Science 9–10

Chapter 14 — Physical sciences A: energy transfer and waves

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Contents

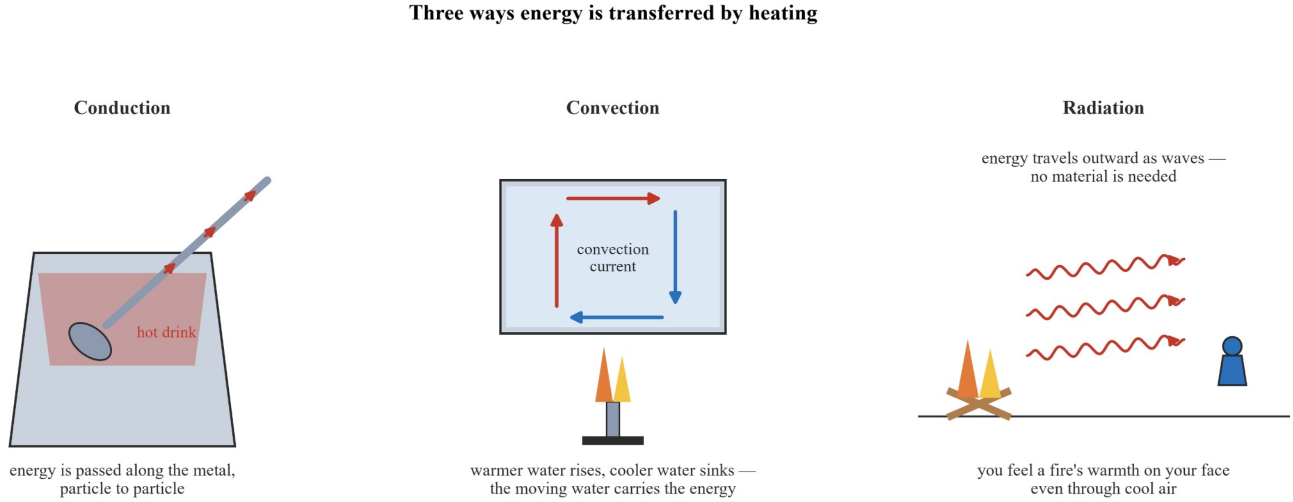
Particle and wave models of energy transfer: conduction, convection and radiation

Chapter 14 — Physical sciences A: energy transfer and waves (Science, Levels 9 and 10)

> **Subtopic 14A** · VC2 Science Understanding — Physical sciences
>
> **CD code:** `VC2S10U14` (split delivery †; this subtopic is the accountable owner of the first limb) **Content description (verbatim):** "wave and particle models can be used to describe energy transfer (conduction, convection and radiation) through different media; waves (electromagnetic and mechanical) have different properties, features (including amplitude, wavelength, frequency and speed) and applications" **This subtopic's limb (TOC §4 clause split):** wave/particle models of energy transfer — conduction, convection, radiation. Partner `14B` delivers the wave properties, features and applications. **Elaboration ids drawn on:** `VC2S10U14.E01` · `VC2S10U14.E04` · `VC2S10U14.E05` (`VC2S10U14.E07` is withheld under the TOC's D10 ICIP decision and is not taught here. Elaborations `.E02`, `.E03` and `.E06` support 14B's limb and are delivered there.) **Achievement standard (extract served):** "They explain how wave and particle models describe energy transfer, and compare the properties, features and applications of waves." **Maths links (D11):** no new maths demand is introduced; reading scales and comparing values re-uses the proportional reasoning of `VC2M9M05` (taught in Subtopic 4B).

Theory

Energy moves from hot to cool. Leave a hot cup on the bench and it cools down; leave a cold cup in the sun and it warms up. Whenever one place is hotter than another, energy is transferred from the hotter place to the cooler one. It always travels that way — from hot to cool — and it goes by one or more of three pathways: **conduction**, **convection** and **radiation**. This section uses two big models — the **particle model** and the **wave model** — to explain how each pathway works.



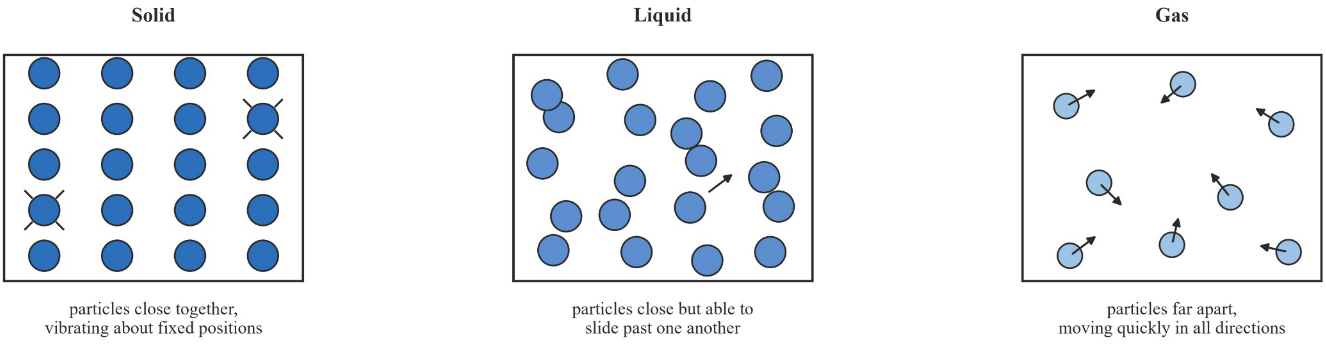
Three panels showing the three pathways: a metal spoon standing in a hot cup with arrows showing energy passing along the handle (conduction); a pot over a flame with arrows showing a circulating loop of rising and sinking water (convection); a campfire sending wavy arrows across open ground to a person, with no material between them (radiation).

The particle model. All matter is made of extremely small particles — atoms and molecules (a **molecule** is a small group of atoms joined together, acting as one particle). The particle model pictures the three states of matter like this:

- In a **solid**, the particles are close together in a regular arrangement, held in fixed positions. They cannot move about, but they **vibrate** — they shake back and forth about their fixed positions.
- In a **liquid**, the particles are still close together, but they are not held in fixed positions. They can slide past one another.
- In a **gas**, the particles are far apart and move quickly in all directions.

Heating a substance gives its particles more energy of motion. In a solid that means the particles vibrate more strongly; in a liquid or a gas it means the particles move faster. This one idea — energy stored in the motion of particles — explains both conduction and convection.

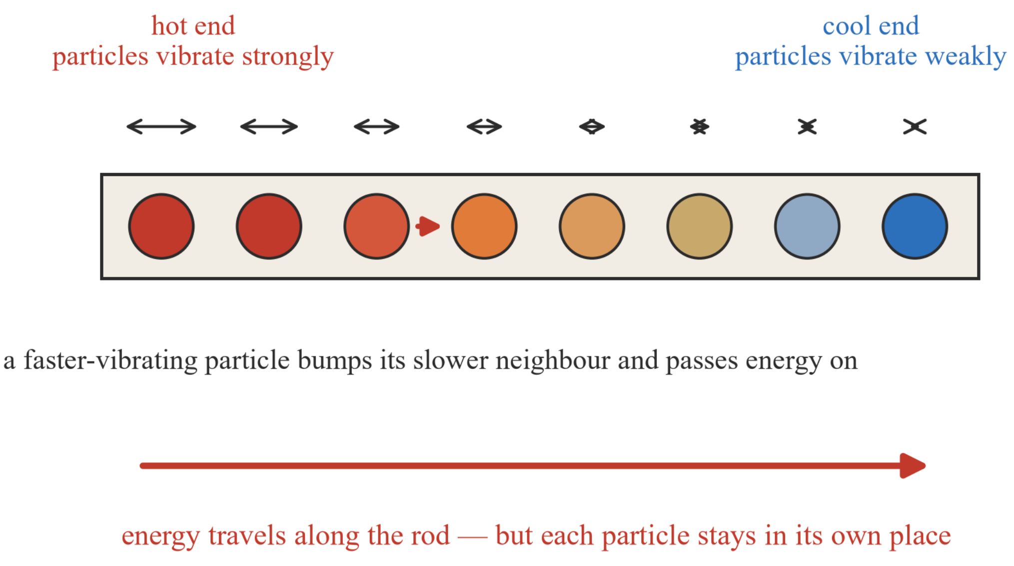
The particle model of matter — and heating gives particles more energy to move



Three boxes side by side: a solid drawn as a regular grid of close-packed particles with small vibration marks on two of them; a liquid drawn as close-packed but jostled particles with one arrow showing a particle sliding past its neighbours; a gas drawn as a few widely spaced particles with arrows showing fast motion in all directions.

Conduction — particles pass energy along, but stay in place. Conduction is the transfer of energy through a material without the material itself moving. Picture a rod with one end in a flame. The particles at the hot end vibrate strongly. Each vibrating particle bumps its neighbours and makes them vibrate more strongly too, so energy is handed along from particle to particle down the rod. The particles themselves stay where they are — only the energy travels. This is why conduction is most important in solids, where the particles are close together and always in contact.

Conduction, particle by particle — the hot end of a metal rod

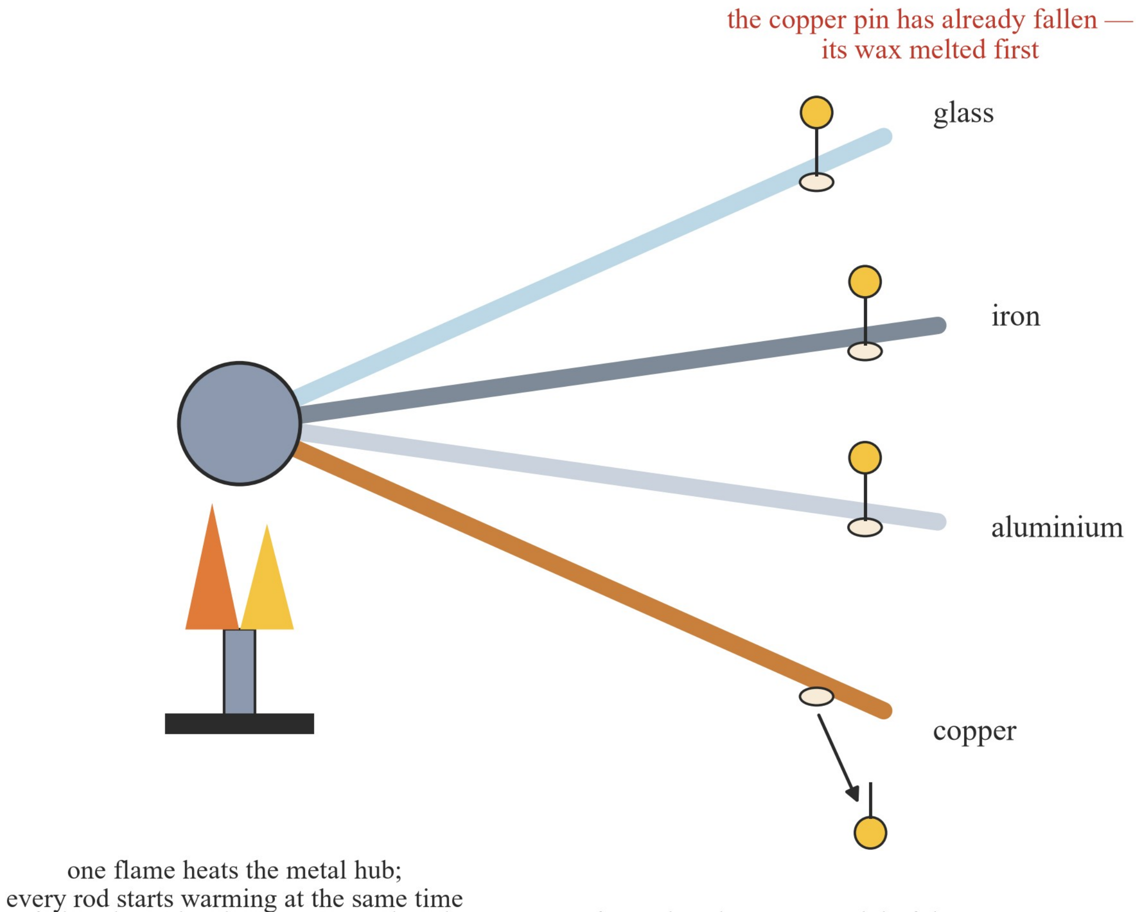


A horizontal rod with its left end hot and its right end cool, drawn as a row of particles coloured from red at the hot end to blue at the cool end; each particle has a double-headed vibration arrow above it, longest at the hot end and shortest at the cool end, with one arrow showing a faster particle bumping its slower neighbour; a long arrow below shows energy travelling from the hot end to the cool end.

Conduction happens in liquids and gases as well, but only weakly, because their particles are further apart and bump into each other less often.

Conductors and insulators. Materials that transfer energy well by conduction are called **conductors**; materials that do not transfer it well are called **insulators**. The metals — copper, aluminium, iron — are the best conductors. In a metal, some of the electrons are not fixed to one atom but are free to move between the atoms. When one end of a metal is heated, these free electrons move faster and carry energy quickly through the metal, which is why metals conduct so much better than non-metals. Wood, plastic, glass and wool are good insulators. Trapped air is also an excellent insulator, because its particles are far apart — many warm clothes and swags work by trapping air, not by being made of a warm material.

