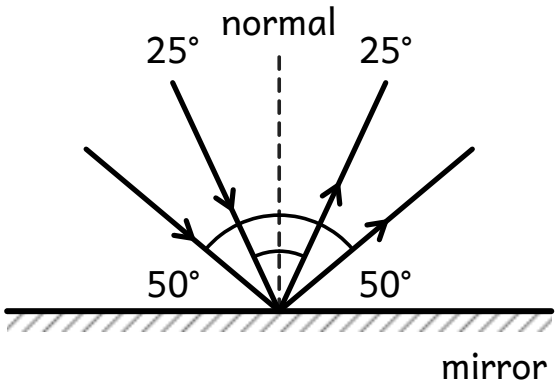
1 Draw the mirror as a straight line. Mark a point on it. Draw the normal from that point with a ruler, at right angles.



2 Draw the ray that comes in, 35° from the normal. Put an arrow on it pointing at the mirror.



3 Draw the ray that leaves on the other side of the normal, also 35° from it. The arrow points away.

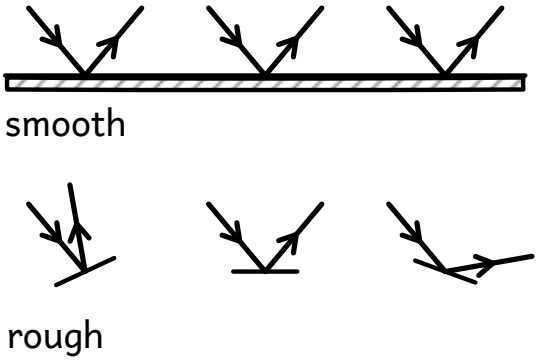


Two rays hit the same spot. Each one leaves at the angle it came in. A ray that arrives lower leaves lower.

Always measure from the normal. Do not measure from the mirror. The mirror is a flat surface, but the angle rule is about the normal.

A ray that travels along the normal, at 0°, hits the mirror straight on. It leaves at 0° too. It goes straight back the way it came.

A rough surface is covered with tiny bumps. Each bump faces a different way. Each ray still obeys the rule, but the bumps tilt, so the rays leave in many directions.



A smooth surface sends light one way, so you see an image. A rough surface scatters light, so you see no image.

SEE IT THREE WAYS

As a picture

angle in	angle out
20°	20°
35°	35°
50°	50°
65°	65°

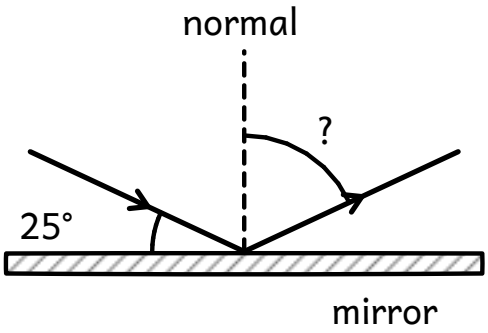
In words

Every row of the table has the same number twice. The angle that leaves is always the angle that arrived.

In symbols

angle of reflection = angle of incidence.

Sometimes you are told the angle between the ray and the mirror. That is not the angle of incidence. The normal and the mirror meet at 90°, so you take the angle away from 90°.



The ray makes 25° with the mirror. What angle does it make with the normal?

WORKED EXAMPLE

A ray meets a flat mirror and makes 25° with the mirror. What is the angle of reflection?

1. The normal is at 90° to the mirror.
2. The angle of incidence = 90° − 25° = 65°.
3. The angle of reflection equals the angle of incidence, so it is 65°.

Answer: 65°

Be safe. Never shine light from a mirror into anyone's eyes. Never look at the Sun or at sunlight bouncing off a mirror or water.

TRY IT

Find the angle with a pencil

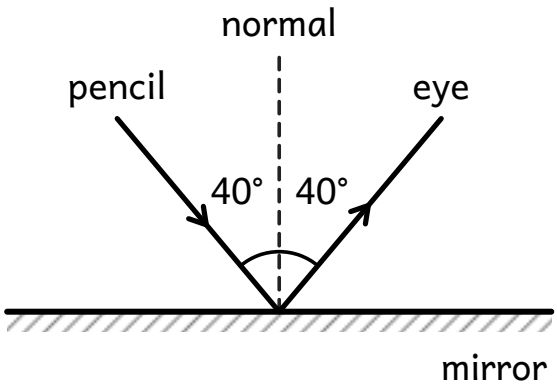
You need: a small flat mirror, a sheet of paper, a pencil standing in a lump of clay or between two stones, a ruler, or a stick with centimetres marked on it.

Be safe: A mirror can break. Keep it away from the edge of the table. If it breaks, leave the pieces and ask an adult to clear them.

1. Draw a straight line on the paper. Stand the mirror upright on it, held by stones.
2. Mark a point in the middle of the line. Use the corner of the paper to draw the normal from it.
3. Stand the pencil on the paper, to one side of the normal, 10 cm from the point.
4. Lay the ruler on the other side of the normal, with its 0 end on the point. Put your eye low at the 10 cm end and look along the ruler.
5. Turn the ruler a little at a time. Stop when you see the pencil in the mirror, right at the point. Draw a line along the ruler.
6. Measure straight across from the pencil to the normal, and from the 10 cm mark to the normal. Compare them.

What you will see: The two distances come out about the same. The pencil and your eye sit at equal angles from the normal. That is the rule: the angle in equals the angle out.

If you cannot try it, this is what happens.



A WRONG IDEA MANY PEOPLE HAVE

~~Light always bounces straight back off a mirror.~~

Why it feels right: When you stand in front of a mirror, you see your own face. That looks like light going straight back.

The test that breaks it: Stand in front of a wall mirror. Ask a friend to stand a few steps to your side. You can see your friend in the mirror, and your friend can see you.

What is true: Light leaves at the same slant it came in. Light from your friend came from the side, so it left towards you at the same slant.

KEY WORDS

reflection
light bouncing off a surface.

normal
a line drawn at right angles to the mirror, to measure angles from.

angle of incidence
the angle between the ray that comes in and the normal.

angle of reflection
the angle between the ray that leaves and the normal.

BACK TO YOUR GUESS

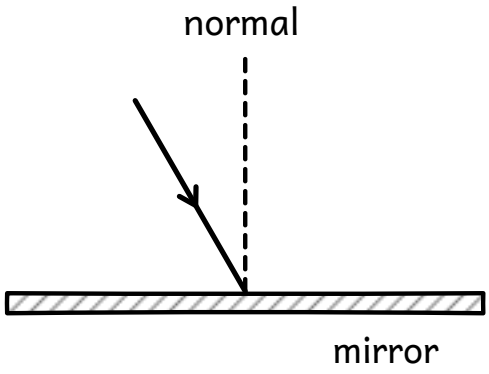
The answer is A: Away at the same slant it came in, on the other side of the upright line.

The light leaves at the same slant it came in, on the other side of the upright line. It is not random, and it does not come straight back unless it arrived straight on.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. A ray hits a flat mirror at 30° from the normal. At what angle from the normal does it leave?



A 60°

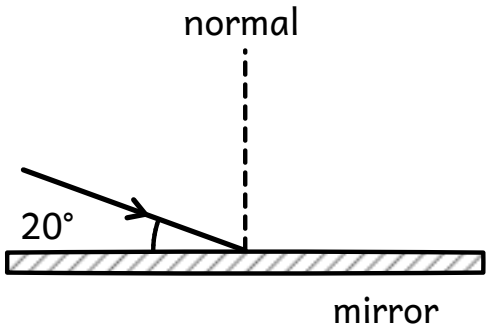
B 30°

C 150°

D 0°

Answer at the back of the book.

2. A ray makes 20° with the surface of a flat mirror. What is the angle of incidence, measured from the normal?



A 20°

B 160°

C 70°

D 110°

Answer at the back of the book.

3. You draw a ray reflecting from a flat mirror with a ruler. Which step must you do first?

   A Draw the normal at right angles to the mirror.

   B Draw the ray that leaves.

   C Measure the angle from the mirror line.

   Answer at the back of the book.

4. Why can you see your face in a smooth mirror, but not in a rough wall?

   A A wall bounces no light.

   B A smooth mirror sends light from your face one way, so it makes a clear picture.

   C A mirror makes its own light.

   Answer at the back of the book.

5. Tariq shines light at a mirror at 50° from the normal. He turns his torch so the angle becomes 20° from the normal. What happens to the angle at which the light leaves?

   A It stays at 50°.

   B It changes to 30°.

   C It changes to 20°.

   Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

The normal is a line at right angles to the mirror. The angle of reflection equals the angle of incidence, both from the normal. A smooth surface reflects one way. A rough one scatters light.

Draw: A mirror line with a dashed normal. A ray in at 30° and a ray out at 30°, with arrows.

S3.9.2 CHAPTER 2

Refraction

Why does a straight stick look bent in water?

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- ☐ **A** Light bends as it leaves the water, so our eyes are fooled.
- ☐ **B** Water really does bend the stick.
- ☐ **C** The stick goes soft when it is wet.

IF THIS FEELS HARD, READ THIS FIRST

- Level 3, Light, colour and sound, S3.9.1. You measure angles from the normal.
- Level 2, Light and shadows, S2.6.3. You see because light reaches your eyes.

BY THE END YOU CAN

- Explain why a stick looks bent in water
- Show how pouring water into a cup makes a hidden coin appear

Amina puts a straight stick into a bowl of water. At the water, the stick looks bent. She lifts it out. It is straight again. What happened?

Light travels at different speeds in different materials. A material that light goes through is a **medium**. Air, water and glass are three media.

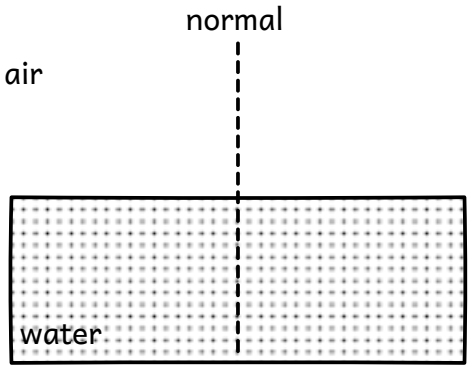
Light is quick in air. It is slower in water and slower still in glass. When a ray goes from air into water, it slows down. If it meets the surface at a slant, it also turns. We call this turning **refraction**.

Think of a cart rolling from a smooth floor onto sand at a slant. The wheel that reaches the sand first slows down first. The cart turns towards the slow side. A ray

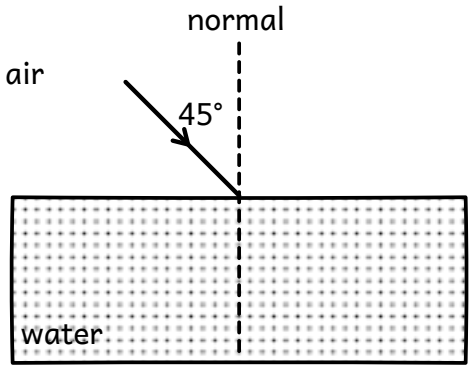
of light turns in the same way.

DRAW IT FIRST

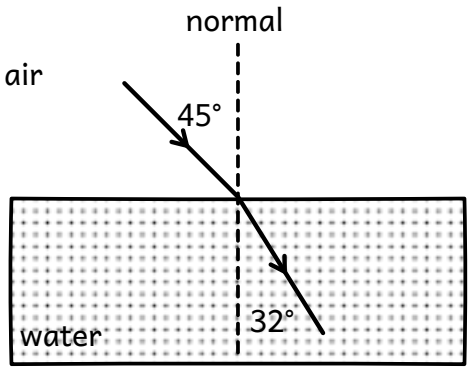
Draw a ray going into water



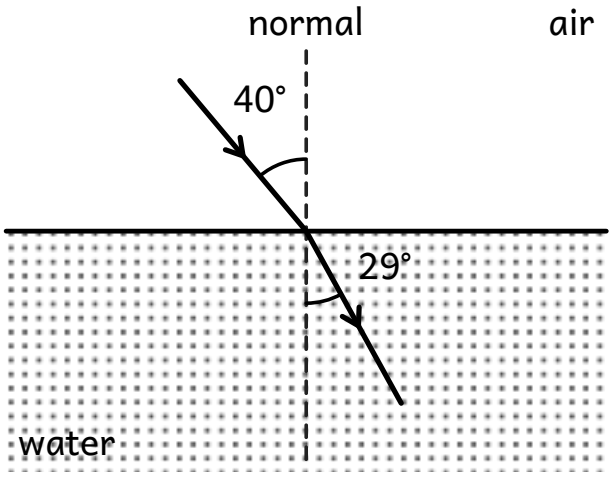
1 Draw the water surface and the normal at right angles to it.



2 Draw the ray in the air, 45° from the normal. It points at the surface.



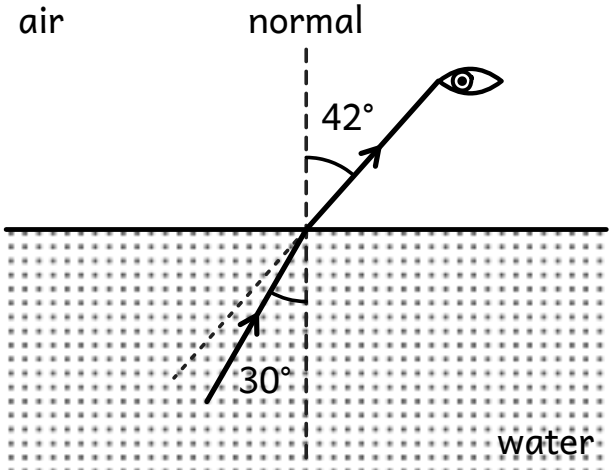
3 In the water the ray is closer to the normal. Draw it 32° from the normal. It bends towards the normal.



From air into water, the ray bends towards the normal. The angle gets smaller.

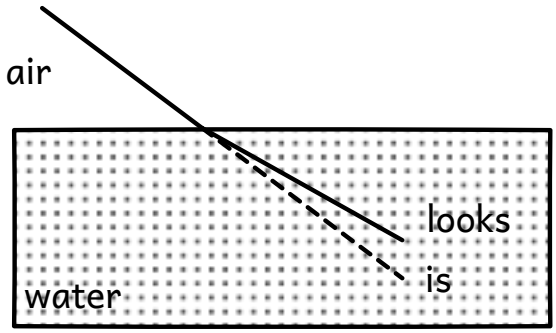
Coming out of water into air, a ray speeds up. It bends away from the normal. The angle gets bigger.

A ray that goes along the normal does not bend. It slows down but keeps going straight on.



The eye cannot know the ray bent. It traces the light back in a straight line, shown dotted. That is where the thing seems to be.

Now you can explain the stick. Light from the part under water bends as it comes out. Your eye traces it straight back, to a higher place. The part under water seems raised, so the stick looks bent.



The solid line is what you see. The dashed line is where the stick really is.

SEE IT THREE WAYS

As a picture

in air	in water
0°	0°
20°	15°
40°	29°
60°	41°

In words

The angle in the water is smaller than the angle in the air. At 0° there is no bend. A bigger angle in the air makes a bigger bend.

In symbols

air to water: the angle gets smaller. Water to air: the angle gets bigger.

Because the eye traces light straight back, water always looks shallower than it is. Looking straight down, it looks about $^{3}/_{4}$ as deep.

real depth	looks about
12 cm	? cm

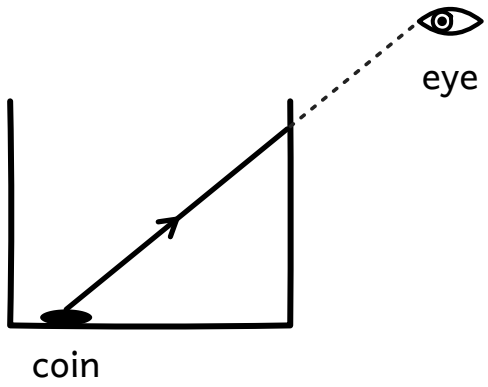
A cup of water that is 12 cm deep. About how deep does it look from straight above?

WORKED EXAMPLE

A cup holds water 12 cm deep. About how deep does it look from straight above?

1. Water looks about 3 quarters as deep as it is.
2. One quarter of 12 cm is 12 ÷ 4 = 3 cm.
3. Three quarters is 3 × 3 = 9 cm.

Answer: 9 cm



With no water, the cup wall blocks the straight line from the coin to the eye.

Now fill the cup. Light from the coin bends as it leaves the water. It now goes over the rim and into the eye. The eye traces it back, and the coin seems to float up.

Be safe. Keep a jar or a glass of water out of direct sunlight near paper or cloth. It can focus the light and start a fire.

TRY IT

Make a coin appear

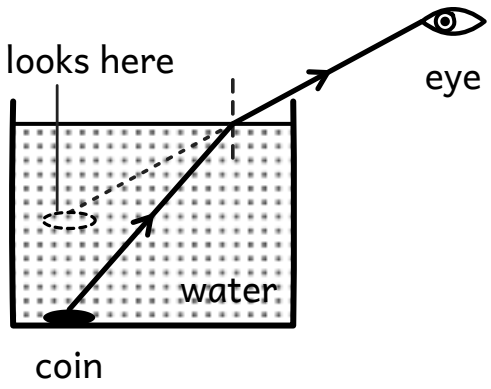
You need: an opaque cup, such as a clay or metal cup, a small flat thing, such as a coin, a button or a flat stone, water in a jug or bottle.

Be safe: Pour slowly and mop up spills so no one slips. Do not look into the Sun through water or glass.

1. Put the coin on the bottom of the empty cup.
2. Sit with your eye low. Move back until the rim just hides the coin.
3. Keep your head still. Ask a friend to pour water slowly into the cup.
4. Watch the coin. Do not move your head.

What you will see: The coin comes into view as the water rises. The coin has not moved. The light from it now bends as it leaves the water, and it reaches your eye.

If you cannot try it, this is what happens.



A WRONG IDEA MANY PEOPLE HAVE

~~Water bends the stick, or it makes things move.~~

Why it feels right: You can see the bend, and the stick looks different in water.

The test that breaks it: Pull the stick out. It is straight. Put it back and move your head until you look down from straight above it. The bend shrinks and then it is gone.

What is true: Only the light bends. Your eye traces the bent light back in a straight line. So the object seems to be in a different place.

KEY WORDS

medium
a material that light travels through, such as air, water or glass.

refraction
the bending of light when it goes from one medium into another.

BACK TO YOUR GUESS

The answer is A: Light bends as it leaves the water, so our eyes are fooled.

The stick stays straight. Light from the part under water bends as it comes out into the air. Our eyes trace it back in a straight line, so the stick seems to bend.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. The water in a well is 8 m deep. About how deep does it look from straight above?

   A 8 m

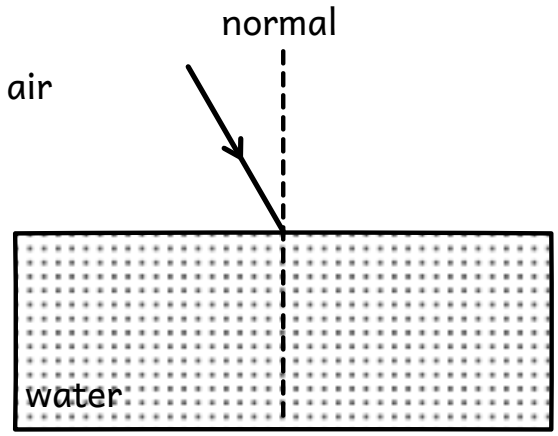
   B 11 m

   C 4 m

   D 6 m

   Answer at the back of the book.

2. A ray in air meets the surface of water at 30° from the normal. Which way does it bend as it goes into the water?



   A Away from the normal.

   B Towards the normal.

   C It does not bend.

   Answer at the back of the book.

3. Why does a straight stick look bent where it goes into water?

   A The water bends the stick.

   B The stick gets shorter in water.

   C Light from the part under water bends as it comes out, so the part seems higher.

   Answer at the back of the book.

4. Mei cannot see a coin at the bottom of an empty cup. She pours in water, and now she can see it. Why?

   A Light from the coin bends as it leaves the water, and now reaches her eye over the rim.

   B The water pushes the coin up into view.

   C The water makes its own light.

   Answer at the back of the book.

5. A ray goes from water into air at a slant. What happens to its speed and direction?

   A It slows down and bends towards the normal.

   B It speeds up and bends away from the normal.

   C It speeds up and bends towards the normal.

   Answer at the back of the book.

6. **From an earlier chapter**

   Review: a ray hits a flat mirror at 35° from the normal. At what angle from the normal does it leave?

   A 55°

   B 70°

   C 35°

   Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

Light slows down in water. A ray going in bends towards the normal. A ray coming out bends away. Eyes trace light straight back, so water looks shallower and a stick looks bent.

Draw: A water surface with a dashed normal. A ray in air at 45°. A ray in water at 32°, closer to the normal.

S3.9.3 CHAPTER 3

Lenses and the eye

> **How does my eye make a picture of the world, and why do some people need glasses?**

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- ☐ **A** The eye bends light from the object into a small upside down picture at the back.
- ☐ **B** The eye sends out light that feels the object.
- ☐ **C** Light goes through the eye and lands straight on the brain.

IF THIS FEELS HARD, READ THIS FIRST

- Level 2, Light and shadows, S2.6.3. You see when light from a thing reaches your eye.
- Level 3, Light, colour and sound, S3.9.2. A lens works by bending light.

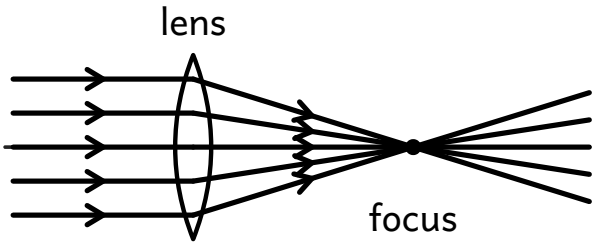
BY THE END YOU CAN

- Explain how the lens in the eye makes an image
- Explain how glasses help people see clearly
- Use a jar of water as a lens to make text look bigger

Kofi cannot see the board at the front of the class. His sister cannot read a page held close to her face. Both of them need glasses, but not the same glasses. Why?

A **lens** is a clear piece of glass or plastic with a curved surface. It bends light by refraction. A lens that is thicker in the middle is a **converging lens**, because it bends rays together.

Send parallel rays at a converging lens. Each ray bends towards the middle. They all cross at one spot, the focus. A fatter lens bends rays more, so its focus is nearer.



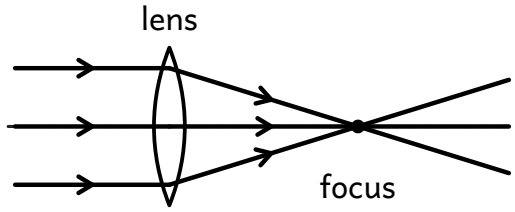
A converging lens makes parallel rays meet at the focus.

Your eye has a lens too. The clear front of the eye, the cornea, does most of the bending. The lens inside fine tunes it. Together they make a picture on the back of the eye.

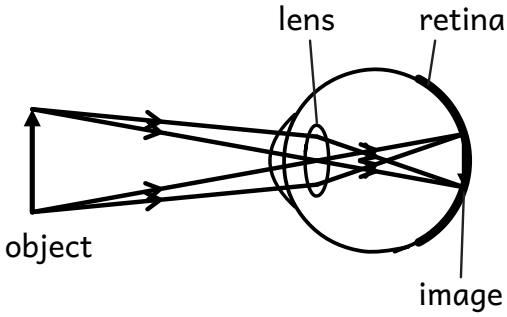
The back of the eye is the **retina**. It is a screen of tiny cells that react to light. They send signals along a nerve to the brain.

DRAW IT FIRST

Draw how a lens makes an image



1 Draw a lens that is thicker in the middle. Draw rays that meet at the focus.



2 In the eye, rays from the top and the bottom of an object cross in the lens. They meet on the retina as a small upside down image.

SEE IT THREE WAYS

As a picture

sight	glasses
short sight	diverging
long sight	converging

In words

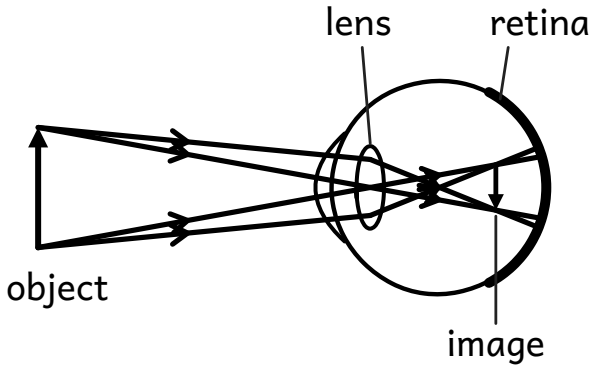
A diverging lens is thinner in the middle and spreads rays out. A converging lens is thicker in the middle and brings rays together.

In symbols

short sight: diverging lens.
long sight: converging lens.

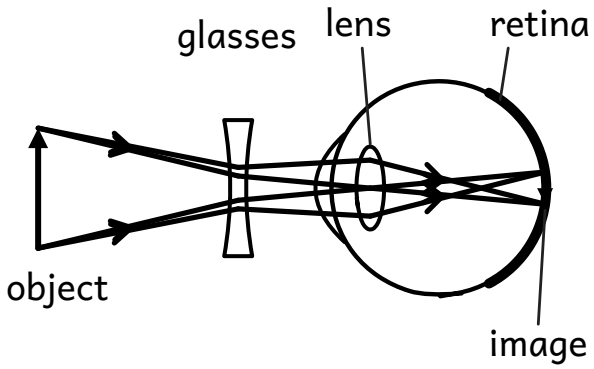
In a clear eye, rays from an object meet exactly on the retina. The picture is sharp. In some eyes, the rays meet in the wrong place. The picture on the retina is blurred.

In **short sight**, far things look blurred. The eye bends the rays too much, so they meet in front of the retina. The person sees near things clearly.