Comparing conduction: drawing pins held by wax on rods of different materials

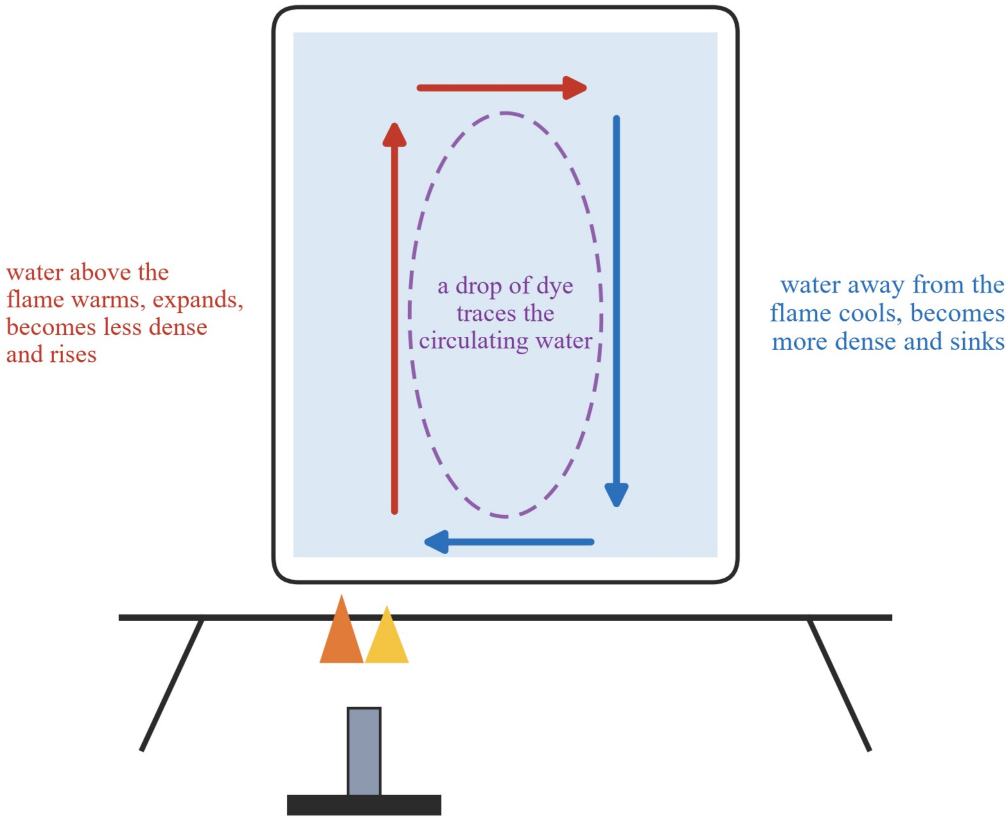


pins fall in the order the energy reaches them: copper first, glass last — a model of the apparatus, not to scale

A metal hub heated by one flame with four rods of different materials — copper, aluminium, iron and glass — sticking out of it; a drawing pin is held to the far end of each rod by a dot of wax, and the pin on the copper rod has fallen because its wax melted first.

Convection — the moving fluid carries the energy. Convection is the transfer of energy by the movement of the heated material itself, and it can only happen in **fluids** — liquids and gases. Picture a beaker of water heated by a flame at one spot of its base. The water above the flame warms, expands and becomes less **dense** (the same amount of matter takes up more room), so it rises. Cooler water nearby is more dense, so it sinks to take its place. That water warms in turn, and a circulating loop — a **convection current** — is set up, carrying energy around the beaker. In a solid, convection cannot happen at all, because the particles are held in fixed positions and cannot flow.

A convection current in a beaker of water



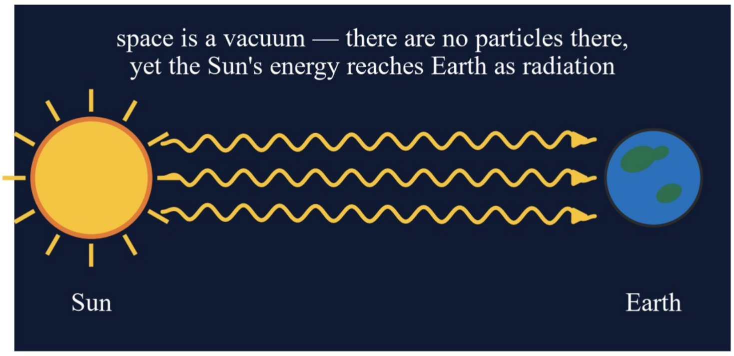
the circulating water carries energy around the beaker — convection happens only in fluids (liquids and gases)

A beaker of water on a tripod over a flame at the left of its base, with a red arrow showing warmed water rising above the flame, arrows across the top, and a blue arrow showing cooled water sinking on the far side; a dashed oval shows the loop traced by a drop of dye.

Convection currents are at work wherever fluids are heated from below: in a pot of soup, in the air of a room above a heater, and in the atmosphere on a much bigger scale, where they create winds and sea breezes.

Radiation — energy that travels as waves, needing no material. The third pathway is **radiation**: the transfer of energy by **electromagnetic waves**, which need no material — no **medium** — at all. Stand beside a fire and your face feels warm even though the air between you and the fire stays cool. The most important example is the Sun. The space between the Sun and the Earth is a **vacuum** — a region containing no matter — so conduction and convection cannot cross it. Yet the Sun's energy reaches us. It arrives as electromagnetic waves, including light and **infrared radiation**, the kind of radiation we feel as warmth. Every object gives out infrared radiation; the hotter the object, the more radiation it gives out. (The properties and features of waves themselves — amplitude, wavelength, frequency and speed — are the subject of Subtopic 14B.)

Radiation needs no medium

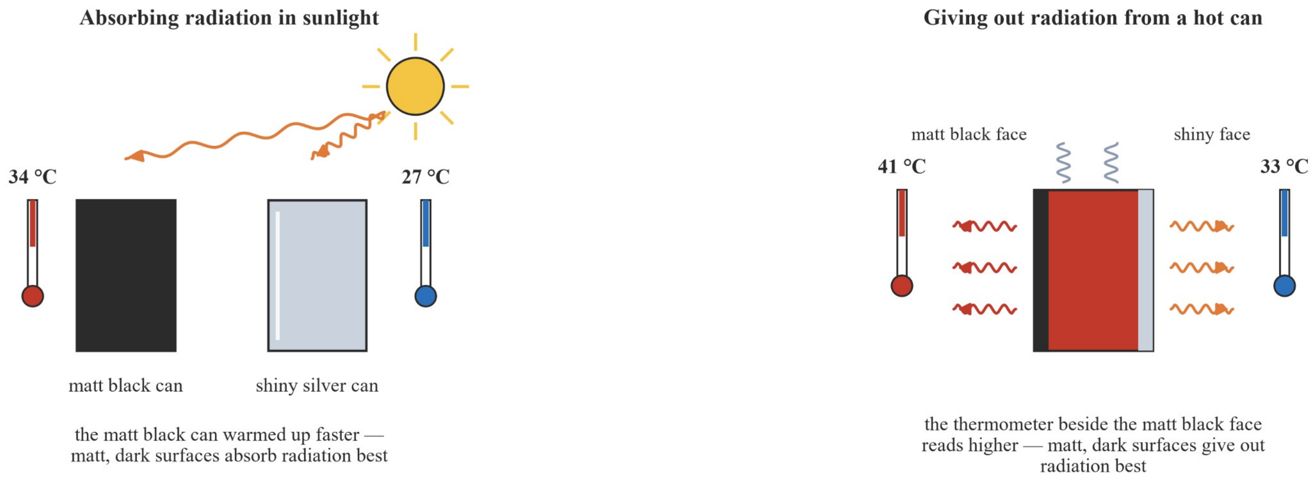


sunlight crosses about 150 million kilometres of almost empty space in about 8 minutes — conduction and convection could never do this

The Sun at the left and the Earth at the right separated by a dark band of space, with wavy arrows travelling from the Sun to the Earth; text in the band reads that space is a vacuum, so conduction and convection cannot cross it.

Surfaces and radiation. How well a surface absorbs or gives out radiation depends on the surface. **Matt, dark surfaces** are the best absorbers and the best emitters of radiation; **shiny, light surfaces** are the worst — they reflect radiation instead. This is why a matt black can of water warms up faster than a shiny silver can in sunlight, and why the same black can, filled with hot water, cools down faster by giving out more radiation.

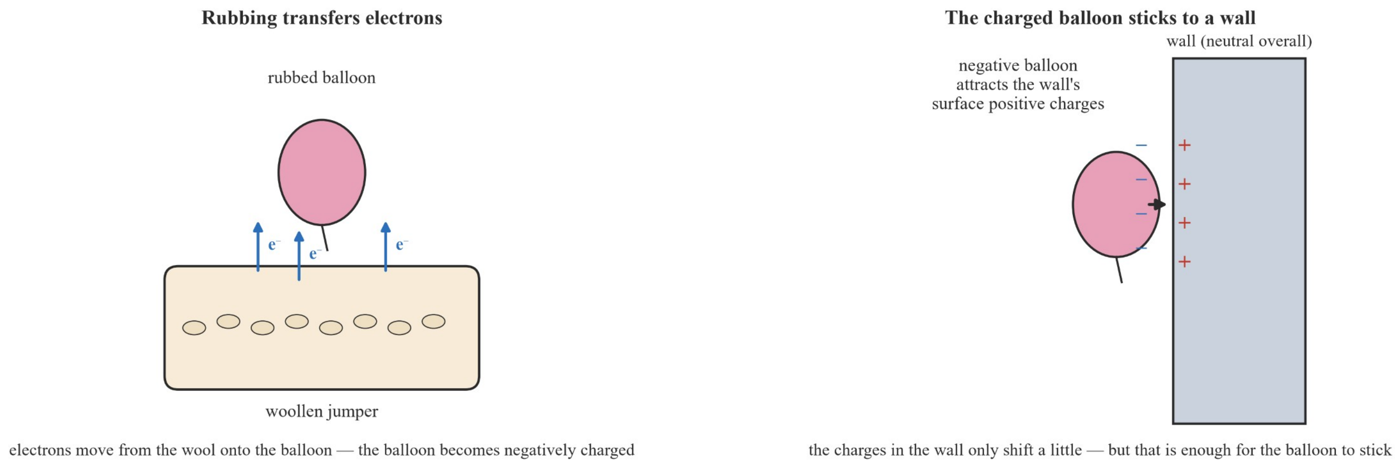
Surfaces and radiation — readings are example values for practice



Two panels. Left: a matt black can and a shiny silver can side by side in sunlight, each beside a thermometer; the thermometer by the black can reads 34 °C and the one by the shiny can reads 27 °C. Right: one hot can with a matt black face on one side and a shiny face on the other, with more wavy arrows leaving the black face than the shiny face; the thermometer beside the black face reads 41 °C and beside the shiny face 33 °C. The readings are example values for practice.

The particle model of electricity — energy carried by moving electrons. Energy can also be transferred by charged particles on the move, and the particle model explains this too. **Static electricity** is the case where the charges are at rest. Rub a balloon on a woollen jumper and some electrons — the negatively charged particles on the outsides of atoms — move from the wool onto the balloon, leaving the balloon negatively charged. Hold the balloon near a wall and it sticks: the balloon’s negative charge pulls the positive charges in the wall’s surface a little closer, and the attraction holds the balloon up. Nothing new is made; electrons have simply been transferred from one material to the other.

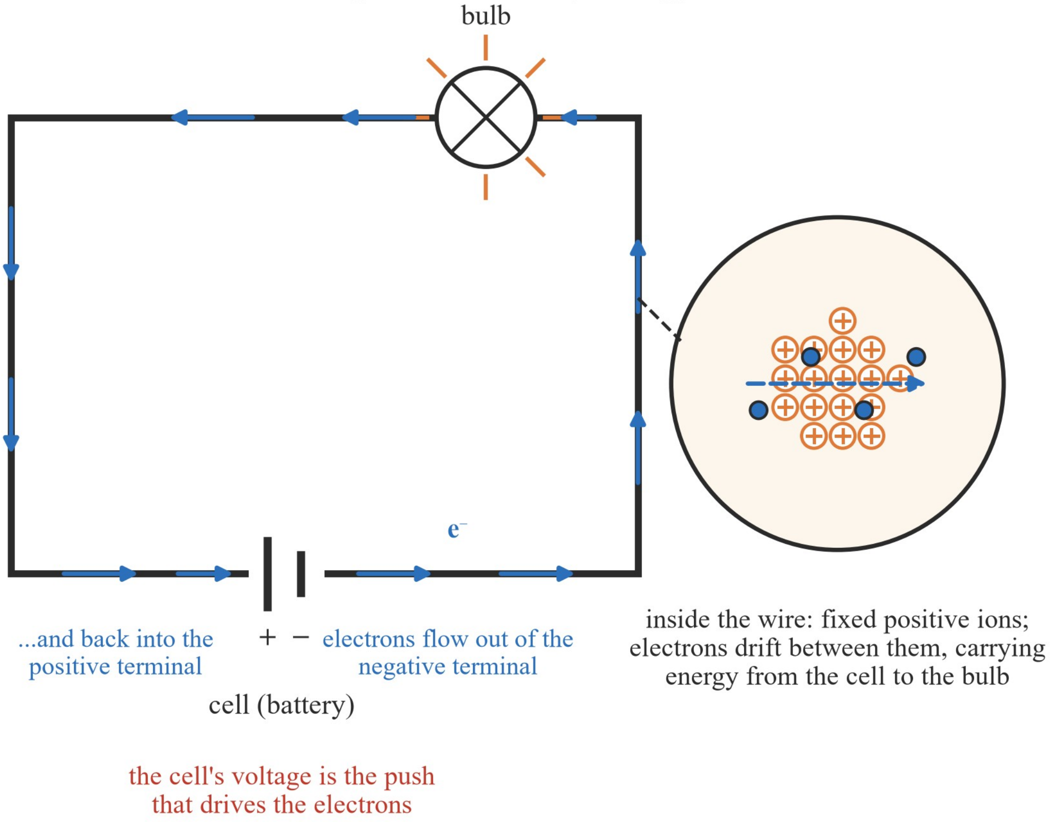
Static electricity — charges at rest, explained by moving electrons



Two panels. Left: a balloon held above a woollen jumper with arrows showing electrons moving from the wool onto the balloon. Right: the charged balloon held against a wall, with negative signs on the balloon's surface and positive signs on the wall's surface nearest the balloon, and an arrow showing the attraction between them.

Electric current is the case where the charges move. In a metal wire, the free electrons drift along the wire when the wire is joined to a cell (battery). The cell's **voltage** is the push that drives the electrons around the circuit. As the electrons drift through the wire they carry energy from the cell to whatever the circuit powers — a bulb, a motor — so the wire transfers energy by the movement of particles. A material such as copper, whose free electrons can drift easily, is an electrical **conductor**; a material such as plastic, whose electrons are held tightly to their atoms, is an electrical **insulator**.

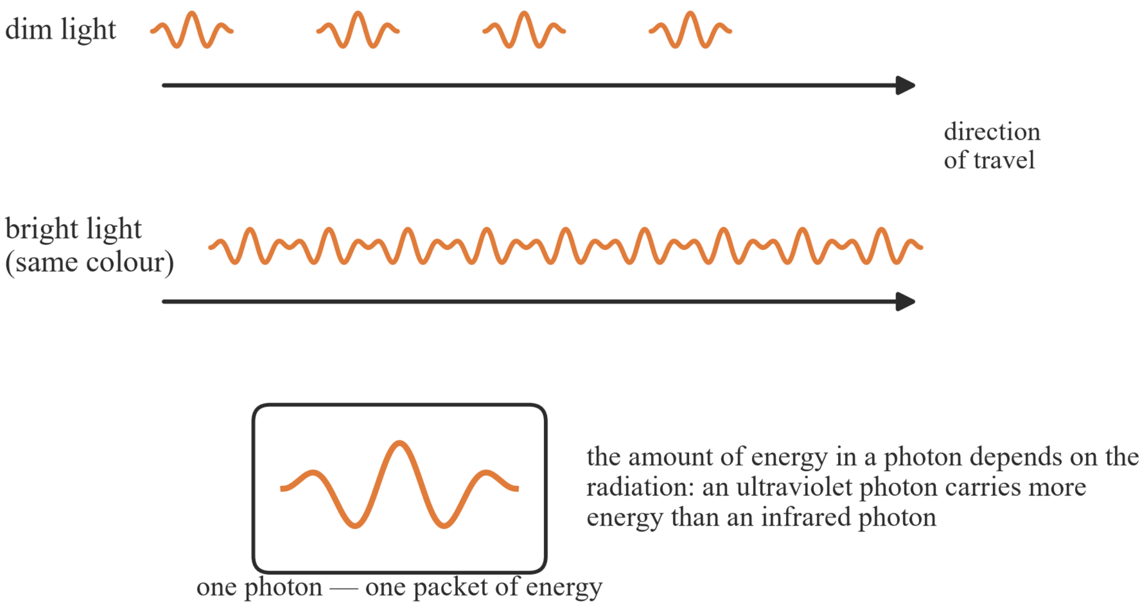
Electric current — moving electrons carry energy around a circuit



A simple circuit: a cell at the bottom connected by wires to a glowing bulb at the top, with arrows on the wires showing electrons flowing out of the negative terminal, around the circuit and back into the positive terminal; a magnified circle shows the wire's inside as a lattice of fixed positive ions with electrons drifting between them.

Two models for the same energy transfer: waves and photons. Radiation is described by **two** models, and both are needed. As a **wave model**, radiation travels as electromagnetic waves that spread out from a source, cross a vacuum, and can be reflected and absorbed by surfaces. As a **particle model**, radiation arrives in tiny packets of energy called **photons**. A brighter beam of a given colour delivers more photons each second, so it transfers more energy each second — which is why standing in bright sunlight warms you faster than standing in dim light. The amount of energy carried by **one** photon depends on the kind of radiation: an **ultraviolet** photon (the kind that causes sunburn) carries more energy than an infrared photon, which is why ultraviolet radiation damages skin in a way that ordinary light and infrared do not. The wave model and the particle model describe the **same** energy transfer from two different points of view — that is exactly what the achievement standard means by "how wave and particle models describe energy transfer".

The photon picture of light

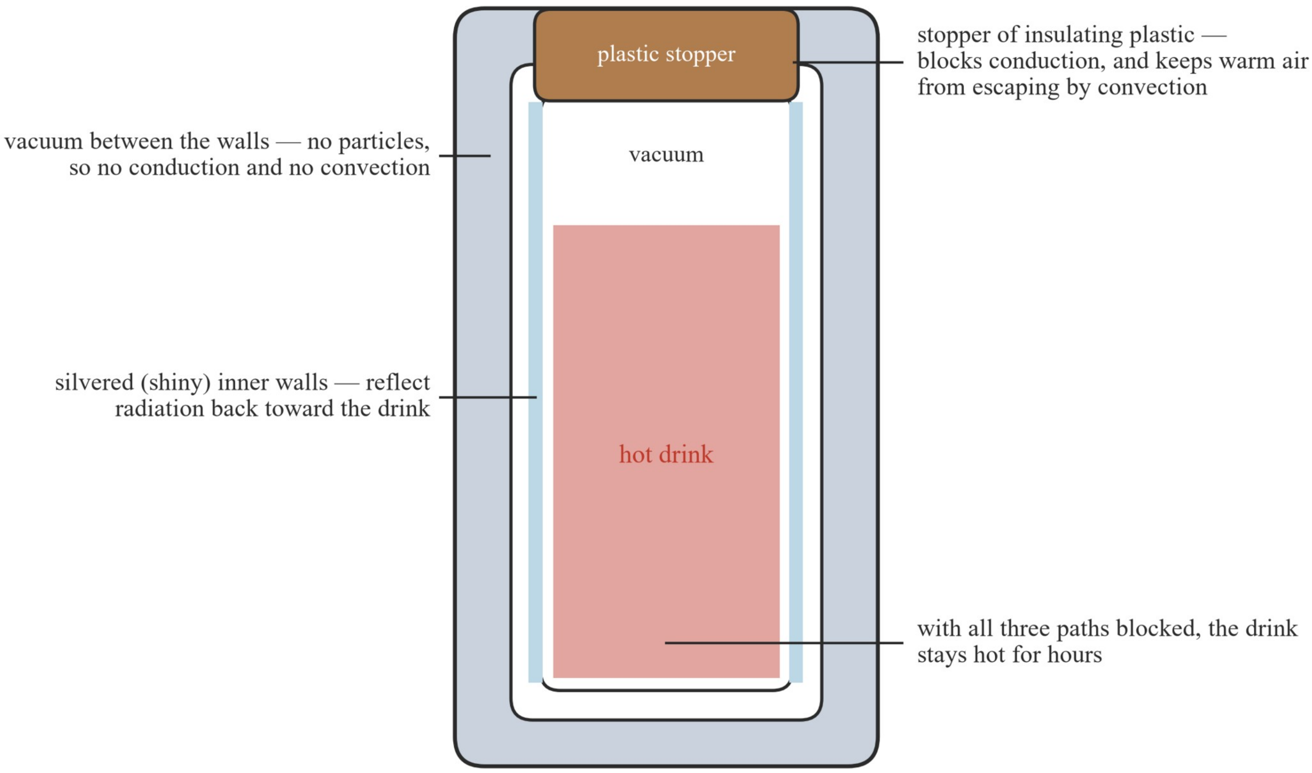


a brighter beam delivers MORE photons each second — each photon still carries the same amount of energy

Two beams travelling to the right: a dim beam drawn as a few separated wave packets and a bright beam of the same colour drawn as many more packets in the same length; below, a magnified single packet is labelled one photon, one packet of energy, with a note that an ultraviolet photon carries more energy than an infrared photon.

Putting it all together — the vacuum flask. A vacuum flask (a thermos) keeps a hot drink hot for hours by blocking all three pathways at once. The **vacuum** between its double walls has no particles in it, so no conduction and no convection can cross the gap. The **silvered (shiny) walls** reflect infrared radiation back towards the drink, cutting down radiation. The **stopper** of insulating plastic blocks conduction through the neck, and stops warm air above the drink from escaping by convection. The same flask also keeps a **cold** drink cold, because the three pathways are blocked in both directions: energy from the warm room cannot get in any more easily than energy from the drink can get out.

A vacuum flask — blocking all three transfer paths



A cross-section of a vacuum flask: an outer case, a double-walled vessel with a vacuum between the walls, shiny silvered inner walls, a plastic stopper at the top and a hot drink inside; labels explain that the vacuum blocks conduction and convection, the silvered walls reflect radiation back, and the stopper blocks conduction and keeps warm air from escaping.

Comparing the three pathways. The three pathways differ in **what carries the energy**, and in whether a material is needed at all — but all three transfer energy from a hotter place to a cooler place.

Comparing the three ways energy is transferred by heating

	what carries the energy	does it need a material (a medium)?	everyday example
conduction	particles bumping into their neighbours (in metals, moving electrons help)	yes — and it works best in solids	a metal spoon warming in a hot drink
convection	the moving fluid itself — warmer, less dense fluid rises; cooler, more dense fluid sinks	yes — in liquids and gases only (fluids)	water circulating in a heated pot
radiation	electromagnetic waves — bundles of energy called photons	no — it can cross a vacuum (empty space)	energy from the Sun reaching Earth

all three transfer energy from a hotter place to a cooler place — they differ in what carries it

A three-row table comparing the pathways: conduction carries energy by vibrating particles and free electrons in a material, needs a medium, example — a spoon warming in a hot cup; convection carries energy by the movement of *the heated fluid itself, needs a liquid or gas, example — water circulating in a pot; radiation carries energy by electromagnetic waves and photons, needs no medium at all, example — the Sun warming the Earth across empty space.*

“Cold” does not flow. One last idea is worth getting right. When an ice cube cools a drink, it can feel as if “cold flows out of the ice” into the drink. In the particle model, the opposite is what happens: the fast-moving particles of the drink bump the particles of the ice and pass energy **to** the ice, so energy is transferred from the hotter drink to the cooler ice until both are at the same temperature. There is no such thing as a flow of cold — there is only energy, transferred from hot to cool.

Activities

Activity 1 — Comparing conduction in rods (elaboration `VC2S10U14.E01`). Work in a small group. Your teacher will set up four rods of the same size — copper, aluminium, iron and glass — with their inner ends dipping into a beaker of hot water, and a drawing pin held to the outer end of each rod by a small dot of wax. (Take care with the hot water and the hot ends of the rods; do not lift the rods out of the beaker, and let everything cool before packing up.)

(a) Before the wax starts to melt, predict the order in which the pins will fall, and write your prediction with a reason for each rod.
(b) Record the actual order in which the pins fall.
(c) Explain the order using the particle model: describe what the heated particles at the inner end of each rod do, and how the energy reaches the wax.
(d) Which rod transfers energy mainly without the help of free electrons? Explain how you know this from your results.

Activity 2 — Watching a convection current (elaboration `VC2S10U14.E01`). Your teacher will set up a beaker of water on a tripod and gauze over a small flame, heating it gently at one edge of the base. When the water is still, the teacher adds one drop of food dye near the base, above the flame. (Tie back long hair, wear eye protection, and keep hands and sleeves clear of the flame and the hot tripod.)

(a) Predict the path the dye will take over the next few minutes. Sketch your prediction.
(b) Watch the dye and describe the path it actually takes.
(c) Explain the path: say why the water above the flame rises, and why water on the far side of the beaker sinks.
(d) Explain why this circulating current could never happen in a solid, such as a block of jelly heated the same way.

Activity 3 — Surfaces and radiation (elaboration `VC2S10U14.E05`). Work in pairs. Take two identical metal cans, one painted matt black and one left shiny silver. Pour the same volume of cool water into each, stand a thermometer in each can, and place both cans the same distance from a strong lamp (or in bright sunlight). Record both temperatures at the start and every 5 minutes for 10 minutes. A set of readings might look like this (example values for practice):

Time (min)	Matt black can (°C)	Shiny can (°C)
0	21	21
5	27	24
10	32	26

(a) Which can warmed up faster? Use the particle model of radiation to explain why.
(b) Now predict: if both cans were filled with **hot** water and stood in a cool room, which can would cool faster? Explain your prediction in terms of giving out radiation.
(c) A student paints the bulb of one thermometer matt black and leaves a second thermometer’s bulb shiny, then stands both the same distance from a heater. Predict and explain which reads higher.

Worked examples

All data in this section are example values for practice.

Example 1 — scaffolded

A student makes three observations while cooking on a camp stove. (a) The metal spoon left standing in the hot pot becomes too hot to hold. (b) The soup in the pot circulates as it heats. (c) Holding a hand to the **side** of the pot, the student feels warmth even though the air is cool. Name the pathway transferring energy in each observation, and give the reason.

Working	Comment
(a) Conduction. The spoon is a solid; energy passes along it from particle to particle, helped by the spoon's free electrons.	In a solid the particles stay in place, so a pathway where energy is handed along the material is conduction.
(b) Convection. The soup is a liquid; warmed soup rises and cooler soup sinks, so the moving fluid itself carries the energy.	Energy carried by the movement of the heated material, in a fluid, is convection.
(c) Radiation. Air is a poor conductor, and convection carries warm air **up**, not sideways to the hand; so the energy crosses the gap as electromagnetic waves.	A pathway that crosses a gap with no material carrying it is radiation.

The key habit is to ask two questions every time: **what carries the energy?** and **is a material needed?** The answers pick out the pathway.

Example 2 — scaffolded

A student rubs a balloon on a woollen jumper, then holds the balloon near a wall and it sticks. Explain, step by step, how the particle model of static electricity accounts for this.

Working	Comment
Rubbing transfers electrons from the wool onto the balloon.	Electrons on the outsides of atoms can move from one material to another when surfaces are rubbed together.
The balloon now carries an overall negative charge; the wool is left positive.	The balloon has extra electrons; the wool has lost the same number. Charge is transferred, not created.
Near the wall, the balloon's negative charge attracts the positive charges in the wall's surface, pulling them slightly closer.	The wall stays neutral overall; its surface charges only shift a little.
The attraction between the negative balloon and the wall's shifted positive surface holds the balloon up.	Opposite charges attract — this is the particle model of static electricity at work.

Notice the explanation never needs the charges to flow: static electricity is charge **at rest**, transferred once by rubbing.

Example 3 — unscaffolded

A vacuum flask has a double wall with a vacuum between the walls, silvered (shiny) inner walls, and a stopper of insulating plastic. Explain how each of these three features helps to keep a hot drink hot, naming the pathway or pathways each one blocks.

The vacuum between the walls contains no particles. Conduction needs particles to bump one another, and convection needs particles to flow, so the vacuum blocks **both** conduction and convection across the gap.

The silvered walls are shiny, light surfaces, the worst emitters and absorbers of radiation. They reflect infrared radiation back towards the drink instead of letting it escape, so they block **radiation** across the gap.

The stopper is made of plastic, a good insulator, so little energy is lost by **conduction** through the neck. It also seals the top, so the warm air above the drink cannot rise out and be replaced by cool air — it blocks **convection** as well.

With all three pathways blocked, energy can only escape very slowly, through the small places where the walls and stopper touch the vessel — so the drink stays hot for hours.

Example 4 — unscaffolded

Two lamps give out light of the same colour; one is dim and one is bright. Held at the same distance, the bright lamp warms your hand more quickly. (a) Explain this using the photon (particle) model of light. (b) A dim ultraviolet lamp can damage skin, while a much brighter infrared lamp mainly warms it. Explain how this is possible, even though the infrared lamp transfers more energy overall.

(a) In the photon model, a beam of light is a stream of packets of energy. Because the two lamps give out the same colour, each photon from each lamp carries the same amount of energy. The bright lamp simply delivers **more photons each second**, so more energy arrives at your hand each second, and your hand warms faster.

(b) The energy carried by one photon depends on the kind of radiation. An ultraviolet photon carries more energy than an infrared photon. To damage skin, energy must arrive in packets big enough to cause the damage; the ultraviolet lamp's photons are individually big enough, even though few arrive each second. The infrared lamp's photons are individually too small to cause that damage — they mainly make the skin's particles move faster, which we feel as warmth — however many of them arrive. Brightness changes the **number** of photons per second; the kind of radiation sets the energy of **each** photon.