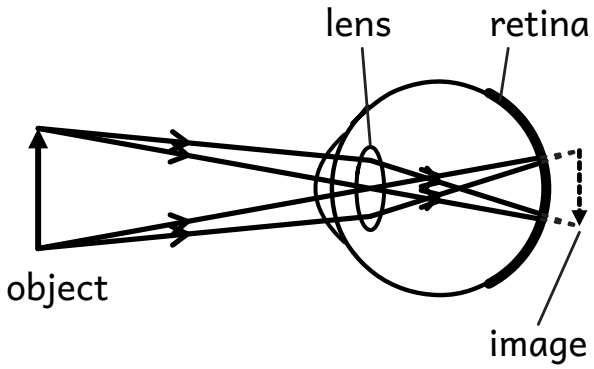
Short sight: the rays meet in front of the retina.

A **diverging lens** is thinner in the middle. It spreads rays out a little before they enter the eye. This moves the meeting point back onto the retina. Glasses with diverging lenses correct short sight.



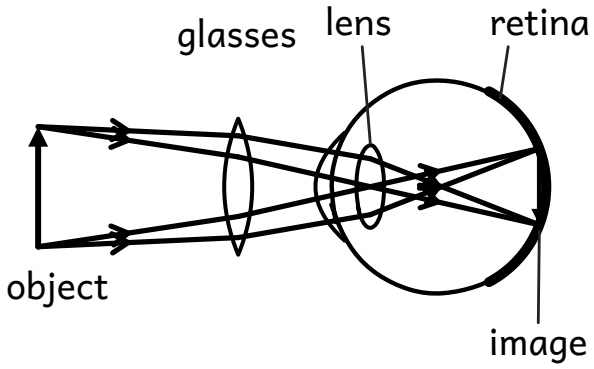
A diverging lens moves the meeting point back onto the retina.

In **long sight**, near things look blurred. The eye does not bend the rays enough. They would meet behind the retina. The person sees far things clearly.



Long sight: the rays would meet behind the retina.

A converging lens in front of the eye helps the eye bend the rays a little more. The meeting point moves forward onto the retina. Glasses with converging lenses correct long sight.



A converging lens moves the meeting point forward onto the retina.

Be safe. A jar or bottle of water can focus sunlight into a hot spot and start a fire. Use it indoors, or in shade, away from paper and cloth. Never look at the Sun through a lens.

TRY IT

Use a jar of water as a lens

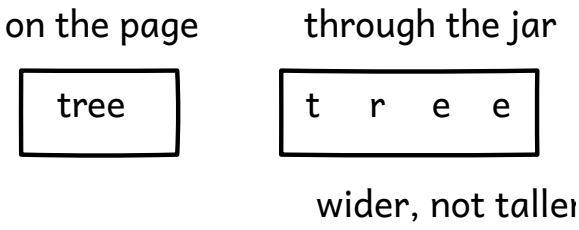
You need: a clear round jar or a clear plastic bottle, water, a page with writing on it.

Be safe: Keep the jar out of direct sunlight, and never point it at the Sun. Wipe up any spilled water.

1. Fill the jar to the top with water, so there is no bubble. Close the lid tightly.
2. Lay the page flat on a table, in a shaded place.
3. Lay the jar on its side, crossing the line of writing at right angles. Look down through the round side.
4. Lift the jar a little way off the page, then lower it. Then take the jar away and compare.

What you will see: The writing looks wider, but no taller. The round side of the jar bends light from side to side only. It is a converging lens in one direction.

If you cannot try it, this is what happens.



A WRONG IDEA MANY PEOPLE HAVE

~~The picture on the back of the eye is the right way up.~~

Why it feels right: We see the world the right way up, so the picture in the eye must be too.

The test that breaks it: On paper draw an arrow, and a lens in the middle of a page. Draw a straight line from the tip of the arrow through the middle of the lens. Draw another from its tail. The lines cross, so the tip ends up lower than the tail.

What is true: The image on the retina is small and upside down. The brain makes sense of it, so the world looks the right way up.

KEY WORDS

lens
a clear curved piece of glass or plastic, or the clear part in the eye, that bends light.

converging lens
a lens that is thicker in the middle. It brings rays together.

diverging lens
a lens that is thinner in the middle. It spreads rays out.

retina
the screen at the back of the eye where the image forms.

short sight
seeing near things clearly but far things blurred.

long sight
seeing far things clearly but near things blurred.

BACK TO YOUR GUESS

The answer is A: The eye bends light from the object into a small upside down picture at the back.

Light from the object goes into the eye, and the eye bends it. A small upside down picture forms at the back. The brain makes sense of it. The eye sends out nothing.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. Mei looks at a tree. Which part of her eye is the screen where the picture forms?

   A The lens.

   B The retina.

   C The brain.

   Answer at the back of the book.

2. What kind of picture does the lens of the eye make on the retina?

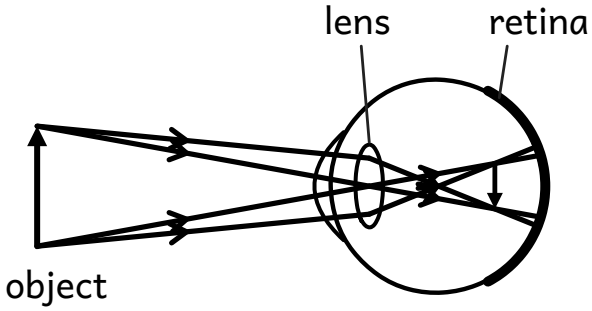
   A A big picture, the right way up.

   B A small picture, the right way up.

   C A small picture, upside down.

   Answer at the back of the book.

3. Kofi sees near things clearly but the board is blurred. In his eye, the rays from the board meet in front of the retina. Which lens in glasses helps?



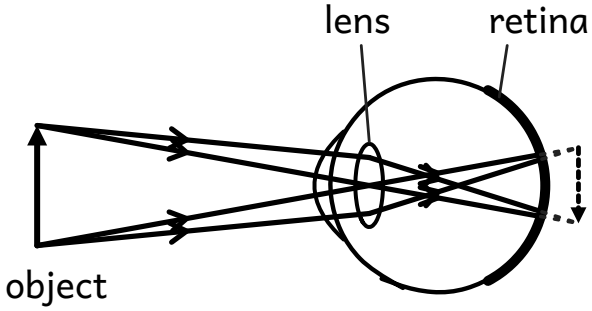
A A diverging lens, thinner in the middle.

B A converging lens, thicker in the middle.

C A flat piece of clear glass.

Answer at the back of the book.

4. Amina cannot read a page held close. In her eye, the rays would meet behind the retina. Which lens in glasses helps?



A A diverging lens, thinner in the middle.

B A converging lens, thicker in the middle.

C A flat piece of clear glass.

Answer at the back of the book.

5. Tariq fills a clear round jar with water and looks at writing through it. What does he see, and why?

   A The writing looks smaller. Water slows light down.

   B The writing looks the same. The jar is clear.

   C The writing looks wider. The round jar of water bends light like a converging lens.

   Answer at the back of the book.

6. **From an earlier chapter**

   Review: a ray goes from air into glass at a slant. What happens to the ray?

   A It slows down and bends towards the normal.

   B It speeds up and bends away from the normal.

   C It goes straight on without bending.

   Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

A converging lens is thicker in the middle and brings rays together. The eye makes a small upside down image on the retina. Short sight needs a diverging lens. Long sight needs a converging lens.

Draw: An eye with two rays from an arrow. Show them crossing in the lens and meeting on the retina, upside down.

S3.9.4 CHAPTER 4

The colours of light

Where do the colours of a rainbow come from?

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- ☐ **A** Rain is coloured, so it colours the light.
- ☐ **B** Sunlight is a mix of colours, and drops of water spread them apart.
- ☐ **C** The Sun makes colours when it shines on clouds.

IF THIS FEELS HARD, READ THIS FIRST

- Level 3, Light, colour and sound, S3.9.2. Colours split because each one bends by a different amount.
- Level 2, Light and shadows, S2.6.1. Sunlight is a source of light.

BY THE END YOU CAN

- Split light into colours with a mirror in a dish of water
- Name the colours of the spectrum in order
- Explain how raindrops make a rainbow

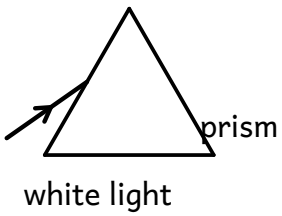
After a shower, Lucía sees a bow of colours in the sky. The Sun is behind her and the rain is in front. Where do the colours come from?

Sunlight looks white. But white light is a mix of many colours. You can pull the mix apart. A **prism** is a block of clear glass with flat sides, shaped like a wedge.

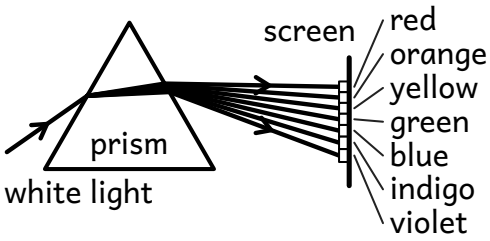
When light goes into a prism and out again, it bends twice. Each colour bends by a different amount. Red bends the least. Violet bends the most.

DRAW IT FIRST

Draw white light going through a prism



1 Draw a ray of white light going towards a prism.



2 The prism spreads the light out. Draw seven bands on a screen. Red is where the light bends least. Violet is where it bends most.

The band of colours is a **spectrum**. The colours run in this order: red, orange, yellow, green, blue, indigo, violet.

In truth, the band changes smoothly from red to violet, with no sharp edges. The seven names are a custom. People agreed on seven names to help them talk about it.

The picture is drawn with a wider fan than real glass makes, so that the names fit. In real life, the bands are much closer together.

SEE IT THREE WAYS

As a picture

order	colour
1	red
2	orange
3	yellow
4	green
5	blue
6	indigo
7	violet

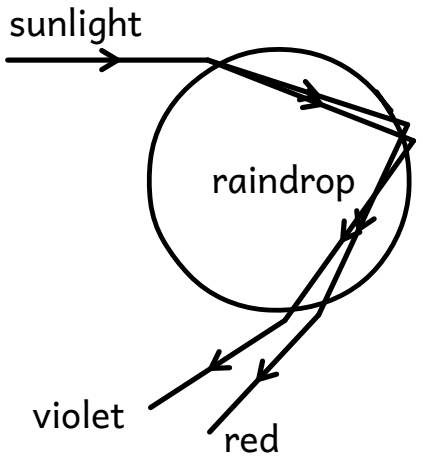
In words

The colours always come in the same order. Red bends the least, so it is at one end. Violet bends the most, so it is at the other.

In symbols

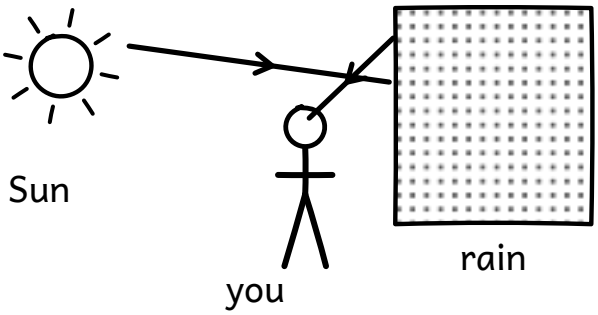
red, orange, yellow, green, blue, indigo, violet.

A rainbow is a spectrum made by raindrops. Each raindrop is a tiny ball of water. Sunlight goes into a drop and bends. It reflects off the back of the drop. Then it bends again as it comes out.



The light bends in, bounces off the back, and bends out. Each colour leaves at its own angle. The colours are drawn farther apart than they really are.

Each colour leaves the drop at a slightly different angle. So you see red light from drops in one place in the sky. You see violet light from drops in another place. All the drops together make the bow. Red is on the outside of the bow.



The Sun is behind you and the rain is in front. The light goes into the drops and back to your eyes.

This is true everywhere on Earth. You need the Sun behind you and rain in front of you. A rainbow is a sign that the Sun is shining while it rains.

Be safe. Never look at the Sun to find a rainbow. Turn your back to it. Never look at sunlight bouncing off a mirror or water, and never shine it into anyone's eyes. Throw it on a wall or the ground.

TRY IT

Make a spectrum with a mirror in water

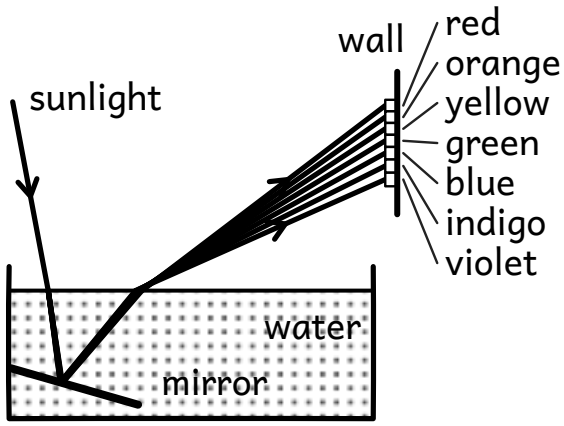
You need: a shallow dish or bowl of water, a small flat mirror, a plain white wall or a sheet of white paper, a sunny window, or a sunny spot outside next to a shaded wall.