Practice questions

Question 1 The three pathways. (a) Name the pathway that needs no material (medium) at all. (b) Name the pathway in which the heated material itself moves and carries the energy. (c) Name the pathway in which energy is handed from particle to particle while the particles stay in place.

Question 2 The particle model. (a) Describe how the particles of a solid move. (b) What happens to the particles of a solid when it is heated? (c) Use the particle model to explain why conduction is much weaker in a gas than in a solid.

Question 3 Conductors and insulators. (a) From this list — copper, plastic, iron, wool, aluminium, glass — pick the three best conductors of energy. (b) On a cool day, a metal bench and a wooden bench in the same park are at the same temperature, yet the metal bench feels colder to sit on. Explain. (c) Explain why saucepans are made of metal but their handles are often made of plastic or wood.

Question 4 Static electricity (elaboration `VC2S10U14.E04`). (a) Name the particle that moves from the wool onto a balloon when the balloon is rubbed on a woollen jumper. (b) What overall charge does the balloon carry after rubbing? (c) The wall is neutral overall. Explain how the charged balloon is still attracted to it.

Question 5 Surfaces and radiation. (a) A matt black can and a shiny silver can, each holding the same volume of cool water, stand side by side in sunlight. Which can's water warms faster, and why? (b) The same two cans are now filled with hot water and stood in a cool room. Which can cools faster, and why? (c) One word or short phrase for each: the best absorber of radiation is a ___ surface; the worst emitter of radiation is a ___ surface.

Question 6 Radiation across space. (a) Explain why conduction and convection cannot carry the Sun's energy to the Earth. (b) Name the kind of waves that carry the Sun's energy across space. (c) Name the particle model's packets of energy that make up light and other electromagnetic radiation.

Question 7 A saucepan of water is heated on a stove. The base of the pan is metal, the handle is plastic, and the water circulates as it heats. A student holding a hand to the side of the pan feels warmth. Identify the pathway transferring energy in each of the four bold situations — **through the base**, **in the water**, **through the handle**, **to the hand at the side** — and give a reason for each.

Question 8 On a sunny day at the beach, the land warms up faster than the sea. The air above the land warms and rises, and cooler air flows in from over the sea — a sea breeze. Explain the whole cycle using the particle model, saying at each step why the air rises or sinks. Why is the breeze much weaker on a calm, cloudy night, when the land cools faster than the sea?

Question 9 Many fridges have the freezer at the **top** of the cabinet. Using the idea of convection currents, explain why this position helps to cool the whole fridge evenly. What would happen to the air at the top of the fridge if the freezer were at the bottom?

Question 10 On a dry day, a student walks across a woollen carpet in rubber-soled shoes, then touches a metal door handle and feels a small shock, with a tiny spark. Explain what has happened, using the particle model of static electricity. Say where the charge came from and why the shock happens at the metal handle.

Question 11 Electrical wiring uses copper wires covered in a plastic coating. (a) Explain, in terms of electrons, why copper is used for the wire. (b) Explain, in terms of electrons, why the plastic coating is needed, and name the word for a material that behaves like the plastic.

Question 12 A student writes: "When I put an ice cube in my drink, cold flows out of the ice and cools the drink." Explain what is wrong with this statement, and rewrite it correctly using the idea of energy transfer between particles.

Question 13 A campfire warms a person standing to the **side** of it, even on a cold, still night. Explain why conduction and convection cannot account for this warmth, and name the pathway that does.

Question 14 A vacuum flask keeps a cold drink cold on a hot day just as well as it keeps a hot drink hot. Explain why the same three features work in both cases, naming the pathway each feature blocks.

Question 15 A bright infrared lamp held near the skin mainly warms it, while a much dimmer ultraviolet lamp can damage the skin. Use the photon model to explain both observations, distinguishing between the number of photons arriving each second and the energy carried by each photon.

Question 16 Compare the three pathways of energy transfer (this question draws on the whole section). For each of conduction, convection and radiation, state: what carries the energy; whether a material (medium) is needed; and one everyday example. Then state which two models scientists use to describe radiation, and why one model alone is not enough.

Answers

Question 1 (a) radiation; (b) convection; (c) conduction. **Question 2** (a) they vibrate (shake back and forth) about fixed positions; (b) they vibrate more strongly / with more energy of motion; (c) the particles of a gas are far apart, so they bump into each other far less often and hand energy along only weakly. **Question 3** (a) copper, iron, aluminium; (b) the metal conducts energy away from your body much faster than the wood does, so energy leaves your skin faster and the metal feels colder, even though both are at the same temperature; (c) the metal base conducts energy quickly from the stove into the food; the plastic or wood handle is an insulator, so the handle stays cool enough to hold. **Question 4** (a) the electron; (b) negative; (c) the balloon's negative charge attracts the positive charges in the wall's surface and pulls them slightly closer, so the attraction holds the balloon — the wall's charges only shift, they do not flow. **Question 5** (a) the matt black can — matt, dark surfaces are the best absorbers of radiation; (b) the matt black can — matt, dark surfaces are also the best emitters, so it gives out radiation fastest; (c) matt, dark; shiny, light. **Question 6** (a) space between the Sun and the Earth is a vacuum — it contains no matter — and both conduction and convection need particles to carry the energy; (b) electromagnetic waves (including light and infrared radiation); (c) photons. **Question 7** Through the base: conduction (a solid metal, with free electrons helping). In the water: convection (warmed water rises, cooler water sinks — the moving fluid carries the energy). Through the handle: conduction, but slowly, because plastic is an insulator. To the hand at the side: radiation (air is a poor conductor and convection carries warm air up, not sideways). **Question 8** Day: the air above the warm land warms, expands, becomes less dense and rises; cooler, more dense air from over the sea flows in to take its place — a convection current, felt as a sea breeze. Night: the land cools faster, the air above the **sea** is now the warmer, less dense air and rises, so the current reverses and is weaker — the small temperature difference drives a weaker current. **Question 9** Air cooled by the freezer becomes more dense and sinks through the cabinet, while warmer air from below rises to the freezer to be cooled — a convection current cools the whole cabinet. With the freezer at the bottom, the cold, dense air it makes would simply stay at the bottom, and the warm air at the top would never reach it, so the top of the fridge would stay warm. **Question 10** Rubbing between the shoes and the carpet transfers electrons, leaving the student's body charged (static electricity). The charge stays put because rubber and wool are insulators. At the metal handle — a conductor — the charge suddenly flows, and the moving charge is felt as a small shock and seen as a spark. **Question 11** (a) copper has free electrons that can drift easily along the wire, carrying energy from the supply to whatever the circuit powers; (b) the plastic holds its electrons tightly to their atoms, so charge cannot leave the wire or reach a person who touches it — plastic is an insulator. **Question 12** There is no flow of "cold". The fast-moving particles of the warmer drink bump the particles of the ice and pass energy to them, so energy is transferred from the hotter drink to the cooler ice; the drink's particles lose energy of motion, so the drink cools. **Question 13** Air is a poor conductor, so conduction across the gap is tiny; convection carries the warmed air **up** above the fire, not sideways to the person. The warmth felt at the side arrives as radiation — infrared electromagnetic waves, which need no medium. **Question 14** The vacuum blocks conduction and convection across the gap in both directions; the silvered walls reflect infrared radiation back into a hot drink and reflect the room's radiation away from a cold drink, blocking radiation; the plastic stopper blocks conduction through the neck and stops convection of air at the top. All three pathways are blocked for energy going out **and** for energy coming in. **Question 15** The infrared lamp delivers many photons each second, but each infrared photon carries little energy — too little to damage skin — so the energy mainly makes skin particles move faster (warmth). The ultraviolet lamp delivers fewer photons each second, but each ultraviolet photon carries enough energy to cause damage, so even a dim ultraviolet lamp damages skin. Number of photons per second sets brightness and total energy; the kind of radiation sets the energy of each photon. **Question 16** Conduction: vibrating particles and (in metals) free electrons carry the energy; a medium is needed; example — a spoon warming in a hot cup. Convection: the moving heated fluid carries the energy; a liquid or gas is needed; example — water circulating in a pot. Radiation: electromagnetic waves (photons) carry the energy; no medium is needed; example — the Sun warming the Earth. Radiation is described by both a wave model (it travels as electromagnetic waves that cross a vacuum and reflect from surfaces) and a particle model (it arrives in photons, packets whose energy depends on the kind of radiation); each model explains different observations, so one model alone is not enough.

Fully-worked solutions

Question 1 The three pathways are picked out by asking what carries the energy. (a) **Radiation** needs no material at all — electromagnetic waves cross a vacuum. (b) In **convection** the heated material itself moves and carries the energy, so it only happens in fluids. (c) In **conduction** the particles stay in place and hand energy along from particle to particle.

Question 2 (a) The particles of a solid are held in fixed positions and vibrate — they shake back and forth about those positions. (b) When the solid is heated, its particles gain energy of motion and vibrate more strongly. (c) Conduction depends on particles bumping their neighbours. In a gas the particles are far apart, so bumps are far less frequent than in a solid, and energy is handed along only weakly. (In a solid the close-packed particles are always in contact, which is why solids conduct best.)

Question 3 (a) The three metals — **copper, iron and aluminium** — are the best conductors; plastic, wool and glass are insulators. (b) Your skin is warmer than either bench. Metal is a good conductor, so it carries energy away from your skin quickly; wood is an insulator, so it carries energy away slowly. It is the **rate** at which energy leaves your skin that makes the metal feel colder, not a difference in temperature. (c) The metal base conducts energy quickly from the stove into the food, which is what a saucepan is for. The handle should stay cool enough to hold, so it is made of an insulator — plastic or wood — which conducts energy only slowly.

Question 4 (a) The **electron** — the negatively charged particle on the outside of the atom. (b) Rubbing transfers electrons from the wool onto the balloon, so the balloon carries an overall **negative** charge. (c) The wall is neutral overall, but the negative balloon attracts the wall's positive surface charges and pulls them slightly closer to the balloon. The attraction between the balloon and this shifted positive surface holds the balloon against the wall.

Question 5 (a) The **matt black** can warms faster: matt, dark surfaces are the best **absorbers** of radiation, so it takes in more of the sunlight's energy each second than the shiny can, which reflects much of it. (b) The **matt black** can also cools faster: the best absorbers are also the best **emitters**, so the black can gives out more infrared radiation each second than the shiny can. (c) Best absorber: a **matt, dark** surface. Worst emitter: a **shiny, light** surface.

Question 6 (a) Both conduction and convection need particles to carry energy — conduction by particles bumping, convection by particles flowing. The space between the Sun and the Earth is a vacuum, containing no matter, so neither pathway can cross it. (b) **Electromagnetic waves** — including light and infrared radiation — cross the vacuum. (c) **Photons**, the packets of energy that make up electromagnetic radiation.

Question 7 Work through each situation by asking what carries the energy and whether a material is needed. *Through the base:* the base is a solid metal in direct contact with the stove — energy is handed along by vibrating particles and carried by free electrons: **conduction**. *In the water:* the water is a liquid; warmed water above the base becomes less dense and rises while cooler water sinks — the moving fluid carries the energy: **convection**. *Through the handle:* the handle is a solid, so the pathway is **conduction** — but plastic is an insulator, so the energy travels slowly and the handle stays cool enough to hold. *To the hand at the side:* the air in the gap is a poor conductor, and convection carries the warm air **up** above the pan rather than sideways to the hand. The warmth felt at the side therefore arrives as electromagnetic waves: **radiation**.

Question 8 During the day the land warms faster than the sea. The air above the land is heated from below: it warms, expands, becomes less dense and rises. Cooler, more dense air from over the sea flows in along the ground to take its place, and this inflow is felt as a **sea breeze** — a convection current on a large scale. At night the land cools faster than the sea, so the warmer air is now over the sea, and it rises there; the current runs the other way (a land breeze). Because the temperature difference between land and sea is smaller at night, the air is pushed about less strongly, the current is weaker, and the breeze is much lighter.

Question 9 Air touching the freezer at the top is cooled, becomes more dense and sinks down through the cabinet. Warmer, less dense air from below rises to the top, is cooled in turn, and sinks — a convection current that carries cooling around the whole cabinet. If the freezer were at the bottom, the cold, dense air it makes would stay pooled at the bottom — cold air does not rise — and the warm air at the top would never be brought down to be cooled. The bottom would be very cold while the top stayed warm.

Question 10 As the rubber soles rub against the woollen carpet, electrons are transferred between the two materials, leaving the student's body with an overall charge. Because rubber, wool and dry air are insulators, the charge cannot escape and stays **static** on the student. When a finger approaches the metal handle — a conductor — the charge suddenly flows across the small gap as a tiny spark. It is this sudden flow of charge that is felt as a small shock.

Question 11 (a) In copper, some electrons are free to move between the atoms. When the wire is joined to a supply, the supply's voltage pushes these free electrons into a drift along the wire, and the drifting electrons carry energy from the supply to whatever the circuit powers. Copper is used because its free electrons drift easily — it is a good electrical conductor. (b) In plastic, the electrons are held tightly to their atoms and cannot drift, so charge cannot pass out of the wire into anything (or anyone) that touches it. A material that behaves this way is called an **insulator**. The coating keeps the current in the wire and makes the cable safe to handle.

Question 12 The statement is wrong because there is no such thing as “cold” that can flow. Temperature reflects the energy of motion of particles: the drink’s particles move faster than the ice’s. Where they touch, the faster particles bump the slower ones and pass energy to them, so energy is transferred **from the hotter drink to the cooler ice**. The drink’s particles lose energy of motion, and the drink cools. Correctly: “Energy is transferred from the drink to the ice, so the drink cools.”

Question 13 Conduction across the gap would need the air to carry the energy by particles bumping, but air is a poor conductor — its particles are far apart — so conduction transfers almost nothing across the gap. Convection does carry energy from the fire, but convection moves the warmed air **upwards**, away from the person at the side. The warmth felt at the side therefore arrives by **radiation**: infrared electromagnetic waves travelling straight from the fire to the person, needing no medium at all.

Question 14 Consider energy trying to cross the gap between the drink and the room, in either direction. The **vacuum** has no particles, so neither conduction (particles bumping) nor convection (particles flowing) can cross it — this works the same whether the drink is hot (energy trying to get out) or cold (energy trying to get in). The **silvered walls** are shiny, light surfaces — the worst emitters and absorbers of radiation. For a hot drink they reflect the drink’s infrared radiation back in; for a cold drink they reflect the room’s radiation away from the drink. Either way, radiation is blocked. The **stopper** of insulating plastic blocks conduction through the neck, and seals the top so that air cannot circulate in or out — blocking convection — again in both directions. Because all three pathways are blocked for energy leaving **and** for energy arriving, the flask slows warming and cooling equally.

Question 15 Two ideas from the photon model must be kept separate. The **number of photons arriving each second** sets how bright the beam is and how much total energy it delivers each second. The infrared lamp is bright, so many photons arrive each second. The **energy carried by each photon** is set by the kind of radiation: an ultraviolet photon carries more energy than an infrared photon. Each infrared photon carries too little energy to damage skin, however many arrive; their energy mainly makes the skin’s particles move faster, which is felt as warmth. Each ultraviolet photon carries enough energy to cause damage, so even the dim ultraviolet lamp — few photons per second — damages skin. This is why brightness alone does not decide whether radiation is harmful.

Question 16 *Conduction:* energy is carried by vibrating particles handing it along, and in metals by free electrons; a material (medium) is needed; example — a metal spoon warming in a hot cup. *Convection:* energy is carried by the movement of the heated fluid itself; a liquid or gas is needed; example — water circulating in a pot on a stove. *Radiation:* energy is carried by electromagnetic waves; **no** medium is needed; example — the Sun warming the Earth across empty space. Radiation is described by two models. The **wave model** explains how the energy travels as electromagnetic waves that cross a vacuum and are reflected or absorbed by surfaces. The **particle model** explains how the energy arrives in discrete packets — photons — whose energy depends on the kind of radiation, accounting for observations (such as ultraviolet damage) that the wave model alone does not. Each model explains a different set of observations of the same energy transfer, which is why scientists use both.

Waves: mechanical and electromagnetic — amplitude, wavelength, frequency, speed and applications

Chapter 14 — Physical sciences A: energy transfer and waves (Science, Levels 9 and 10)

Subtopic 14B · VC2 Science Understanding — Physical sciences

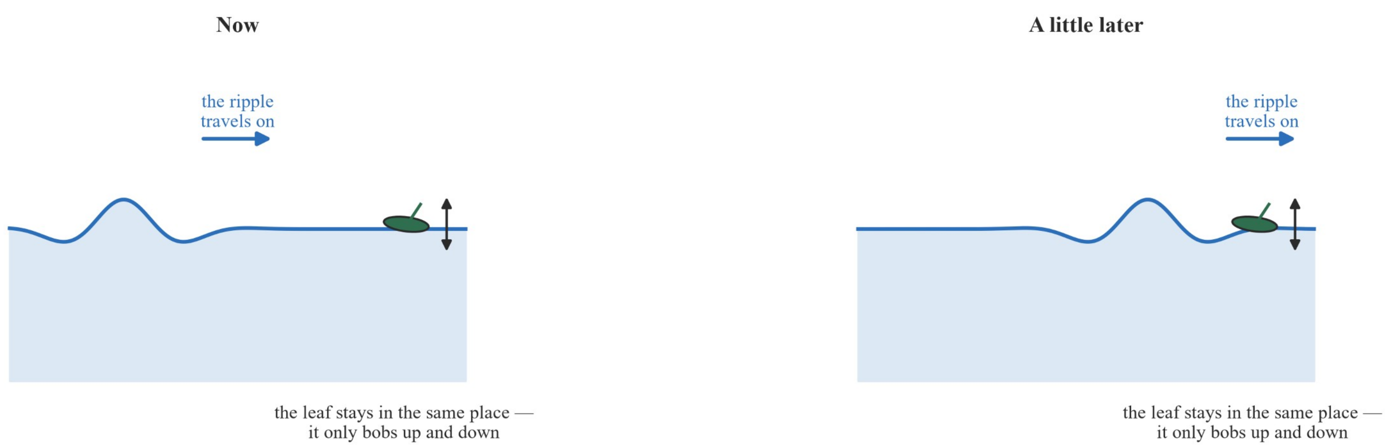
CD code: `VC2S10U14` (split delivery †; this subtopic is the partner, not the accountable owner) **Content description (verbatim):** "wave and particle models can be used to describe energy transfer (conduction, convection and radiation) through different media; waves (electromagnetic and mechanical) have different properties, features (including amplitude, wavelength, frequency and speed) and applications" **This subtopic's limb (TOC §4 clause split):** wave properties, features and applications. Owner `14A` delivers the wave and particle models of energy transfer — conduction, convection and radiation. **Elaboration ids drawn on:** `VC2S10U14.E02` · `VC2S10U14.E03` · `VC2S10U14.E06` (`VC2S10U14.E07` is withheld under the TOC's D10 ICIP decision and is not taught here. Elaborations `.E01`, `.E04` and `.E05` support 14A's limb and are delivered there.) **Achievement standard (extract served):** "They explain how wave and particle models describe energy transfer, and compare the properties, features and applications of waves." **Maths links (D11):** substituting into and rearranging $v = f\lambda$ re-uses the formula skills of `VC2M10A05` (taught in Subtopic 15B) and the inverse relationship between frequency and wavelength re-uses the proportional reasoning of `VC2M9M05` (taught in Subtopic 4B). No new maths demand is introduced.

Theory

What a wave is. In Subtopic 14A you saw energy being transferred by conduction, convection and radiation. Waves are another way energy moves from place to place. A **wave** is a repeating disturbance that travels through a material or through space, carrying **energy** with it.

The key idea is this: a wave carries energy, but it does **not** carry matter from one place to another. Watch a leaf floating on a pond as ripples pass. The leaf bobs up and down and sways a little — it moves in a small repeated motion — but the ripples travel on past while the leaf stays where it is. The disturbance moves; the water does not travel across the pond with it.

A wave carries energy — not matter



the ripples travel across the pond, carrying energy with them — the water itself does not travel across the pond with the wave

Two drawings of a pond, one labelled Now and one labelled A little later. In the first drawing a ripple is on the left of the pond and a leaf floats on the right; in the second drawing the ripple has travelled to the right, past the leaf, but the leaf is in the same place, only bobbing up and down. The ripples travel across the pond, carrying energy with them; the water itself does not travel across the pond with the wave.

The medium. The material a wave travels through is called the **medium** (plural: media). For sound the medium might be air, water or steel; for water waves the medium is the water itself. Some waves need no medium at all — more on that below.

When we say the particles of a medium **oscillate**, we mean they move back and forth, or up and down, repeatedly about a fixed position. Each particle passes the disturbance on to its neighbour, then returns to where it started.

Mechanical waves. A **mechanical wave** is a wave that needs a medium in order to travel. The particles of the medium oscillate and pass the disturbance along. Sound waves, water waves, and waves on a rope or a spring are all mechanical waves. Remove the medium and the wave stops: in empty space there is nothing to oscillate, so a mechanical wave cannot travel there.

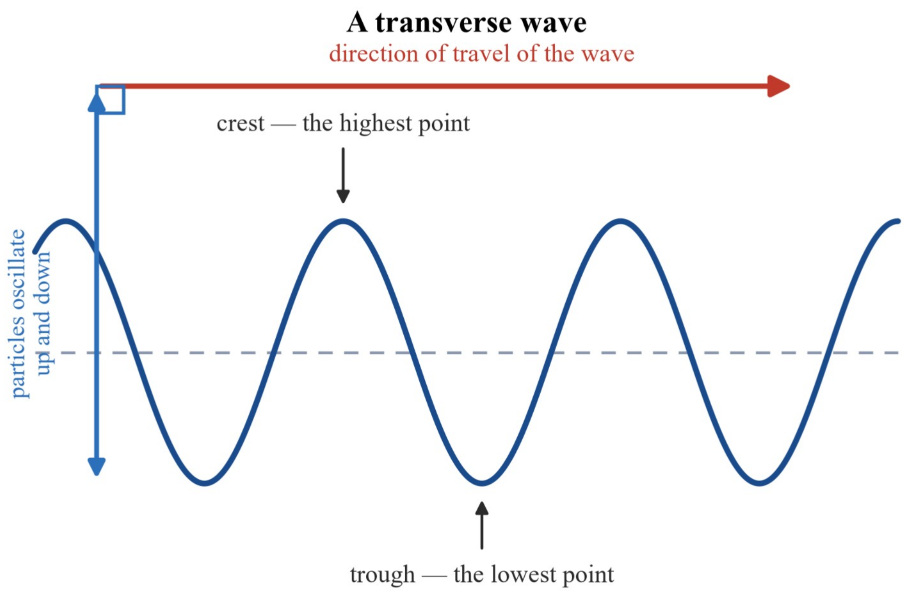
Electromagnetic waves. An **electromagnetic (EM) wave** is a wave that does **not** need a medium. Light from the Sun reaches Earth across 150 million kilometres of almost empty space, and radio signals reach spacecraft far beyond the planets. Electromagnetic waves travel through a **vacuum** — a region containing no matter. All electromagnetic waves travel through a vacuum at the same speed, the **speed of light**:

$$c = 3.0 \times 10^{8}\ \text{m/s}$$

which is 300 000 000 m/s, three hundred million metres per second. Light in air travels at almost exactly this speed. We return to the electromagnetic waves below, after building up the language used to describe every wave.

Transverse waves. Waves are sorted by the direction of the oscillations, compared with the direction the wave travels. In a **transverse wave** the oscillations are at right angles to the direction of travel. Shake one end of a rope up and down and a wave travels along the rope while each part of the rope moves only up and down. Water ripples on a pond are roughly transverse, and **all electromagnetic waves are transverse**.

The highest point of a transverse wave is called a **crest** and the lowest point is called a **trough**.



the oscillations are at right angles to the direction of travel — like a rope shaken up and down; all electromagnetic waves are transverse

A drawing of a transverse wave. The highest point is labelled crest and the lowest point is labelled trough. A double arrow shows the particles oscillating up and down, at right angles to the direction of travel of the wave, which is shown by a long arrow along the top.

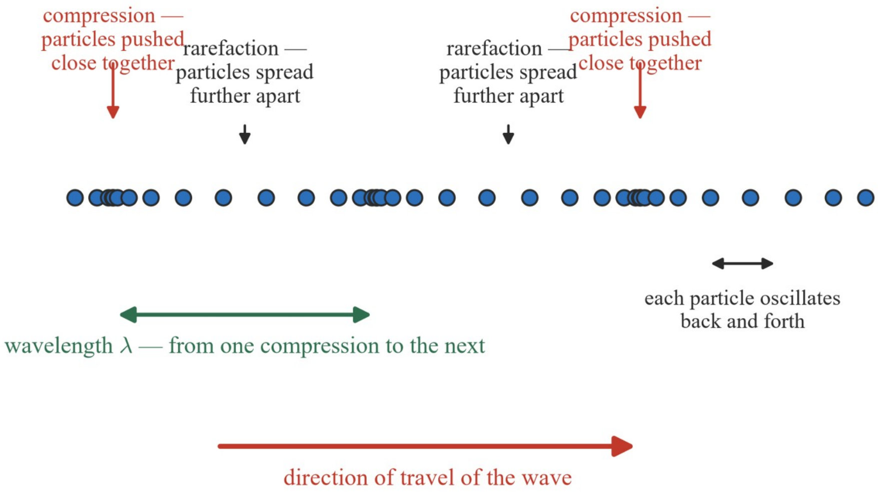
Longitudinal waves. In a **longitudinal wave** the oscillations are along (parallel to) the direction of travel. **Sound** is the main example you will meet. When a drum is hit, the drum skin vibrates in and out, pushing on the air beside it. The air particles oscillate back and forth along the same line that the sound travels, forming a pattern of:

- **compressions** — regions where the particles are pushed close together, and

- **rarefactions** — regions where the particles are spread further apart.

The compressions and rarefactions travel outward from the source. The particles themselves only oscillate about their fixed positions.

A longitudinal wave — compressions and rarefactions



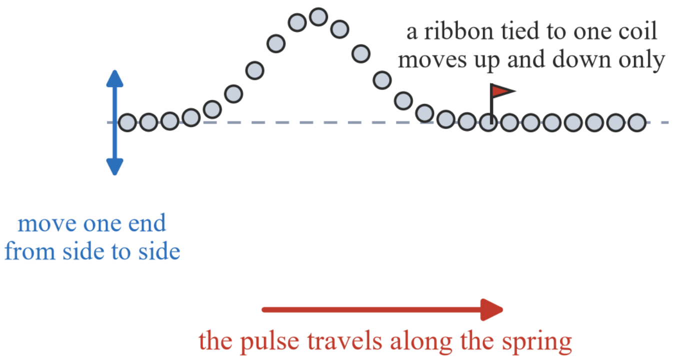
sound is a longitudinal wave — the oscillations are along the direction of travel, and only the pattern of compressions and rarefactions moves on

A drawing of a longitudinal wave as a line of particles. In the compressions the particles are pushed close together, and in the rarefactions they are spread further apart. The wavelength is marked from one compression to the next, and a small double arrow shows each particle oscillating back and forth along the direction of travel of the wave.

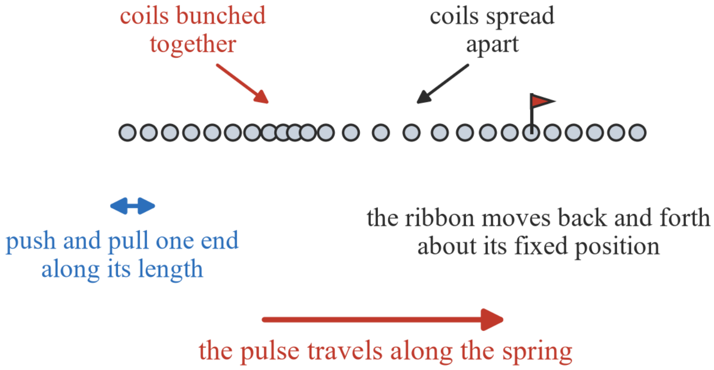
A stretched slinky spring can show both kinds of wave. Move one end side to side and a transverse pulse travels along it; push and pull one end along its length and a longitudinal pulse travels along it, with coils bunched together in places and spread apart in others (elaboration `VC2S10U14.E02`).