Be safe: Never look at the Sun or at the mirror. Look only at the wall. Never point the light at anyone's face. A mirror can break, so keep it away from the edge of the table.

1. Put the dish near a window where sunlight reaches it. Hold the paper or stand near a plain wall.
2. Lean the mirror in the water, so part of the mirror is under water.
3. Turn the mirror a little at a time until sunlight bounces up onto the wall.
4. Look at the wall only. You should see a band of colours. Find the red end and the violet end.

What you will see: The colours are in the same order as with a prism. Red is at one end and violet is at the other. The water in front of the mirror is a wedge. It bends each colour by a different amount.

If you cannot try it, this is what happens.



A WRONG IDEA MANY PEOPLE HAVE

~~A prism, or the rain, adds colour to light.~~

Why it feels right: The colours come out of the prism, so it seems the prism made them.

The test that breaks it: Look at the glass, the water or a raindrop. It has no colour. The colours on the wall were already hidden in the sunlight.

What is true: White light is a mix of colours. The prism, the water and the raindrop only spread the colours apart.

KEY WORDS

prism
a block of clear glass with flat sides. It spreads white light into colours.

spectrum
the band of colours from red to violet that white light spreads into.

BACK TO YOUR GUESS

The answer is B: Sunlight is a mix of colours, and drops of water spread them apart.

Sunlight looks white, but it is a mix of colours. Water drops bend each colour by a different amount, so the colours spread apart. The drops add no colour.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. White light goes through a prism. Which colour bends the least?

   A Violet.

   B Green.

   C Red.

Answer at the back of the book.

2. Which list gives the colours of the spectrum in the right order, starting from red?

   A Red, orange, yellow, green, blue, indigo, violet.

   B Red, yellow, orange, green, blue, violet, indigo.

   C Red, orange, yellow, blue, green, indigo, violet.

   Answer at the back of the book.

3. Lucía wants to see a rainbow after a shower. How should she stand?

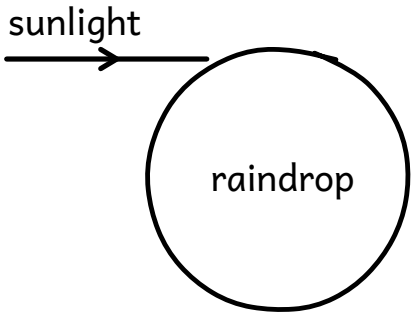
   A With the Sun in front of her, and the rain behind her.

   B With the Sun behind her, and the rain in front of her.

   C With the rain on one side and the Sun on the other.

   Answer at the back of the book.

4. How does a raindrop make colours?



   A The drop colours the light red, orange and so on.

   B The drop only reflects the light, like a mirror.

   C Light bends going in, reflects off the back, and bends again coming out. Each colour bends by a different amount.

   Answer at the back of the book.

5. Mei leans a mirror in a dish of water. Sunlight makes a band of colours on the wall. Why does the water matter?

   A The water in front of the mirror is a wedge. It bends each colour by a different amount.

   B The water adds colour to the light.

   C The water makes the light brighter.

   Answer at the back of the book.

6. **From an earlier chapter**

   Review: which glasses help a long sighted eye?

   A A diverging lens, thinner in the middle.

   B A converging lens, thicker in the middle.

   C Flat clear glass.

   Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

White light is a mix of colours. A prism spreads it into a spectrum: red, orange, yellow, green, blue, indigo, violet. Red bends the least. A rainbow is made by raindrops, with the Sun behind you.

Draw: A ray of white light going through a prism and spreading into bands. Write red at one end and violet at the other.

S3.9.5 CHAPTER 5

Why things have colour

Why is a leaf green, and what colour would it look under a red lamp?

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- ☐ **A** A leaf makes its own green light.
- ☐ **B** A leaf absorbs green light and reflects all the others.
- ☐ **C** A leaf reflects green light and absorbs the other colours.

IF THIS FEELS HARD, READ THIS FIRST

- Level 3, Light, colour and sound, S3.9.4. White light is a mix of colours.
- Level 2, Light and shadows, S2.6.3. You see a thing when its light reaches your eye.

BY THE END YOU CAN

- Explain why a leaf looks green in white light
- Predict the colour an object appears under coloured light

Joseph picks a green leaf and holds it under a red lamp. The leaf looks almost black. In daylight it was green. What changed?

You know white light is a mix of colours. For the sums in this chapter, think of it as three parts. There is a red part, a green part and a blue part. Mixed together they look white.

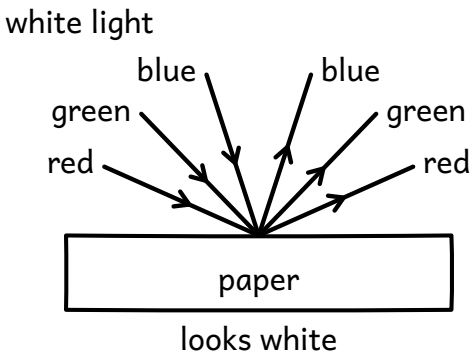
Light of one colour has only some of the parts. Red light has only the red part. Yellow light has the red part and the green part.

A thing does not make its colour. It sorts the light that falls on it. It sends some colours back, and that is reflection. It ***absorbs*** the rest. Absorb means to take in and not send on.

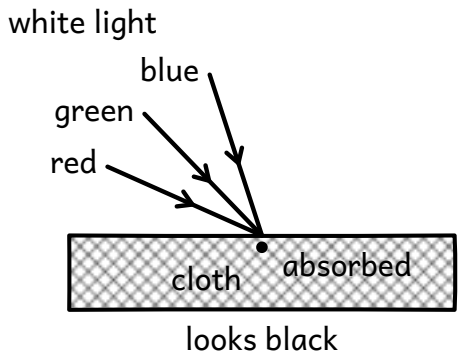
The colours that come back reach your eyes. They give the thing its colour. A red apple reflects the red part and absorbs the green and blue parts.

DRAW IT FIRST

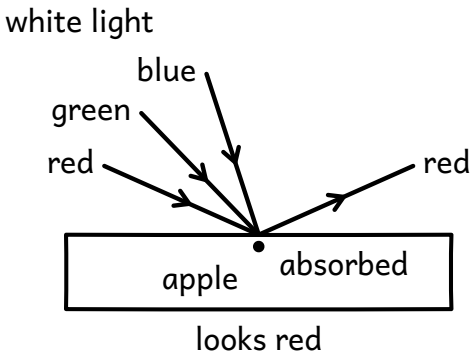
Draw white light falling on three things



1 White paper reflects all three parts. All of them reach your eyes, so it looks white.



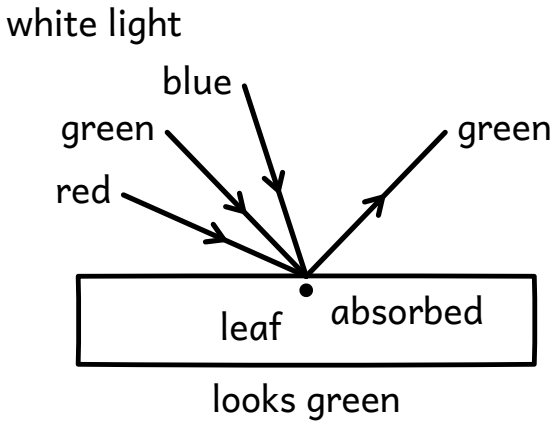
2 Black cloth absorbs all three parts. Nothing comes back, so it looks black.



3 A red apple reflects only the red part and absorbs the rest, so it looks red.

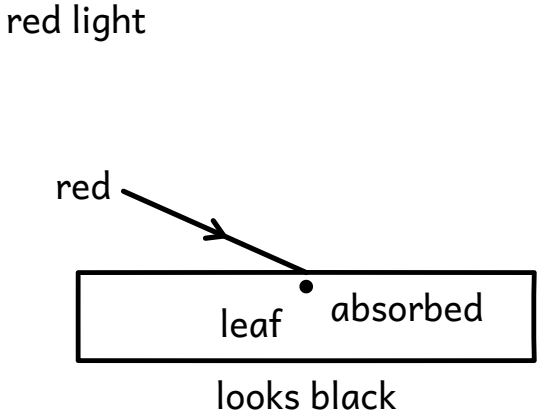
Paper, cloth and leaves scatter light every way. The pictures show just one ray of each colour, to keep them clear.

Now the leaf. In white light, a green leaf reflects the green part and absorbs the red and the blue.



A green leaf in white light reflects the green part. That is the part you see.

Under a red lamp there is only the red part. The leaf reflects green, but there is no green to reflect. It absorbs the red. Nothing comes back, so the leaf looks black or very dark.



A green leaf in red light has no green to reflect. It looks black.

So the colour you see depends on two things. One is the colours the thing reflects. The other is the colours that fall on it.

SEE IT THREE WAYS

As a picture

object	light	looks
green	white	green
green	red	black
red	green	black
white	blue	blue

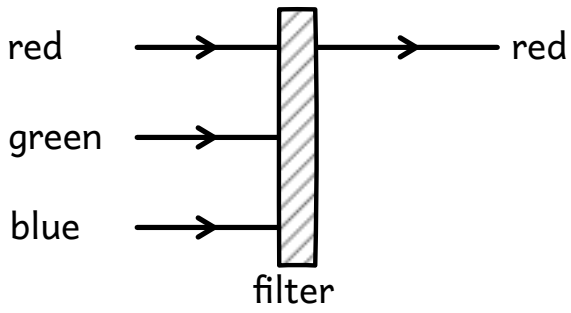
In words

A thing looks the colour of the light it reflects. If the light has none of its colour, it reflects nothing and looks black.

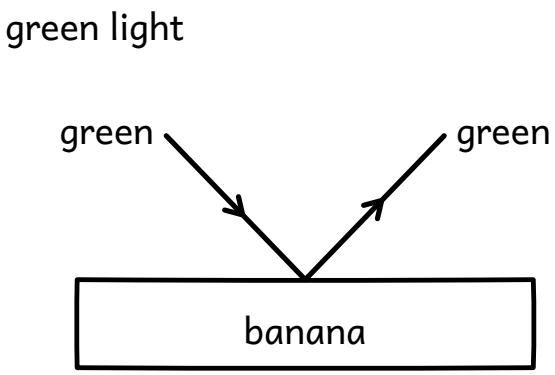
In symbols

colour seen = the colours the thing reflects that the light has.

A **filter** is a clear coloured sheet. It lets its own colour through and absorbs the rest. A red filter held up to white light lets only the red part pass.



A red filter lets the red ray through and absorbs the green and the blue.



A yellow banana reflects the red part and the green part. What does it look like in green light?

WORKED EXAMPLE

A yellow banana is in green light. What colour does it look?

1. Green light has only the green part.
2. A yellow thing reflects the red part and the green part. Out of 3 parts, it reflects 2.
3. The light has just the green part, so the banana reflects only the green part.
4. The green part reaches your eyes. The banana looks green.

Answer: green

Be safe. Never look at the Sun, even through a coloured bottle or filter. Do not drink the coloured water. Keep the bottle out of direct sunlight near paper or cloth.

TRY IT

Look through a red filter

You need: a clear plastic bottle of water coloured red with a little beetroot juice or red food colour, a green leaf, a piece of red cloth, a sheet of white paper.

Be safe: Never look at the Sun, and never point the bottle at it. Do not drink the coloured water.

1. Work in a bright room or in the shade, with daylight coming from a window.
2. Lay the leaf, the red cloth and the paper side by side on a table.
3. Look at them with your eyes. Note the colour of each.
4. Hold the bottle in front of one eye and look through it. Note the colour of each thing again.

What you will see: Through the red bottle, the leaf looks dark. The cloth looks bright red. The paper looks red. The red water is a filter. It lets only red light through to your eye.

If you cannot try it, this is what happens.

thing	looks
green leaf	black
red cloth	red
white paper	red

A WRONG IDEA MANY PEOPLE HAVE

~~A green leaf always looks green.~~

Why it feels right: In daylight we always see the leaf as green, so green seems to be a part of it.

The test that breaks it: Look at the leaf through the red bottle. It looks dark. The leaf did not change. The red filter let no green light through for it to reflect.

What is true: The colour you see depends on the light as well as the thing. The leaf only reflects green if there is green light to reflect.

KEY WORDS

absorb
to take in light and not send it on.

filter
a clear coloured sheet that lets its own colour through and absorbs the rest.

BACK TO YOUR GUESS

The answer is C: A leaf reflects green light and absorbs the other colours.

A leaf reflects green light into your eyes and absorbs the other colours. It makes no light of its own, and it does not reflect the colours it absorbs.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. Why does a leaf look green in white light?

   A It reflects the green part of the light and absorbs the other colours.

   B It makes its own green light.

   C It absorbs the green part and reflects the other colours.

Answer at the back of the book.

2. A red apple is in blue light. What colour does it look?

   A Red.

   B Blue.

   C Purple.

   D Black.

   Answer at the back of the book.

3. A white shirt is in green light. What colour does it look?

   A White.

   B Green.

   C Black.

   Answer at the back of the book.