A stretched slinky spring can show both kinds of wave

A transverse pulse on a slinky



A longitudinal pulse on a slinky



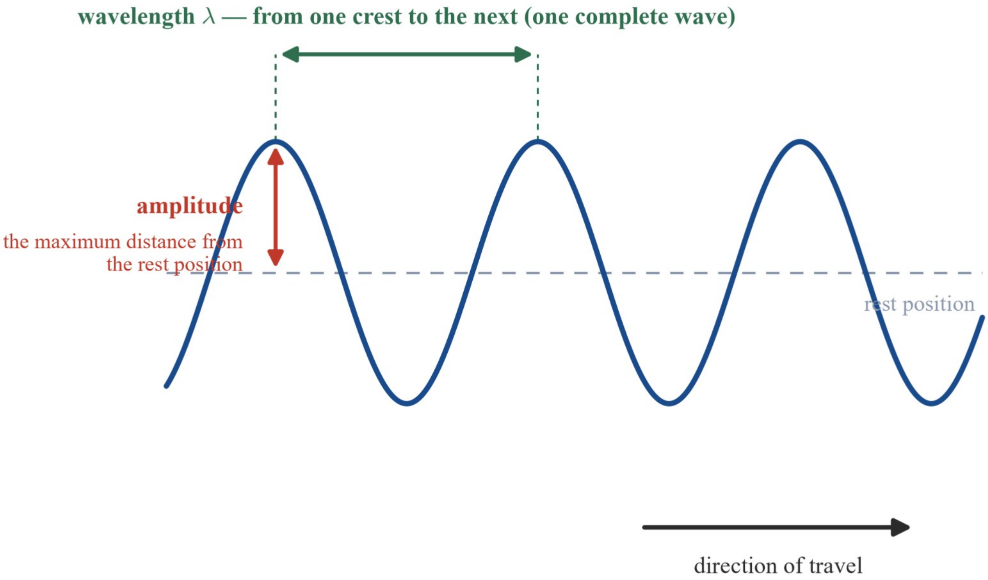
Two drawings of a stretched slinky spring seen from the side. In the top drawing, a transverse pulse: the coils move up and down while the pulse travels along the spring, and a ribbon tied to one coil moves up and down only. In the bottom drawing, a longitudinal pulse: the coils are bunched together in the compression and spread apart in the rarefaction, and the ribbon moves back and forth about its fixed position while the pulse travels along the spring.

The features of a wave. Every wave — mechanical or electromagnetic, transverse or longitudinal — is described by the same set of features. Four of them are named in the content description itself: amplitude, wavelength, frequency and speed.

1. **Amplitude.** The **amplitude** of a wave is the maximum distance a particle of the medium moves from its fixed (rest) position as the wave passes. For a transverse wave it is the height of a crest above the rest position. A wave with a larger amplitude carries more energy.
2. **Wavelength.** The **wavelength**, given the symbol λ (the Greek letter *lambda*), is the distance from one point on a wave to the next point that is at exactly the same stage of the cycle. For a transverse wave this is usually measured from crest to crest, or trough to trough. For a longitudinal wave it is the distance from one compression to the next. Wavelength is measured in metres (m).
3. **Frequency.** The **frequency**, *f*, of a wave is the number of complete waves that pass a fixed point each second. Frequency is measured in **hertz** (Hz): one hertz is one complete wave per second. A wave of frequency 5 Hz means five complete waves pass a point every second.

4. **Speed.** The **wave speed**, *v*, is the distance the wave travels each second, in metres per second (m/s). Like any speed, it can be found from distance divided by time.

The features of a transverse wave



frequency counts how many of these complete waves pass a point each second; every wave — mechanical or electromagnetic — has these features

A drawing of a transverse wave with its features labelled. The amplitude is marked from the rest position to a crest, and the wavelength is marked from one crest to the next, one complete wave. An arrow shows the direction of travel.

One more quantity is useful. The **period**, *T*, of a wave is the time taken for one complete wave to pass a point. Period and frequency are reciprocal quantities:

$$T = \frac{1}{f}$$

A wave of frequency 5 Hz has a period of 1 ÷ 5 = 0.2 s; each wave takes 0.2 s to pass.

The wave equation. The four features are linked by one equation. In one second, *f* complete waves pass a point, and each one is λ metres long, so the distance covered by the wave in one second is *f* × λ. That distance is the speed:

$$v = f\lambda$$

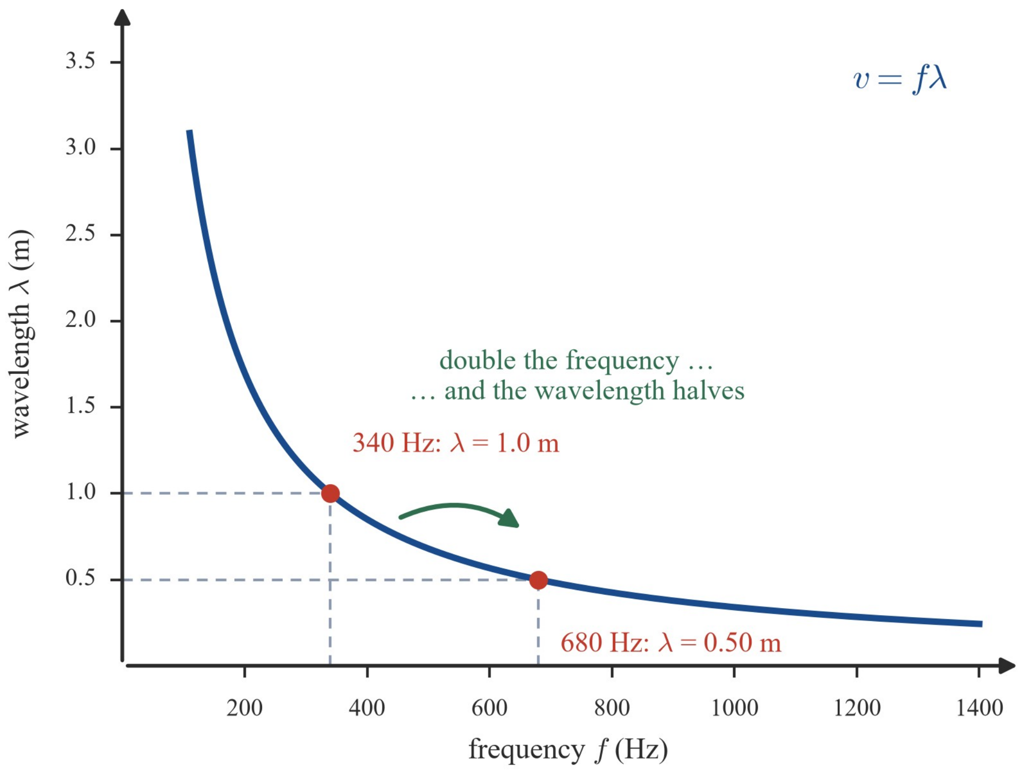
The wave equation can be rearranged to find any one quantity when the other two are known:

$$f = \frac{v}{\lambda} \lambda = \frac{v}{f}$$

The speed of a wave is usually set by the medium it is travelling through. Sound in air at room temperature travels at about 340 m/s whatever its frequency. So for waves in the same medium, frequency and wavelength are **inversely proportional**: doubling the frequency halves the wavelength. This inverse relationship is the same kind of proportional reasoning you met in Subtopic 4B (`VC2M9M05`), and rearranging the wave equation uses the same formula skills as *F* = *ma* in Subtopic 15B (`VC2M10A05`).

Worked check. A sound wave of frequency 680 Hz travels through air at 340 m/s. Its wavelength is λ = v ÷ f = 340 ÷ 680 = 0.50 m.

At a fixed speed, frequency and wavelength are inversely proportional



sound in air at room temperature: the speed is fixed at about 340 m/s by the medium, so a higher frequency always means a shorter wavelength

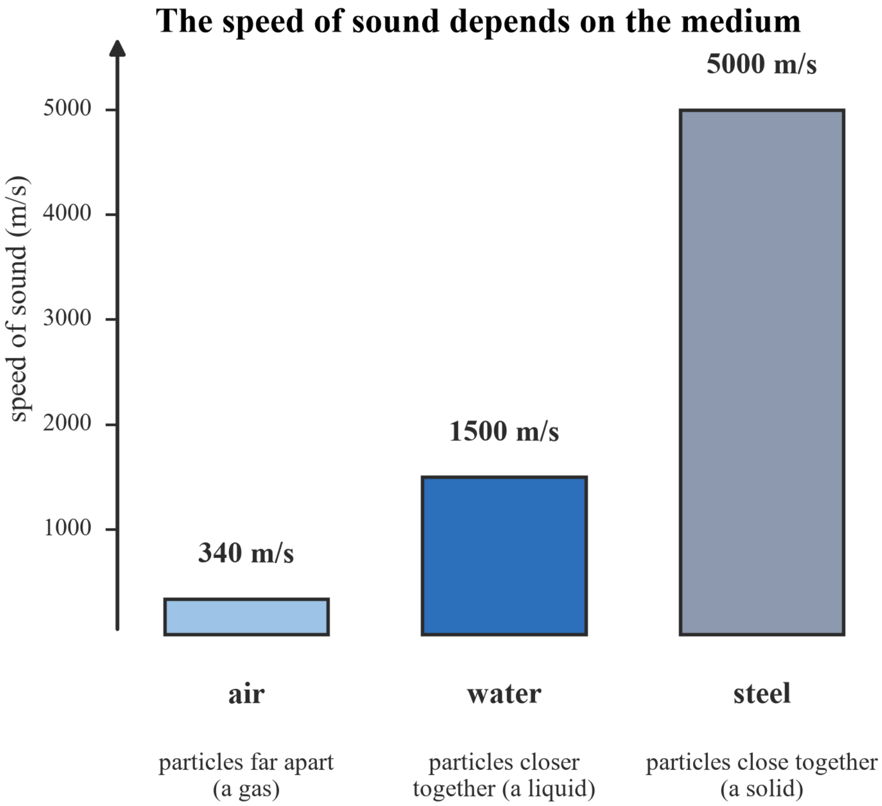
A graph of wavelength against frequency for sound in air at a fixed speed of 340 metres per second. The curve shows that as the frequency increases the wavelength decreases: at 340 hertz the wavelength is 1.0 metre, and when the frequency doubles to 680 hertz the wavelength halves to 0.50 metre.

Sound waves (elaborations `VC2S10U14.E02` and `VC2S10U14.E03`). Sound is a longitudinal mechanical wave. It is produced whenever something vibrates — vocal cords, a guitar string, a loudspeaker cone — and the vibration is passed on to the surrounding medium. Sound can travel through gases, liquids and solids, but it can never travel through a vacuum, because there are no particles to oscillate. That is why no sound can be heard in outer space, whatever films may suggest.

The speed of sound depends on the medium. Approximate values are:

medium	speed of sound
air (room temperature)	340 m/s
water	1 500 m/s
steel	5 000 m/s

Sound travels faster in water than in air, and faster again in steel, because the particles in liquids and solids are closer together and pass the disturbance on more quickly.



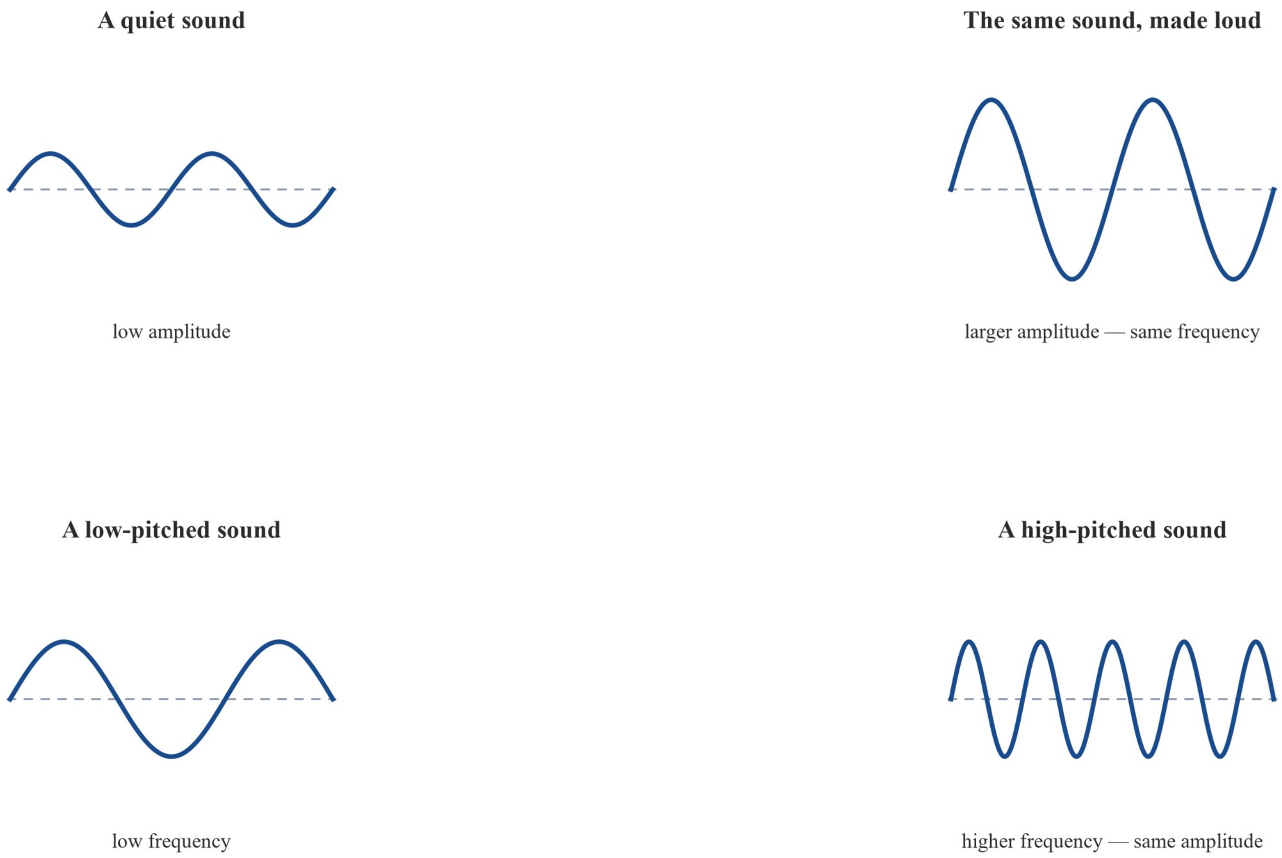
sound travels faster in water than in air, and faster again in steel — particles in liquids and solids are closer together, so they pass the disturbance on more quickly

A bar chart of the speed of sound in three media: air, 340 metres per second; water, 1 500 metres per second; and steel, 5 000 metres per second. Notes under the bars say the particles are far apart in a gas, closer together in a liquid, and close together in a solid.

Two properties of sound connect directly to wave features (elaboration `VC2S10U14.E03`):

- **Loudness depends on amplitude.** Hit a drum harder and the drum skin moves further in and out. The sound wave it produces has a larger amplitude, carries more energy, and sounds louder.
- **Pitch depends on frequency.** A high-pitched sound, like a whistle, is produced by a high-frequency wave. A low-pitched sound, like a bass drum, is produced by a low-frequency wave. A guitar string vibrating 440 times each second produces the musical note A above middle C, which orchestras use for tuning.