4. A yellow banana is in red light. What colour does it look?

   A Yellow.

   B Black.

   C Red.

   Answer at the back of the book.

5. A blue filter is held up to white light. What comes out of the other side?

   A Blue light. The filter absorbs the rest.

   B All the colours, but dimmer.

   C White light with blue added to it.

   Answer at the back of the book.

6. **From an earlier chapter**

   Review: which colour of the spectrum does a prism bend the most?

   A Red.

   B Violet.

   C Green.

   Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

A thing reflects the colours it looks and absorbs the rest. White reflects all, black absorbs all. A leaf looks black in red light. A filter lets its own colour through.

Draw: White light falling on an apple. Draw the red ray bouncing back and the green and blue rays stopping.

S3.9.6 CHAPTER 6

Sound as a wave

How does sound get from a drum to my ear, and why is space silent?

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- ☐ **A** Air rushes from the drum to your ear.
- ☐ **B** Sound travels best through empty space, where nothing is in the way.
- ☐ **C** The drum shakes the air next to it. The shake passes from one bit of air to the next.

IF THIS FEELS HARD, READ THIS FIRST

- Level 2, Sound, S2.7.1. Every sound starts with something shaking.
- Level 2, Sound, S2.7.2. Sound travels through air, water and solids.

BY THE END YOU CAN

- Explain why sound cannot cross empty space
- Model a sound wave with a stretched spring or a row of people

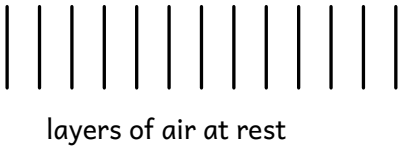
Mei beats a drum. Ravi hears it from across the yard. Nothing flew from the drum to Ravi. So how did the sound travel?

Air is made of tiny **particles**, too small to see. They move about all the time and bump into each other. A drum skin that moves out pushes the particles next to it together. A drum skin that moves back leaves them spread out.

A place where the particles are crowded together is **squashed**. A place where they are spread out is **stretched**. The squashed parts push the next particles. Those push the next ones. This pattern of squashed and stretched parts is a **sound wave**.

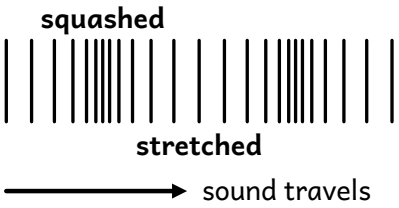
DRAW IT FIRST

Draw a sound wave in air

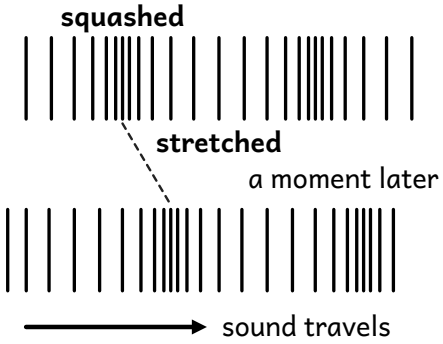


layers of air at rest

1 Draw a row of evenly spaced lines. Each line is a layer of air at rest.

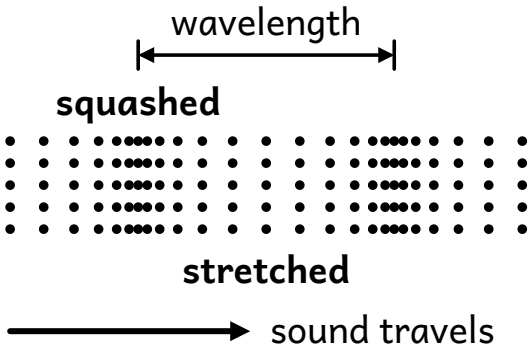


2 The drum pushes. Draw some lines close together, which is squashed, and some far apart, which is stretched.



3 A moment later the pattern has moved on. The squashed parts are farther along, but the lines themselves have only shaken a little.

Look at the third picture. The squashed parts moved to the right. But each layer of air only moves a tiny way to and fro. The pattern travels. The air stays about where it was.



The distance from one squashed part to the next is the wavelength.

The distance from one squashed part to the next is the **wavelength**. A sound wave is a pattern that moves. The wave carries the shake from the drum to your ear.

SEE IT THREE WAYS

As a picture

material	sound
air	yes
water	yes
wood	yes
empty space	no

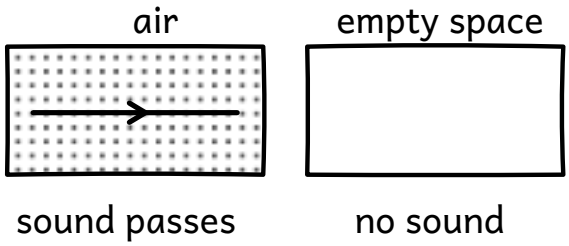
In words

Sound can pass through air, water and solids, because they are made of particles. It cannot pass through empty space, which has none.

In symbols

sound needs particles. No particles, no sound.

Far above the air, space is a **vacuum**. A vacuum has almost no particles. There is nothing to squash and stretch. So sound cannot cross it. Space is silent.



Sound goes through air. It cannot go through empty space.

Light is different. Light is not a squashing of particles, so it can cross empty space. That is how sunlight reaches us across the space between the Sun and the Earth.

TRY IT

Model a sound wave with people

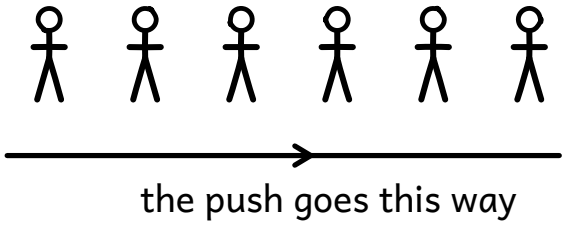
You need: six or more people, or a few friends and some space, flat ground with room to stand in a line.

Be safe: Push very gently, and stand on flat ground away from roads. Stop if anyone feels unsteady. No one should run.

1. Stand in a line, a short step apart, all facing the same way. Each person puts both hands lightly on the shoulders of the person in front.
2. The person at the back gives a gentle push forward, and then steps back.
3. Watch the push pass along the line. Each person is pushed forward a little, then comes back.

What you will see: The push travels all the way along the line. No one walks from the back to the front. Each person only moves a little forward and back. This is how a sound wave moves through air. In air, a loud sound and a quiet sound travel at the same speed.

If you cannot try it, this is what happens.



A WRONG IDEA MANY PEOPLE HAVE

~~Air rushes from the drum to your ear and carries the sound.~~

Why it feels right: You can feel a breath of air from a loud drum, so it seems that the air travels.

The test that breaks it: Hold a thin strip of paper a hand away from a drum while a friend beats it. The paper trembles in place. It is not blown away along the room.

What is true: Each particle of air only shakes a tiny way to and fro. The pattern of squashed and stretched parts travels, not the air.

KEY WORDS

particles
the tiny bits that air, water and solids are made of.

sound wave
a pattern of squashed and stretched parts that moves outwards from a source.

wavelength
the distance from one squashed part to the next.

vacuum
a place with almost no particles, such as space.

BACK TO YOUR GUESS

The answer is C: The drum shakes the air next to it. The shake passes from one bit of air to the next.

The drum shakes the air next to it. The shake passes from one bit of air to the next, like a push through a crowd. With no air, there is nothing to pass it on.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. Why can sound not cross empty space?

    A There are no particles to pass the shake along.

    B Space is too far across.

    C Space is too cold.

    Answer at the back of the book.

2. A sound wave passes through air. What do the air particles do?

    A They travel from the source to your ear.

    B Each one shakes a tiny way to and fro.

    C They stay completely still.

    Answer at the back of the book.

3. What is a squashed part of a sound wave?

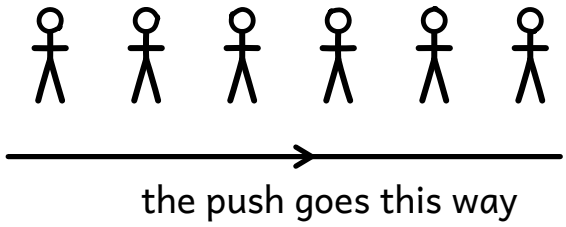
    A A place where the air particles are spread far apart.

    B A place where the air has stopped moving.

    C A place where the air particles are crowded close together.

    Answer at the back of the book.

4. Six friends stand in a line. The first one pushes the second, who pushes the third, and so on. What does this model?



    A A sound wave. The push moves along, but each person stays near the same place.

    B Air rushing from a drum. Each person walks to the end of the line.

    C Light crossing empty space. The people are not needed.

    Answer at the back of the book.

5. Which materials can sound travel through?

   A Air only.

   B Air, water and solids, but not empty space.

   C Everything, including empty space.

   Answer at the back of the book.

6. **From an earlier chapter**

   Review: a white shirt is in red light. What colour does it look?

   A White.

   B Black.

   C Red.

   Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

Sound is a pattern of squashed and stretched parts that moves through particles. The particles only shake to and fro. It needs air, water or a solid, so space is silent.

Draw: A row of lines with some close together and some far apart. Label squashed and stretched. Draw an arrow for the way the sound goes.

S3.9.7 CHAPTER 7

The speed of sound

Why do I see lightning first and hear the thunder later?

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- ☐ **A** Light travels far faster than sound, so the flash reaches you almost at once.
- ☐ **B** The thunder happens a little after the lightning.
- ☐ **C** Sound is faster, but it has farther to go.

IF THIS FEELS HARD, READ THIS FIRST

- Level 3, Speed, forces and pressure, S3.7.1. You work out a distance from a speed and a time.
- Level 3, Light, colour and sound, S3.9.6. Sound is a wave that passes through a material.

BY THE END YOU CAN

- Explain why we see lightning before we hear thunder
- Estimate a storm's distance by counting from flash to thunder

Tariq watches a storm far away. A flash lights up the sky. A few seconds later he hears a rumble. The flash and the thunder began at the same moment. Why did they reach him at different times?

The **speed of sound** in air is about 340 metres each second. We write about 340 m/s. It changes a little with the temperature.

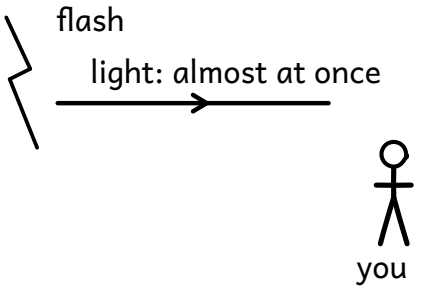
Light is far faster. The **speed of light** is about 300 000 kilometres each second. That is more than 7 times round the Earth in one second.

DRAW IT FIRST

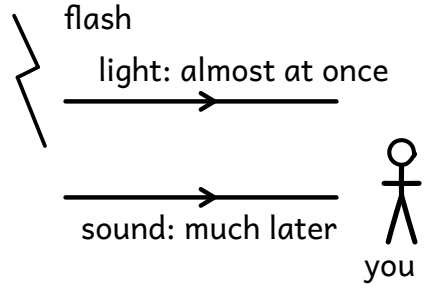
Draw a flash, light and sound



1 Draw the flash on one side and yourself on the other.

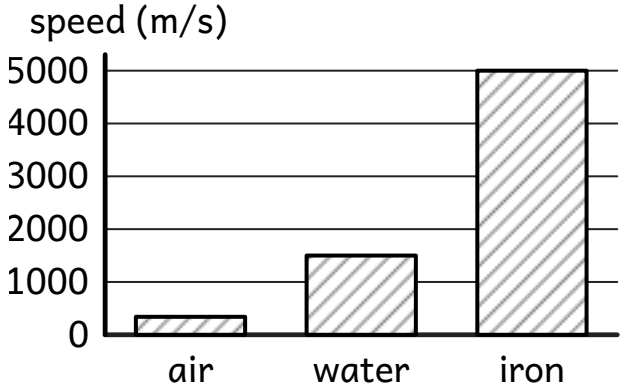


2 Draw an arrow for the light. It arrives almost at once, so you see the flash.



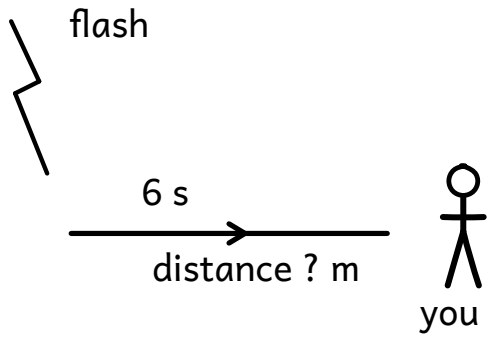
3 Draw an arrow for the sound. It is slower, so it arrives much later, and you hear the thunder.

Sound is not the same speed in everything. It travels about 340 m/s in air. It is faster in water, at about 1500 m/s. It is faster still in a solid, such as iron, at about 5000 m/s or more.



Sound goes fastest in a solid and slowest in air. In a solid the particles are held tightly to each other. Each one passes the push on quickly.

Now you can work out how far away a storm is. The sound goes about 340 metres every second. So distance = speed × time.



Tariq counts 6 seconds from the flash to the thunder. How far away is the storm?