Loudness and pitch — what changes in the waves

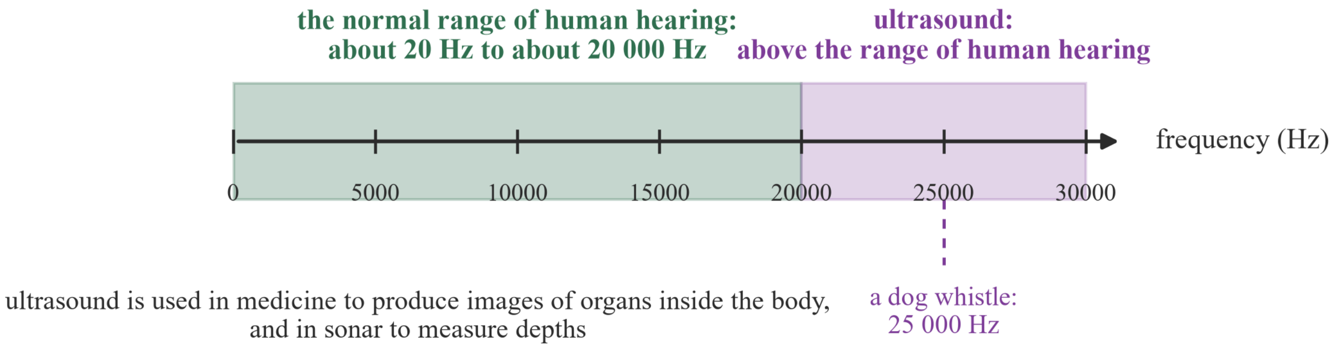


loudness depends on amplitude — hit harder, and the wave has a larger amplitude; pitch depends on frequency — a higher frequency sounds higher pitched

Four traces of sound waves. A quiet sound has a low amplitude, and the same sound made loud has a larger amplitude at the same frequency. A low-pitched sound has a low frequency, and a high-pitched sound has a higher frequency at the same amplitude.

The normal human ear can detect sounds with frequencies from about 20 Hz to about 20 000 Hz. Sound waves with frequencies above the range of human hearing are called **ultrasound**. Ultrasound is used in medicine to produce images of organs inside the body, and in sonar to measure depths, as you will see in the worked examples.

The frequency range of human hearing



A number line of frequency in hertz, from 0 to 30 000. A green band shows the normal range of human hearing, about 20 hertz to about 20 000 hertz, and a purple band beyond it shows ultrasound, above the range of human hearing. A dog whistle at 25 000 hertz is marked in the ultrasound band.

The slinky as a model of sound (elaboration `VC2S10U14.E02`). A long spring such as a slinky is a useful model for the way sound energy is transferred by a wave. Push and pull one end of a stretched slinky along its length and a pulse of bunched-up coils travels along the spring — much like a compression travelling through the air. A small ribbon tied to one coil shows what each part of the medium does: the ribbon moves back and forth about its fixed position while the pulse moves on. The energy travels along the spring; the coils do not.

Every model has limits. The slinky shows the *pattern* of a longitudinal wave — the bunching and spreading — in a slow, visible form. Real sound in air travels far faster, and the oscillating air particles cannot be seen. The model helps you picture the wave, but it is not the wave itself.

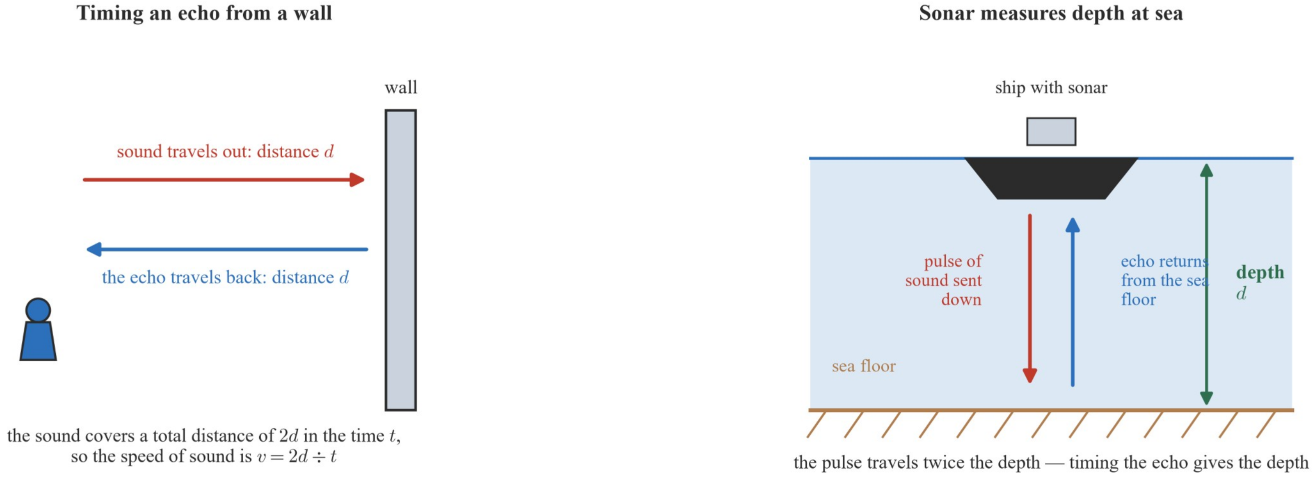
How fast is sound? Because light travels so much faster than sound, you can estimate how far away lightning is. The flash of lightning and the crash of thunder happen at the same time and place, but light reaches you almost at once while the sound takes about 3 s to travel each kilometre. Count the seconds between the flash and the thunder, then divide by 3 to get the distance in kilometres.

Sound can also be used to measure distances by timing an **echo** — a reflection of sound from a surface. If you stand a distance d from a large wall and clap, the sound travels to the wall and back, a total distance of $2d$. Measuring the time t for the echo gives the speed of sound:

$$v = \frac{2d}{t}$$

Ships use the same idea underwater. A device called sonar sends out a short pulse of sound (often ultrasound) and times the echo from the sea floor, and medical scanners time echoes of ultrasound returning from boundaries inside the body to build up an image.

Measuring distances with echoes



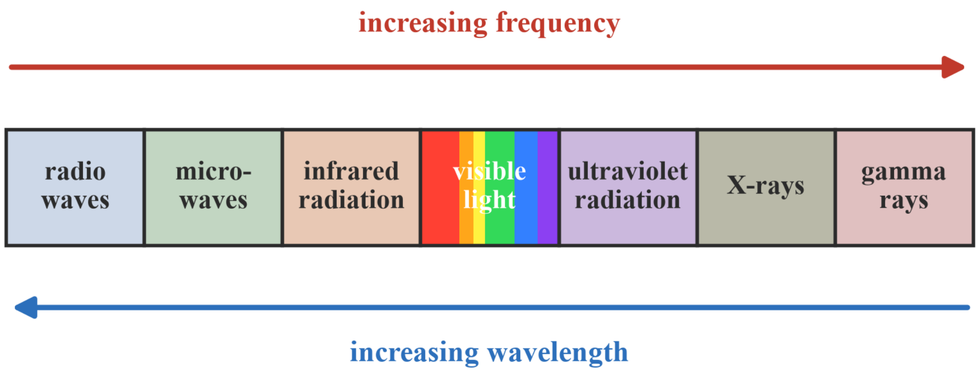
Two drawings. Left: a person claps at a distance d from a wall; the sound travels out a distance d, the echo travels back a distance d, and the sound covers a total distance of 2d in the time t, so the speed of sound is v = 2d divided by t. Right: a ship with sonar sends a pulse of sound down to the sea floor and times the echo to measure the depth.

The electromagnetic spectrum (elaboration `VC2S10U14.E06`). Electromagnetic waves form a continuous range, the **electromagnetic spectrum**, from waves of very low frequency and long wavelength to waves of very high frequency and short wavelength. In order of **increasing frequency** (and decreasing wavelength), the regions are:

1. radio waves
2. microwaves
3. infrared radiation
4. visible light
5. ultraviolet radiation
6. X-rays
7. gamma rays

Every one of these is the same kind of wave. They are all transverse, and they all travel through a vacuum at the same speed, $c = 3.0 \times 10^8$ m/s. They differ only in frequency and wavelength — and because the speed is fixed, the two are linked by $c = f\lambda$. A high-frequency electromagnetic wave always has a short wavelength; a low-frequency one always has a long wavelength.

The electromagnetic spectrum



all seven regions are transverse waves, and all travel through a vacuum at the same speed — $c = 3.0 \times 10^8$ m/s — so a higher frequency always means a shorter wavelength ($c = f\lambda$)

The electromagnetic spectrum drawn as seven bands in order of increasing frequency: radio waves, microwaves, infrared radiation, visible light (shown as a rainbow of colours), ultraviolet radiation, X-rays and gamma rays. An arrow above shows increasing frequency and an arrow below shows increasing wavelength. All seven regions are transverse waves that travel through a vacuum at the same speed, c = 3.0 × 10 to the power 8 metres per second.

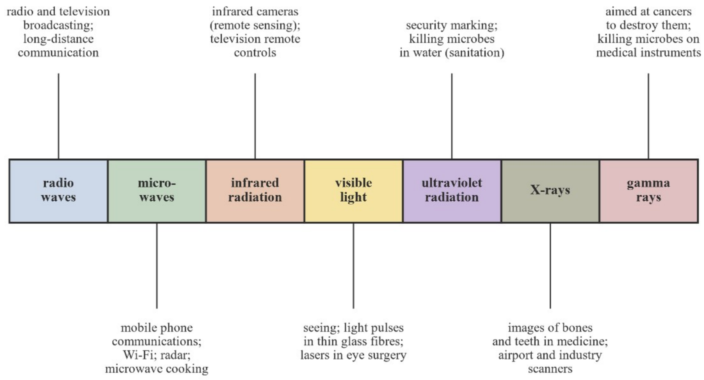
Visible light is the tiny part of the spectrum that our eyes detect. Within it, red light has the lowest frequency and longest wavelength, and violet light has the highest frequency and shortest wavelength. Electromagnetic waves also travel through materials such as air, glass and water, but at a lower speed than in a vacuum.

Uses of electromagnetic waves (elaboration `VC2S10U14.E06`). The properties of each region of the spectrum — how it is absorbed, reflected or passed through materials — decide what it is used for.

- **Radio waves** have the longest wavelengths and the lowest frequencies. They are used for radio and television broadcasting and for long-distance communication, because they travel long distances and pass around hills and through buildings.
- **Microwaves** are used for **mobile phone communications** and for Wi-Fi, because they can carry data over short distances. They are also used in **radar**: a radar set sends out short pulses of microwaves and detects the pulses reflected from aircraft, ships or storm clouds. The direction and the time delay of the echo give the object's position — the same echo principle as sonar. And in **microwave cooking**, microwaves are absorbed by the water in food; the absorbed energy heats the food from within.
- **Infrared radiation** is given out by all warm objects. The hotter the object, the more infrared it gives out. Infrared cameras detect this radiation and use it to form an image — a form of **remote sensing**. They can find people in the dark, spot heat leaking from buildings, and map hotspots in bushfires from aircraft or satellites. A television remote control sends data to the television as pulses of infrared.
- **Visible light** lets us see, and it carries information too. Light pulses sent along thin glass fibres carry telephone and internet data, and lasers — intense beams of light — are used in eye surgery.
- **Ultraviolet radiation** makes some materials glow, which is used in security marking. It also kills tiny living things called microbes, so it is used in **sanitation** — for example, to make drinking water safe by killing the microbes in it. Too much ultraviolet damages skin cells and causes sunburn, which is why we use sunscreen and shade when the UV level is high.
- **X-rays** pass easily through soft material such as skin and muscle but are absorbed by denser material such as bone and metal. This is why they are used in **medicine** to produce images of bones and teeth, and in airport scanners and industry to look inside objects without opening them.

- **Gamma rays** have the highest frequencies and the shortest wavelengths. They can kill living cells. In medicine this is put to careful use: gamma rays can be aimed at a cancer to destroy it. They are also used to kill microbes on medical instruments and on some foods, keeping them free of germs.

Uses of electromagnetic waves



the properties of each region — how it is absorbed, reflected or passed through materials — decide what it is used for; ultraviolet, X-rays and gamma rays can damage living cells, so the higher the frequency, the greater the care needed

The seven regions of the electromagnetic spectrum with their uses. Radio waves: radio and television broadcasting, and long-distance communication. Microwaves: mobile phone communications, Wi-Fi, radar and microwave cooking. Infrared radiation: infrared cameras for remote sensing, and television remote controls. Visible light: seeing, light pulses in thin glass fibres, and lasers in eye surgery. Ultraviolet radiation: security marking, and killing microbes in water for sanitation. X-rays: images of bones and teeth in medicine, and airport and industry scanners. Gamma rays: aimed at cancers to destroy them, and killing microbes on medical instruments.

A safety note. Ultraviolet, X-rays and gamma rays can damage living cells. The higher the frequency of an electromagnetic wave, the greater the care needed when we use it. Sunscreen and shade limit ultraviolet exposure; workers who use X-ray or gamma equipment stand behind shielding and limit their time near the source.

Comparing waves. The achievement standard for this content description asks you to *compare* the properties, features and applications of waves. The two big comparisons to know are:

	mechanical waves	electromagnetic waves
medium needed?	yes	no — they travel through a vacuum
examples	sound, water waves, waves on ropes and springs	light, radio, microwaves, X-rays
wave type	transverse or longitudinal	all transverse
typical speed	sound in air: 340 m/s	all 3.0×10^8 m/s in a vacuum

And within any comparison, the four features — amplitude, wavelength, frequency and speed — are the quantities you should name, link with $v = f\lambda$, and use.

Activities

Activity 1 — Slinky waves: transverse and longitudinal (elaboration `VC2S10U14.E02`). Work in pairs. Stretch a slinky spring along a smooth floor or bench, each of you holding one end. (Keep fingers clear of the coils, and do not let the spring snap back at anyone.)

- (a) Move your end quickly from side to side once, at right angles to the spring. Watch the pulse travel to the other end. This is a transverse wave.
- (b) Now push and pull your end once along the length of the spring. Watch the pulse of bunched coils travel along. This is a longitudinal wave.

(c) Tie a short ribbon or strip of tape to one coil in the middle. Repeat both waves and watch the ribbon. Describe how the ribbon moves in each case, and use it to explain why the wave carries energy but not the spring itself.

Activity 2 — Loudness and pitch with a ruler (elaboration `VC2S10U14.E03`). Hold a plastic or steel ruler down tight on the bench, with about half its length sticking out over the edge. Pull the free end down a little and let it go so the ruler vibrates and makes a sound.