WORKED EXAMPLE

Tariq counts 6 s from the flash to the thunder. How far away is the lightning?

1. Distance = speed × time. The speed of sound is about 340 m/s.
2. 340 × 6 = 2040 m.
3. There are 1000 m in 1 km. So the storm is about 2 km away.

Answer: 2040 m

There is a quicker way. In 3 seconds, sound goes about 1 kilometre, because 3 × 340 is about 1000. So divide the seconds by 3 to get the kilometres.

SEE IT THREE WAYS

As a picture

seconds	km
3	1
6	2
9	3
12	4

In words

Count the seconds from the flash to the thunder. Every 3 seconds is about 1 kilometre of distance.

In symbols

kilometres ≈ seconds ÷ 3.

WORKED EXAMPLE

Kofi counts 10 s from the flash to the thunder. How far away is the storm in kilometres?

1. Distance = speed × time. The speed of sound is about 340 m/s.
2. 340 × 10 = 3400 m.
3. 3400 m ÷ 1000 = 3.4 km.

Answer: 3.4 km

Be safe. If you can hear thunder, lightning can reach you. Go indoors or into a closed vehicle at once. Count only from a safe place. Never stand under a tree, or in open ground, to count.

TRY IT

Learn to count seconds, and make a storm ruler

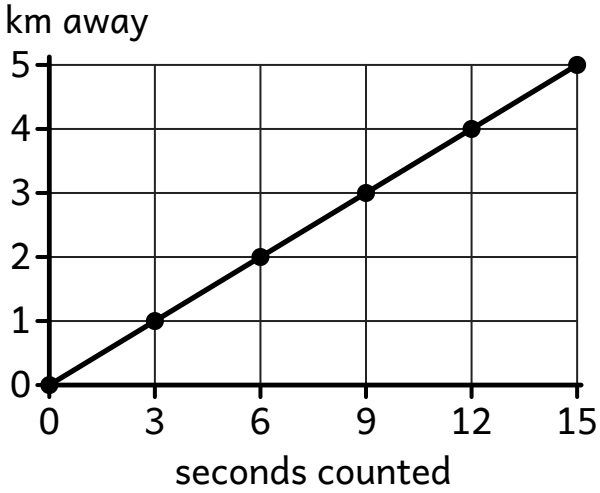
You need: a friend with a watch or a clock that shows seconds, paper and a pencil.

Be safe: Count a real storm only from indoors or from inside a closed vehicle. Stay away from windows, water and metal. If you can hear thunder, stay inside.

1. Say "one thousand and one, one thousand and two" aloud. Each count should take one second.
2. Ask your friend to time ten counts. Adjust your speed until ten counts take ten seconds.
3. Now divide each of these counts by 3: 3, 6, 9, 12 and 15. Write the kilometres next to each.
4. Next time there is a storm, count only from indoors or a closed vehicle. Count from the flash to the thunder, and use your ruler.

What you will see: Each count of 3 seconds adds about 1 kilometre. If the gap grows from one flash to the next, the storm is moving away. If it shrinks, the storm is coming closer.

If you cannot try it, this is what happens.



A WRONG IDEA MANY PEOPLE HAVE

~~The thunder happens later than the lightning.~~

Why it feels right: You always see the flash first and hear the rumble afterwards.

The test that breaks it: Ask a friend to hit two pots together far away across a field, and watch. You see the pots meet. A moment later, you hear the clang. The clang was made when the pots met.

What is true: The flash and the thunder start together. Light arrives almost at once, and sound arrives later.

KEY WORDS

speed of sound
how far sound goes in one second. In air it is about 340 m/s.

speed of light
how far light goes in one second. It is about 300 000 km.

BACK TO YOUR GUESS

The answer is A: Light travels far faster than sound, so the flash reaches you almost at once.

The flash and the thunder start together. Light is far faster than sound, so the flash reaches you almost at once. The sound is left behind and arrives later.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. Why do we see lightning before we hear thunder?

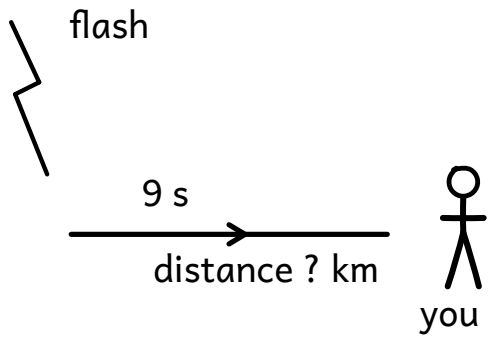
   A The thunder happens after the lightning.

   B Light travels far faster than sound.

   C Sound travels faster, but it has farther to go.

   Answer at the back of the book.

2. Ana counts 9 seconds from a flash to the thunder. About how far away is the storm?



   A 9 km

   B 27 km

   C 6 km

   D 3 km

   Answer at the back of the book.

3. Sound goes 340 m each second in air. How far does it go in 5 s?

   A 68 m

   B 345 m

   C 1700 m

   Answer at the back of the book.

4. In which of these does sound travel fastest?

   A Iron.

   B Air.

   C Water.

   Answer at the back of the book.

5. Joseph is outside and hears thunder. What should he do?

   A Stay out and keep counting, to see how far it is.

   B Go indoors, or into a closed vehicle.

   C Stand under a tall tree.

   Answer at the back of the book.

6. **From an earlier chapter**

   Review: why can sound not cross empty space?

   A Space is too cold.

   B Space is too far across.

   C There are no particles to pass the shake along.

   Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

Light is far faster than sound, so we see lightning first. Sound goes about 340 m/s. Divide the seconds from flash to thunder by 3 to find the kilometres.

Draw: A flash on the left and you on the right. A short arrow for light and a long wait for sound. Write seconds ÷ 3 = km.

S3.9.8 CHAPTER 8

Pitch, loudness and hearing

What makes one sound high and another loud, and how do loud sounds hurt my ears?

YOUR GUESS

Pick one before you read on. It is fine to be wrong.

- ☐ **A** A high sound shakes faster. A loud sound shakes bigger.
- ☐ **B** A high sound is the same as a loud sound.
- ☐ **C** A low sound shakes faster than a high sound.

IF THIS FEELS HARD, READ THIS FIRST

- Level 2, Sound, S2.7.6. A faster vibration gives a higher note.
- Level 2, Sound, S2.7.5. A bigger vibration gives a louder sound.
- Level 3, Light, colour and sound, S3.9.6. Sound is a wave of squashed and stretched parts.

BY THE END YOU CAN

- Link pitch to frequency in hertz and loudness to vibration size
- Explain why animals hear different ranges of sound
- Explain how loud sounds, measured in decibels, damage hearing

Ana plucks a short guitar string. It makes a high note. She plucks a long string. It makes a low note. She plucks the long string hard. The note is the same, but louder. What changed?

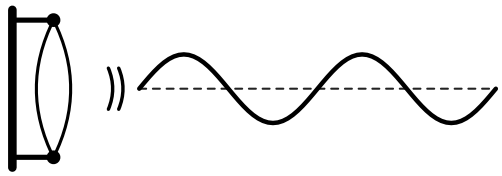
How high or low a note is, is its **pitch**. Pitch depends on **frequency**. Frequency is the number of vibrations in each second. We measure it in **hertz**, written Hz. One hertz is one vibration each second.

A string that vibrates 200 times each second has a frequency of 200 Hz. A string that vibrates 400 times each second has a frequency of 400 Hz. Its note is higher.

How loud a sound is depends on the size of the vibration. That size is the ***amplitude***. A bigger vibration pushes the air harder and carries more energy. Plucking harder makes a bigger vibration.

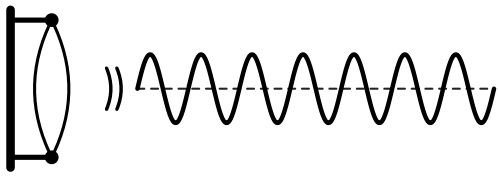
DRAW IT FIRST

Draw a low note, a high note and a loud note



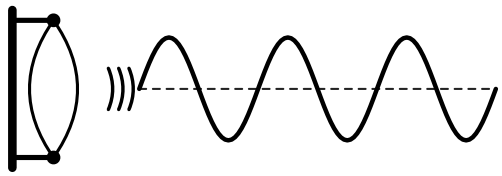
few waves: low pitch

1 Draw a wave with only a few humps in the space. It is a low pitch, a small frequency.



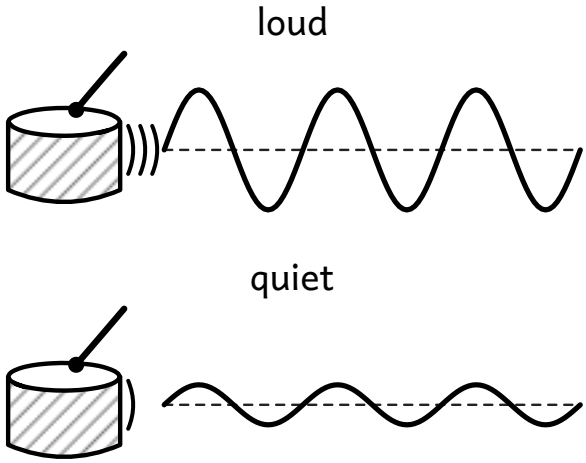
many waves: high pitch

2 Draw a wave with many humps in the same space. It is a high pitch, a large frequency.

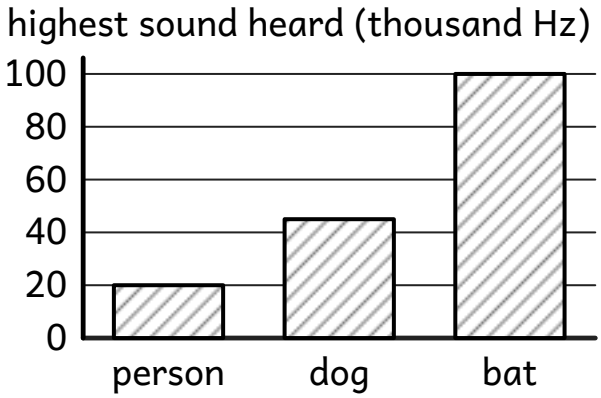


tall: loud, middle pitch

3 Draw a tall wave. The vibration is big, so the sound is loud. Pitch is about how many humps, and loudness is about how tall.



The same pitch, but a bigger vibration makes a louder sound.



About how high each animal can hear, in thousands of hertz. Some bats hear 100 000 Hz or more.

People hear sounds from about 20 Hz to about 20 000 Hz. Dogs hear higher, up to about 45 000 Hz. Bats hear much higher still. Elephants hear very low sounds, below 20 Hz, that people cannot.

Bats make very high squeaks and listen for the echoes to find insects in the dark. Elephants call with very low sounds that carry far. The herd hears them from a long way off.

Each kind of animal has ears and a brain fitted to its own life. A sound that is too high or too low for one animal can be clear to another. A dog whistle sounds silent to us. A dog hears it well.

vibrations	seconds
600	3

A string vibrates 600 times in 3 seconds. What is its frequency?

WORKED EXAMPLE

A string vibrates 600 times in 3 seconds. What is its frequency in hertz?

1. Frequency = number of vibrations ÷ seconds.
2. 600 ÷ 3 = 200.
3. The frequency is 200 Hz.

Answer: 200 Hz

Loudness is measured in **decibels**, written dB. Each 10 dB more is a sound with about ten times the energy. So 20 dB more is 10 × 10 = 100 times the energy.

SEE IT THREE WAYS

As a picture

sound	dB
whisper	30
talking	60
traffic	80
loud music	100

In words

A whisper is quiet and a loud band is very loud. The numbers climb fast, because each 10 dB is ten times the energy.

In symbols

each 10 dB more = about 10 times the energy.

WORKED EXAMPLE

Loud music is 100 dB. Traffic is 80 dB. How many times more sound energy does the music have?

1. 100 − 80 = 20 dB more.
2. Count the steps of 10 dB. 20 ÷ 10 = 2.
3. Each step is 10 times the energy. 10 × 10 = 100.

Answer: 100 times

Deep inside your ear are thousands of tiny **hair cells**. They shake when sound arrives and send signals to the brain. A very loud sound shakes them too hard. They can be damaged, and they do not grow back.

Sounds above about 85 dB, heard for a long time, damage hearing. A very loud sudden sound, such as a firework close by, can harm at once. Damage builds up slowly, and you may not notice it for years.

To protect your hearing, turn the sound down and move away from the source. Cover your ears. Take breaks from loud places.

Be safe. Never put anything into an ear, not even to clean it. Keep every sound in these activities quiet.

TRY IT

Make high and low notes with a ruler

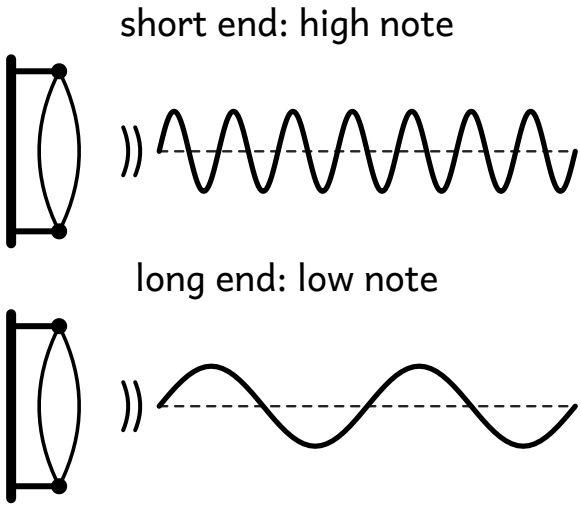
You need: a plastic ruler, or a flat strip of wood or card, a table with a firm edge.

Be safe: Flick gently, and keep your face clear of the free end. Keep the sound quiet.

1. Hold one end of the ruler flat against the table with your hand. Let the other end stick out over the edge.
2. Flick the free end gently down, and let go. Listen to the note.
3. Slide the ruler so less of it sticks out. Flick it gently again.
4. Now flick the long end, first softly and then a little harder. Listen for loud and quiet, and for high and low.

What you will see: The short end buzzes quickly. It makes a higher note. The long end moves slowly. It makes a lower note. A harder flick makes a bigger movement and a louder sound, but the note stays the same.

If you cannot try it, this is what happens.



A WRONG IDEA MANY PEOPLE HAVE

~~A high sound is a loud sound.~~

Why it feels right: In daily talk, "high" can sound like "up" or "strong". A shriek is high and loud.

The test that breaks it: Whisper in a high squeaky voice. It is high and quiet. Then hum low and strong. It is low and loud.

What is true: Pitch is how fast the vibration is. Loudness is how big it is. They are two separate things.

KEY WORDS

pitch
how high or low a note is. It depends on frequency.

frequency
the number of vibrations in one second.

hertz
the unit of frequency. One hertz is one vibration each second. We write Hz.

amplitude
the size of a vibration. A bigger one gives a louder sound.

decibels
the unit of loudness. We write dB.

hair cells
tiny cells in the inner ear that sense sound. They do not grow back.

BACK TO YOUR GUESS

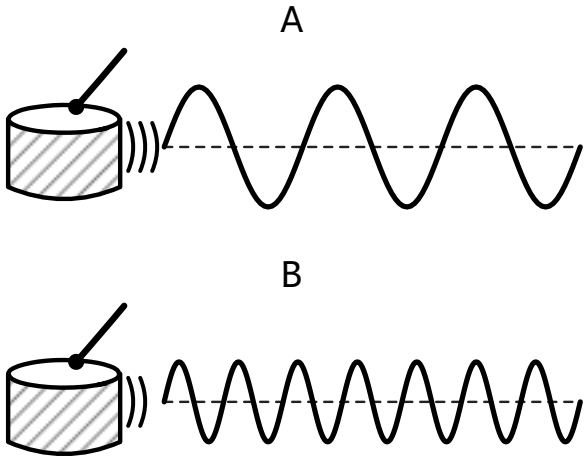
The answer is A: A high sound shakes faster. A loud sound shakes bigger.

Pitch depends on how fast the vibration is. Loudness depends on how big it is. A sound can be high and quiet, or low and loud.

CHECK YOURSELF

Try each one before you look. A wrong answer tells you where to go next.

1. Look at the two waves. Which sound is louder, and which has the higher pitch?



   A A is louder and has the higher pitch.

   B A is louder. B has the higher pitch.

   C B is louder. A has the higher pitch.

   Answer at the back of the book.

2. A string vibrates 800 times in 4 seconds. What is its frequency?

   A 3200 Hz

   B 800 Hz

   C 796 Hz

   D 200 Hz

   Answer at the back of the book.

3. A dog hears a whistle that a person cannot hear. Why?

   A The whistle is louder to a dog.

   B Dogs have bigger ears, so they hear everything.

   C The whistle is too high for people to hear, but not too high for a dog.

   Answer at the back of the book.

4. One sound is 70 dB. Another is 90 dB. About how many times more sound energy does the 90 dB sound have?

   A 20 times

   B 10 times

   C 2 times

   D 100 times

   Answer at the back of the book.

5. Lucía listens to loud music at 100 dB for hours, day after day. What can happen to her hearing?

   A The hair cells in her ears can be damaged, and they do not grow back.

   B Her ears get used to it and grow stronger.

   C The damage mends itself after a night of sleep.

   Answer at the back of the book.

6. **From an earlier chapter**

   Review: Kofi counts 12 seconds from a flash to the thunder. About how far away is the storm?

   A 12 km

   B 4 km

   C 36 km

   Answer at the back of the book.

KEEP IT

Copy this into your exercise book.

Pitch depends on frequency in hertz, the vibrations each second. Loudness depends on the size of the vibration, in decibels. Each 10 dB more is about 10 times the energy. Loud sound damages hair cells for good.

Draw: A wave with few humps, labelled low. A wave with many humps, labelled high. A tall wave, labelled loud.

Key words, A to Z

Every key word in this book, what it means, and the chapter that teaches it.

absorb
to take in light and not send it on. S3.9.5

amplitude
the size of a vibration. A bigger one gives a louder sound. S3.9.8

angle of incidence
the angle between the ray that comes in and the normal. S3.9.1

angle of reflection
the angle between the ray that leaves and the normal. S3.9.1

converging lens
a lens that is thicker in the middle. It brings rays together. S3.9.3

decibels
the unit of loudness. We write dB. S3.9.8

diverging lens
a lens that is thinner in the middle. It spreads rays out. S3.9.3

filter
a clear coloured sheet that lets its own colour through and absorbs the rest. S3.9.5

frequency
the number of vibrations in one second. S3.9.8

hair cells
tiny cells in the inner ear that sense sound. They do not grow back. S3.9.8

hertz
the unit of frequency. One hertz is one vibration each second. We write Hz. S3.9.8

lens
a clear curved piece of glass or plastic, or the clear part in the eye, that bends light. S3.9.3

long sight
seeing far things clearly but near things blurred. S3.9.3

medium
a material that light travels through, such as air, water or glass. S3.9.2

normal
a line drawn at right angles to the mirror, to measure angles from. S3.9.1

particles
the tiny bits that air, water and solids are made of. S3.9.6

pitch
how high or low a note is. It depends on frequency. S3.9.8

prism
a block of clear glass with flat sides. It spreads white light into colours. S3.9.4

reflection
light bouncing off a surface. S3.9.1

refraction
the bending of light when it goes from one medium into another. S3.9.2

retina
the screen at the back of the eye where the image forms. S3.9.3

short sight
seeing near things clearly but far things blurred. S3.9.3

sound wave
a pattern of squashed and stretched parts that moves outwards from a source. S3.9.6

spectrum
the band of colours from red to violet that white light spreads into. S3.9.4

speed of light
how far light goes in one second. It is about 300 000 km. S3.9.7

speed of sound
how far sound goes in one second. In air it is about 340 m/s. S3.9.7

vacuum
a place with almost no particles, such as space. S3.9.6

wavelength
the distance from one squashed part to the next. S3.9.6

Answers

S3.9.1. Reflection

1. **30°**

   The two angles are equal. A ray that comes in at 30° leaves at 30°.

   - **If you chose A:** You measured from the mirror, 90° − 30°. Measure both angles from the normal. Go to S3.9.1.
   - **If you chose C:** You took the angle away from 180°. The angle of reflection is the same as the angle of incidence, so just copy it. Go to S3.9.1.
   - **If you chose D:** Only a ray along the normal goes straight back. This ray came in at a slant, so it leaves at a slant. Go to S3.9.1.

2. **70°**

   The normal is at 90° to the mirror. The angle from the normal is 90° − 20° = 70°.

   - **If you chose A:** That is the angle with the mirror. The angle of incidence is measured from the normal, which is at 90° to the mirror. Go to S3.9.1.
   - **If you chose B:** You took the angle away from 180°. The normal and the mirror make 90°, so use 90°. Go to S3.9.1.
   - **If you chose D:** You added the angle to 90°. Take it away from 90° instead. Go to S3.9.1.

3. **Draw the normal at right angles to the mirror.**

   The two angles are measured from the normal, so it comes first. Then draw the ray that comes in, and then the ray that leaves at the same angle.

   - **If you chose B:** You cannot place the ray that leaves until you know the angle in. Start with the mirror and the normal. Go to S3.9.1.
   - **If you chose C:** Angles are measured from the normal, not from the mirror. Draw the normal first. Go to S3.9.1.

4. **A smooth mirror sends light from your face one way, so it makes a clear picture.**

   Each ray from your face follows the rule on a smooth surface, so the rays stay in order. A rough wall scatters them, so no picture forms.

   - **If you chose A:** You can see a wall, so light must bounce off it into your eyes. Go to S2.6.7.
   - **If you chose C:** A mirror only bounces light. With no light to bounce, it shows nothing. Go to S2.6.7.

5. **It changes to 20°.**

   The angle out equals the angle in. The new angle in is 20°, so the new angle out is 20°.

   - **If you chose A:** The light leaves at the angle it came in. When the angle in changes, the angle out changes too. Go to S3.9.1.
   - **If you chose B:** You took one angle away from the other. The angle out simply matches the new angle in. Go to S3.9.1.

S3.9.2. Refraction

1. **6 m**

   Water looks about 3 quarters as deep. 8 ÷ 4 = 2, and 2 × 3 = 6 m.

   - **If you chose A:** The light bends, so the water does not look its true depth. Go to S3.9.2.
   - **If you chose B:** Water looks shallower, not deeper. The eye traces light back to a higher place. Go to S3.9.2.
   - **If you chose C:** That is half. Water looks about 3 quarters as deep. Go to S3.9.2.

2. **Towards the normal.**

   The light slows down in water. A ray at a slant turns towards the normal, so the angle in the water is smaller.

   - **If you chose A:** That is what happens coming out of water. Going in, the light slows down and turns towards the normal. Go to S3.9.2.
   - **If you chose C:** Only a ray along the normal goes straight on. A ray at a slant bends when it changes medium. Go to S3.9.2.

3. **Light from the part under water bends as it comes out, so the part seems higher.**

   Your eye traces the bent light back in a straight line. That line leads to a higher place, so the part under water seems raised.

   - **If you chose A:** The stick is still straight when you pull it out. Only the light bends. Go to S3.9.2.
   - **If you chose B:** The stick has not changed. Light from it bends, and your eye is fooled about where it is. Go to S3.9.2.

4. **Light from the coin bends as it leaves the water, and now reaches her eye over the rim.**

   Without water the rim blocks the straight line. The bent ray passes over the rim. The eye traces it back to a place higher than the coin.

   - **If you chose B:** The coin has not moved. It only seems higher because light bends. Go to S3.9.2.
   - **If you chose C:** Water gives off no light. It only bends the light that comes from the coin. Go to S3.9.2.

5. **It speeds up and bends away from the normal.**

   Light is quicker in air than in water. A ray that speeds up turns away from the normal.

   - **If you chose A:** That is going into water. Coming out, the light speeds up and bends away. Go to S3.9.2.
   - **If you chose C:** Light that speeds up turns away from the normal. Light that slows turns towards it. Go to S3.9.2.

6. **35°**

   The angle of reflection equals the angle of incidence, so the ray leaves at 35°.

   - **If you chose A:** You measured from the mirror. Measure both angles from the normal. Go to S3.9.1.
   - **If you chose B:** You added the two angles together. The angle of reflection simply equals the angle of incidence. Go to S3.9.1.

S3.9.3. Lenses and the eye

1. **The retina.**

   The cornea and lens bend the light so it meets on the retina. The retina is the screen. Its cells send signals along a nerve to the brain.

   - **If you chose A:** The lens bends the light to make the picture. The picture forms farther back, on the retina. Go to S3.9.3.
   - **If you chose C:** The brain makes sense of the signals. The picture itself forms on the retina at the back of the eye. Go to S3.9.3.

2. **A small picture, upside down.**

   Rays from the top of the object cross in the lens and reach the bottom of the retina. The brain makes sense of the picture, so we see the world the right way up.

   - **If you chose A:** Rays from the top of an object cross in the lens. So the picture comes out upside down and small. Go to S3.9.3.
   - **If you chose B:** The rays cross in the lens. So the top of the object ends up at the bottom. Go to S3.9.3.

3. **A diverging lens, thinner in the middle.**

   The eye bends the light too much, so the meeting point is in front of the retina. A diverging lens spreads the rays a little, and the meeting point moves back onto the retina.

   - **If you chose B:** That bends rays together even more, so they would meet even farther in front of the retina. Go to S3.9.3.
   - **If you chose C:** Flat glass bends each ray going in, and back again coming out. The rays leave going the same way. The rays must be spread out a little first. Go to S3.9.3.

4. **A converging lens, thicker in the middle.**

   The eye does not bend the light enough, so the meeting point is behind the retina. A converging lens helps bend the rays, and the meeting point moves forward onto the retina.

   - **If you chose A:** That spreads the rays, so they would meet even farther behind the retina. Go to S3.9.3.
   - **If you chose C:** Flat glass bends each ray going in, and back again coming out. The rays leave going the same way. The rays need to bend a little more. Go to S3.9.3.

5. **The writing looks wider. The round jar of water bends light like a converging lens.**

   The jar is thicker in the middle from side to side. It bends light together across the jar. The writing looks wider, but no taller.

   - **If you chose A:** Slowing light is why it bends, but the bending brings the rays together. A converging lens makes the writing look larger. Go to S3.9.3.
   - **If you chose B:** Clear things can still bend light. A round jar of water bends light like a lens. Go to S3.9.2.

6. **It slows down and bends towards the normal.**

   Light is slower in glass than in air. A ray that slows down at a slant turns towards the normal.

   - **If you chose B:** That is what happens coming out of glass. Going in, light slows down and bends towards the normal. Go to S3.9.2.
   - **If you chose C:** Only a ray along the normal goes straight on. A ray at a slant bends when it changes medium. Go to S3.9.2.

S3.9.4. The colours of light

1. **Red.**

   Red bends the least and violet bends the most. The other colours are in between.

   - **If you chose A:** Violet bends the most. Red is at the other end, bent the least. Go to S3.9.4.
   - **If you chose B:** Green is in the middle. The ends are red, bent the least, and violet, bent the most. Go to S3.9.4.

2. **Red, orange, yellow, green, blue, indigo, violet.**

   The colours always come in this order. Red is bent least and violet is bent most.

   - **If you chose B:** Orange comes before yellow, and indigo comes before violet. The order is the same every time. Go to S3.9.4.
   - **If you chose C:** Green comes before blue. Check the order in the table. Go to S3.9.4.

3. **With the Sun behind her, and the rain in front of her.**

   Sunlight goes over her head into the drops. The drops send coloured light back to her eyes. She never has to look at the Sun.

   - **If you chose A:** Never look at the Sun. The light must come from behind you and bounce back from the rain in front. Go to S3.9.4.
   - **If you chose C:** The bow forms opposite the Sun. The rain must be in front of you and the Sun behind you. Go to S3.9.4.

4. **Light bends going in, reflects off the back, and bends again coming out. Each colour bends by a different amount.**

   The two bends spread the colours apart. The reflection sends the light back towards the person looking.

   - **If you chose A:** A drop has no colour to add. The colours were already in the sunlight. Go to S3.9.4.
   - **If you chose B:** A mirror would not spread the colours apart. It is the bending that splits them, and the drop bends light twice. Go to S3.9.2.

5. **The water in front of the mirror is a wedge. It bends each colour by a different amount.**

   The water makes a wedge like a prism. Each colour bends by a different amount, so the white light spreads into a spectrum on the wall.

   - **If you chose B:** Water is clear. The colours were already in the sunlight, and the water only spreads them apart. Go to S3.9.4.
   - **If you chose C:** Brighter light would still be white. The bending is what separates the colours. Go to S3.9.4.

6. **A converging lens, thicker in the middle.**

   A long sighted eye does not bend the light enough. A converging lens brings the rays together a little before they enter the eye.

   - **If you chose A:** That helps short sight. A long sighted eye needs a lens that brings rays together. Go to S3.9.3.
   - **If you chose C:** Flat glass bends light in, and back out by the same amount. The rays leave going the same way. A long sighted eye needs a lens that brings rays together. Go to S3.9.3.

S3.9.5. Why things have colour

1. **It reflects the green part of the light and absorbs the other colours.**

   White light has red, green and blue parts. The leaf sends the green part back to your eyes and absorbs the red and the blue.

   - **If you chose B:** A leaf makes no light. It only sends back some of the light that falls on it. Go to S3.9.5.
   - **If you chose C:** It is the other way round. The colour you see is the colour that is reflected, not the colour that is absorbed. Go to S3.9.5.

2. **Black.**

   Blue light has no red part. The red apple reflects only red, so it reflects nothing and looks black.

   - **If you chose A:** The apple reflects red, but there is no red in blue light. There is nothing for it to reflect. Go to S3.9.5.
   - **If you chose B:** The light is blue, but the apple only reflects red. It absorbs the blue. Go to S3.9.5.
   - **If you chose C:** Colours of light do not mix in the apple. It reflects only its own colour, and there is none in the light. Go to S3.9.5.

3. **Green.**

   White reflects all the colours that fall on it. Only green falls on it, so it reflects green and looks green.

   - **If you chose A:** A white shirt reflects every colour it gets. But the light here is green only, so only green comes back. Go to S3.9.5.
   - **If you chose C:** White things reflect all colours. There is green in the light, so the shirt reflects it. Go to S3.9.5.

4. **Red.**

   A yellow thing reflects the red part and the green part. Red light has only the red part, so the banana reflects red.

   - **If you chose A:** Yellow needs both the red and the green parts. Red light has only the red part. Go to S3.9.5.
   - **If you chose B:** A yellow banana reflects the red part. There is red in the light, so it reflects it. Go to S3.9.5.

5. **Blue light. The filter absorbs the rest.**

   A filter lets its own colour through and absorbs the rest. A blue filter lets the blue part pass and absorbs the red and the green.

   - **If you chose B:** A filter does not just dim the light. It absorbs the colours that are not its own. Go to S3.9.5.
   - **If you chose C:** A filter adds nothing. It only takes colours out of the light. Go to S3.9.5.

6. **Violet.**

   A prism bends violet the most and red the least. The other colours are in between.

   - **If you chose A:** Red is bent the least. It is at the other end of the spectrum. Go to S3.9.4.
   - **If you chose C:** Green is in the middle. The ends are red and violet. Go to S3.9.4.

S3.9.6. Sound as a wave

1. **There are no particles to pass the shake along.**

   A sound wave is squashed and stretched particles. In a vacuum there are almost none, so a sound cannot cross it.

   - **If you chose B:** Distance is not the reason. In space a sound cannot even start to travel, because there is nothing to shake. Go to S3.9.6.
   - **If you chose C:** Cold air still carries sound. What is missing in space is the particles themselves. Go to S3.9.6.

2. **Each one shakes a tiny way to and fro.**

   A particle is pushed forward, then comes back. It passes the push to the next particle. The pattern moves, but the particles stay near their places.

   - **If you chose A:** The particles do not travel the whole way. Only the pattern does. Go to S3.9.6.
   - **If you chose C:** They must move, or they could not pass the shake on. They move a tiny way and come back. Go to S3.9.6.

3. **A place where the air particles are crowded close together.**

   A squashed part has the particles close together. A stretched part has them far apart. The wave is the two of them moving outwards.

   - **If you chose A:** That is a stretched part. A squashed part is the opposite. Go to S3.9.6.
   - **If you chose B:** Air in a squashed part is still moving. It is just crowded together. Go to S3.9.6.

4. **A sound wave. The push moves along, but each person stays near the same place.**

   The people are like particles. The push passes along the line, as a sound wave does along air. Each person only moves a little.

   - **If you chose B:** No one walks to the end. Each person only moves a little, like a particle of air. Go to S3.9.6.
   - **If you chose C:** Light does not need a material. A sound wave does, and the people stand in for the particles. Go to S3.9.6.

5. **Air, water and solids, but not empty space.**

   Sound needs particles to pass the shake along. Air, water and solids have them. Empty space does not.

   - **If you chose A:** Sound also travels through water and through solids. You can hear a knock on a table through the wood. Go to S3.9.6.
   - **If you chose C:** Sound needs particles. Empty space has none, so sound cannot cross it. Go to S3.9.6.

6. **Red.**

   White reflects all colours that fall on it. Red light has only red, so the shirt reflects red and looks red.

   - **If you chose A:** White reflects every colour that falls on it, but only red falls on it here. Go to S3.9.5.
   - **If you chose B:** White reflects all colours. There is red in the light, so it reflects red. Go to S3.9.5.

S3.9.7. The speed of sound

1. **Light travels far faster than sound.**

   Light goes about 300 000 km each second and sound about 340 m each second. The flash arrives almost at once, and the thunder arrives later.

   - **If you chose A:** They start together. Sound takes longer to reach you. Go to S3.9.7.
   - **If you chose C:** They go the same distance. Sound is much slower than light. Go to S3.9.7.

2. **3 km**

   Sound goes about 1 km in 3 s. 9 ÷ 3 = 3 km.

   - **If you chose A:** You used the seconds as kilometres. Divide the seconds by 3 to get kilometres. Go to S3.9.7.
   - **If you chose B:** You multiplied by 3. Sound goes 1 km in 3 s, so you divide by 3. Go to S3.9.7.
   - **If you chose C:** You took 3 away. The rule is to divide the seconds by 3. Go to S3.9.7.

3. **1700 m**

   Distance = speed × time = 340 × 5 = 1700 m.

   - **If you chose A:** You divided the speed by the time. To find a distance, multiply the speed by the time. Go to S3.9.7.
   - **If you chose B:** You added the numbers. A speed of 340 m/s means 340 metres every second, so multiply by the seconds. Go to S3.9.7.

4. **Iron.**

   In a solid the particles are held tightly together, so the shake passes quickly. Sound goes about 5000 m/s in iron, 1500 m/s in water and 340 m/s in air.

   - **If you chose B:** Air is the slowest of the three. Its particles are only loosely joined, so the shake passes on slowly. Go to S3.9.7.
   - **If you chose C:** Water is faster than air, but a solid is faster still. Go to S3.9.7.

5. **Go indoors, or into a closed vehicle.**

   If you can hear thunder, lightning can reach you. Go inside at once. You can count from there.

   - **If you chose A:** If you can hear thunder, lightning can reach you. Count only from a safe place. Go to S3.9.7.
   - **If you chose C:** A tall tree can be struck. Never shelter under one in a storm. Go to S3.9.7.

6. **There are no particles to pass the shake along.**

   A sound wave is squashed and stretched particles. Empty space has almost none, so sound cannot cross it.

   - **If you chose A:** Cold air still carries sound. What is missing in space is the particles. Go to S3.9.6.
   - **If you chose B:** Distance is not the reason. A sound cannot even start to travel with nothing to shake. Go to S3.9.6.

S3.9.8. Pitch, loudness and hearing

1. **A is louder. B has the higher pitch.**

   A taller wave is a bigger vibration, so it is louder. More waves in the same space is a higher frequency, so it is a higher pitch.

   - **If you chose A:** Pitch is about how many waves, not how tall. B has more waves, so B has the higher pitch. Go to S3.9.8.
   - **If you chose C:** Loudness is about how tall the wave is. A is taller, so A is louder. Go to S3.9.8.

2. **200 Hz**

   Frequency = vibrations ÷ seconds = 800 ÷ 4 = 200 Hz.

   - **If you chose A:** You multiplied. Frequency is the number of vibrations in one second, so divide by the seconds. Go to S3.9.8.
   - **If you chose B:** That is the vibrations in all of the seconds. Divide by the seconds to find the number in one second. Go to S3.9.8.
   - **If you chose C:** You took the seconds away. Divide the vibrations by the seconds instead. Go to S3.9.8.

3. **The whistle is too high for people to hear, but not too high for a dog.**

   People hear about 20 Hz to 20 000 Hz. Dogs hear up to about 45 000 Hz. A whistle in between is silent to us and clear to a dog.

   - **If you chose A:** Loudness is not the reason. The whistle is too high in pitch for a person, but a dog can hear higher. Go to S3.9.8.
   - **If you chose B:** Ear size is not the whole story. Each kind of animal hears its own range, and a dog's range reaches higher than ours. Go to S3.9.8.

4. **100 times**

   90 − 70 = 20 dB, which is 2 steps of 10 dB. Each step is 10 times the energy, so it is 10 × 10 = 100 times.

   - **If you chose A:** You took the numbers away and stopped. Each 10 dB is a step of 10 times, so count the steps and multiply. Go to S3.9.8.
   - **If you chose B:** That is only one step of 10 dB. There are 2 steps from 70 to 90, so 10 × 10. Go to S3.9.8.
   - **If you chose C:** You counted the steps and stopped. Each step is 10 times the energy, so multiply 10 by itself. Go to S3.9.8.

5. **The hair cells in her ears can be damaged, and they do not grow back.**

   Loud sound for a long time damages the tiny hair cells. They do not grow back, so the hearing loss stays. She can protect her hearing by turning the music down, moving away, and taking breaks.

   - **If you chose B:** Ears do not toughen. The hair cells are damaged by loud sound, and they cannot be rebuilt. Go to S2.7.8.
   - **If you chose C:** Hair cells do not grow back. Damage from long loud sound lasts, and it adds up over time. Go to S2.7.8.

6. **4 km**

   Sound goes about 1 km in 3 s. 12 ÷ 3 = 4 km.

   - **If you chose A:** You used the seconds as kilometres. Divide the seconds by 3. Go to S3.9.7.
   - **If you chose C:** You multiplied by 3. Sound goes about 1 km in 3 s, so divide by 3. Go to S3.9.7.

About this book

For learners who can read a page alone and do sums with the four operations. In many schools this fits children of about 11 to 13, and older learners can use it too. Activities use a small mirror, a cup and water, a jar, a dish, paper, a pencil and a ruler, string, and a row of people. Nothing needs the Sun except one sunlight activity by a window, and nobody ever looks at the Sun or points a mirror at a face. A learner can work alone: every exercise has its answer and the reason for it.

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The newest copy is at https://attnom.com/academy/light-colour-and-sound.