(a) Pull the end down a little, then a lot, before letting go. Watch the size of the vibration and listen. What changes — the amplitude of the wave, the loudness of the sound, or both?
(b) Change the length of ruler sticking out over the edge to about one quarter of its length, and vibrate it again. Listen to the pitch. Explain what happened to the frequency of the vibration.
(c) Write one sentence linking amplitude to loudness, and one linking frequency to pitch.

Activity 3 — Measuring the speed of a wave on a rope. Work in a pair or a small group, in a clear space at least 6 m long. Lay a soft rope about 5 m long straight on the ground. One student holds one end still; the other sends a single sharp pulse along the rope by flicking their end once to the side.

(a) Measure the length of the rope, d, and time the pulse travelling from one end to the other, t. Repeat three times and take an average time. Calculate the wave speed from $v = d \div t$.
(b) Now generate waves steadily, counting how many complete waves are sent in 10 s, and estimate the wavelength by measuring the distance between two crests when the pattern is steady. Calculate a second value of the speed from $v = f\lambda$ and compare it with the value from part (a).
(c) Suggest two reasons why your two values might not agree exactly.

Worked examples

All data in this section are given to two significant figures, so final answers are also given to two significant figures unless the arithmetic is exact.

Example 1 — scaffolded

A sound wave of frequency 680 Hz travels through air at 340 m/s. Calculate the wavelength of the sound wave.

Working	Comment
f = 680 Hz, v = 340 m/s	List the known quantities.
$v = f\lambda$, so $\lambda = v \div f$	Rearrange the wave equation for wavelength.
λ = 340 ÷ 680 = 0.50 m	Substitute and divide.

The wavelength of the sound is 0.50 m. Notice that we did not need to change any units: hertz means “per second”, so it combines with m/s to give metres.

Example 2 — scaffolded

A mobile phone signal travels as a microwave with a wavelength of 0.15 m. (a) Calculate the frequency of the signal, using $c = 3.0 \times 10^8$ m/s. (b) An FM radio wave has a frequency of 1.0×10^8 Hz. Calculate its wavelength. (c) State which of the two signals travels faster through the air, and explain.

Working	Comment
$c = f\lambda$, so $f = c \div \lambda$	Rearrange the wave equation for frequency.
(a) $f = 3.0 \times 10^8 \div 0.15 = 2.0 \times 10^9$ Hz	All EM waves travel at c in a vacuum, and at almost c in air.
2.0×10^9 Hz = 2.0 GHz	1 GHz = 10^9 Hz.
(b) $\lambda = c \div f = 3.0 \times 10^8 \div (1.0 \times 10^8) = 3.0$ m	Rearrange for wavelength.
(c) They travel at the same speed.	All electromagnetic waves travel at c in a vacuum and at almost the same speed in air.

Example 3 — unscaffolded

A survey ship sends a short pulse of sound straight down into the sea. The echo from the sea floor returns to the ship 0.60 s later. The speed of sound in seawater is 1 500 m/s. Calculate the depth of the sea under the ship.

The sound travels down to the sea floor and back up again, so it covers twice the depth, $2d$, in the time $t = 0.60$ s. The total distance travelled is

$$v \times t = 1\,500 \times 0.60 = 900\,\text{m}.$$

The depth is half of this:

$$d = \frac{900}{2} = 450\,\text{m}.$$

The sea is 450 m deep at this point. The same echo calculation is used in medical ultrasound imaging, where the pulse reflects from boundaries between different soft tissues inside the body.

Example 4 — unscaffolded

During a storm, an observer sees a flash of lightning and hears the thunder 6.0 s later. The speed of sound in air is 340 m/s, and the speed of light is 3.0×10^8 m/s. (a) Calculate how far away the lightning struck. (b) Explain why it is reasonable to treat the light from the flash as arriving instantly.

(a) The flash and the bang happen together at the lightning. The sound takes 6.0 s to reach the observer, travelling at 340 m/s, so the distance is

$$d = v \times t = 340 \times 6.0 = 2\,040\,\text{m} \approx 2.0\,\text{km}.$$

(b) Light travels at 3.0×10^8 m/s, which is about 900 000 times faster than sound. Over a distance of 2.0 km, the light takes only about 0.000 007 s to arrive — far shorter than a person can measure. So the delay the observer counts is entirely the time the sound takes, and the light can be treated as arriving instantly.

Practice questions

Scaffolded questions

Question 1 The features of a wave. (a) Define the amplitude of a wave. (b) Define the wavelength of a wave. (c) Define the frequency of a wave and give its unit. (d) A wave has a frequency of 5.0 Hz. Calculate its period.

Question 2 Mechanical and electromagnetic waves. (a) State the difference between a mechanical wave and an electromagnetic wave in terms of the medium. (b) Sort these waves into mechanical and electromagnetic: sound, radio waves, water waves, X-rays, waves on a rope. (c) Explain why an astronaut standing on the Moon could not hear another astronaut's voice without a radio link, even if they stood close together.

Question 3 Transverse and longitudinal waves. (a) Describe the difference between a transverse wave and a longitudinal wave, in terms of the direction of the oscillations. (b) Sort these into transverse and longitudinal: sound in air, light, a wave sent up and down a rope, water ripples. (c) Name the two regions that make up a longitudinal wave, and say what is different about the spacing of the particles in each.

Question 4 The wave equation. (a) Write the wave equation linking wave speed v, frequency f and wavelength λ. (b) A wave has a frequency of 50 Hz and a wavelength of 0.40 m. Calculate its speed. (c) A sound wave travels at 340 m/s and has a frequency of 170 Hz. Calculate its wavelength. (d) The frequency of this sound wave is doubled while its speed stays the same. State what happens to its wavelength, and explain your reasoning.

Question 5 Loudness and pitch (elaboration `VC2S10U14.E03`). (a) A drummer hits a drum softly, then hits it much harder. State which feature of the sound wave changes, and how. (b) State what you hear change when the drummer hits harder. (c) One drum produces a sound wave of frequency 220 Hz and another produces a sound wave of frequency 440 Hz. State which drum sounds higher pitched. (d) State which feature of a sound wave determines its pitch, and which feature determines its loudness.

Question 6 The electromagnetic spectrum (elaboration `VC2S10U14.E06`). (a) List the seven regions of the electromagnetic spectrum in order of increasing frequency. (b) State the speed of all electromagnetic waves in a vacuum. (c) State which region has the longest wavelength, and which has the shortest. (d) Name the region of the spectrum used for each of these: making drinking water safe by killing microbes; producing images of broken bones; sending signals from a television remote control.

Unscaffolded questions

Question 7 A ripple tank's wave generator makes 30 complete waves in 5.0 s. The wavelength of the waves is 0.040 m. (a) Calculate the frequency of the waves. (b) Calculate the speed of the waves.

Question 8 In a medical scan, a pulse of ultrasound is sent into the body and reflects from a boundary between two tissues. The echo returns to the scanner 0.000 080 s later. The speed of ultrasound in the body is 1 500 m/s. Calculate the depth of the boundary below the skin.

Question 9 The normal range of human hearing is from about 20 Hz to about 20 000 Hz. (a) A dog whistle produces a sound of frequency 25 000 Hz. Explain why a person cannot hear it, even though the sound is travelling through the air to their ear. (b) Calculate the wavelength of a 20 000 Hz sound in air, where the speed of sound is 340 m/s.

Question 10 At an athletics meeting, a starter stands 200 m from the timekeepers and fires a starting pistol. The speed of sound in air is 340 m/s. (a) Calculate the time taken for the sound of the pistol to reach the timekeepers. (b) The timekeepers start their stopwatches when they see the smoke from the pistol, not when they hear the bang. Explain why this gives a fairer start.

Question 11 A microwave oven produces microwaves of frequency 2.45 GHz (2.45×10^9 Hz). (a) Calculate the wavelength of these microwaves, using $c = 3.0 \times 10^8$ m/s. (b) Explain why the food in a microwave oven heats up, in terms of energy transfer.

Question 12 A radar set on the ground sends out a short pulse of microwaves towards an aircraft. The reflected pulse returns to the radar set 0.000 40 s later. Calculate the distance from the radar set to the aircraft.

Question 13 Two applications of electromagnetic waves rely on how the waves are absorbed. (a) Explain why X-rays, but not visible light, are used to produce images of bones inside the body. (b) Explain why ultraviolet radiation is used to make drinking water safe.

Question 14 Ultraviolet radiation, X-rays and gamma rays can all damage living cells. (a) Explain why a person who works with X-rays every day stands behind a protective screen and limits the time spent near the X-ray source. (b) Give one way a person can reduce their exposure to ultraviolet radiation from the Sun.

Question 15 A student writes: "When a wave travels along a rope, the particles of the rope travel from one end to the other with the wave." Explain what is wrong with this statement, and state what the particles of the rope actually do.

Question 16 Compare sound waves and light waves (this question draws on the whole subtopic). (a) State two features or properties that sound waves and light waves have in common. (b) State three differences between sound waves and light waves, including one difference about the medium and one difference about speed.

Answers

Question 1 (a) the maximum distance a particle moves from its rest position; (b) the distance from one point on a wave to the next point at the same stage of the cycle; (c) the number of complete waves passing a point each second, in hertz (Hz); (d) 0.20 s. **Question 2** (a) mechanical waves need a medium; electromagnetic waves do not; (b) mechanical: sound, water waves, waves on a rope; electromagnetic: radio waves, X-rays; (c) there is no air in the vacuum between them — space is a vacuum, so no medium carries the sound. **Question 3** (a) transverse: oscillations at right angles to the direction of travel; longitudinal: oscillations along the direction of travel; (b) transverse: light, rope wave, water ripples; longitudinal: sound in air; (c) compressions (particles close together) and rarefactions (particles spread apart). **Question 4** (a) $v = f\lambda$; (b) 20 m/s; (c) 2.0 m; (d) the wavelength halves — frequency and wavelength are inversely proportional at fixed speed. **Question 5** (a) the amplitude increases; (b) the sound becomes louder; (c) the 440 Hz drum; (d) pitch is set by frequency, loudness by amplitude. **Question 6** (a) radio, microwaves, infrared, visible light, ultraviolet, X-rays, gamma rays; (b) 3.0×10^8 m/s; (c) longest: radio waves; shortest: gamma rays; (d) ultraviolet; X-rays; infrared. **Question 7** (a) 6.0 Hz; (b) 0.24 m/s. **Question 8** 0.060 m (6.0 cm). **Question 9** (a) 25 000 Hz is above the human hearing range — it is ultrasound; (b) 0.017 m. **Question 10** (a) 0.59 s; (b) light travels much faster than sound, so the smoke is seen almost at once by all timekeepers, while the sound arrives later — see solution. **Question 11** (a) 0.12 m; (b) the microwaves are absorbed by water in the food and transfer energy that heats it. **Question 12** 60 000 m (60 km). **Question 13** (a) X-rays pass through soft tissue but are absorbed by dense bone; visible light does not pass through the body at all; (b) ultraviolet kills the microbes in the water — see solution. **Question 14** (a) X-rays can damage living cells; the screen and the short time near the source reduce the amount of X-rays the worker's body receives; (b) any one from sunscreen, shade, clothing, hat — see solution. **Question 15** The particles do not travel along the rope; they oscillate about fixed positions — see solution. **Question 16** (a) any two from: both transfer energy, both have amplitude, wavelength, frequency and speed, both obey $v = f\lambda$; (b) sound is mechanical / light is electromagnetic; sound is longitudinal / light is transverse; sound about 340 m/s in air / light 3.0×10^8 m/s — see solution.

Fully-worked solutions

Question 1 (a) The amplitude is the maximum distance a particle of the medium moves from its fixed (rest) position as the wave passes. (b) The wavelength is the distance from one point on a wave to the next point that is at exactly the same stage of the cycle — for example, crest to crest. (c) The frequency is the number of complete waves passing a fixed point each second, measured in hertz (Hz). (d) The period is the time for one complete wave: $T = 1 \div f = 1 \div 5.0 = 0.20$ s.

Question 2 (a) A mechanical wave needs a medium (a material) to travel through; an electromagnetic wave does not need a medium and can travel through a vacuum. (b) Mechanical: sound, water waves, waves on a rope. Electromagnetic: radio waves, X-rays. (c) Sound is a mechanical wave, so it needs a medium such as air. The space around the Moon is a vacuum — there are no particles to oscillate and carry the sound — so the voice cannot travel from one astronaut to the other. A radio link works because radio waves are electromagnetic and travel through a vacuum.

Question 3 (a) In a transverse wave the oscillations are at right angles to the direction the wave travels. In a longitudinal wave the oscillations are along (parallel to) the direction the wave travels. (b) Transverse: light, a wave sent up and down a rope, water ripples. Longitudinal: sound in air. (c) A longitudinal wave is made of compressions, where the particles of the medium are pushed close together, and rarefactions, where the particles are spread further apart.

Question 4 (a) $v = f\lambda$ (b) $v = f\lambda = 50 \times 0.40 = 20$ m/s. (c) $\lambda = v \div f = 340 \div 170 = 2.0$ m. (d) Since $v = f\lambda$ and v is fixed, frequency and wavelength are inversely proportional. Doubling the frequency halves the wavelength, from 2.0 m to 1.0 m.

Question 5 (a) The amplitude of the sound wave increases, because the drum skin moves further in and out. (b) The sound becomes louder. (c) The drum producing 440 Hz sounds higher pitched, because higher frequency means higher pitch. (d) Pitch is determined by frequency; loudness is determined by amplitude.

Question 6 (a) Radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays, gamma rays. (b) 3.0×10^8 m/s. (c) Radio waves have the longest wavelength; gamma rays have the shortest. (d) Making drinking water safe by killing microbes: ultraviolet radiation. Producing images of broken bones: X-rays. Television remote control: infrared radiation.

Question 7 (a) Frequency is the number of complete waves each second: $f = 30 \div 5.0 = 6.0$ Hz. (b) Using the wave equation, $v = f\lambda = 6.0 \times 0.040 = 0.24$ m/s.

Question 8 The pulse travels down to the boundary and back, so it covers twice the depth in 0.000 080 s. Total distance travelled: 1 500 × 0.000 080 = 0.12 m. The depth is half of this: $d = 0.12 \div 2 = 0.060$ m, or 6.0 cm.

Question 9 (a) The frequency 25 000 Hz is above the normal upper limit of human hearing (20 000 Hz). Sound above this range is called ultrasound; the wave reaches the ear, but the ear cannot detect it. Dogs can hear to higher frequencies than humans. (b) $\lambda = v \div f = 340 \div 20\,000 = 0.017$ m.

Question 10 (a) Time = distance ÷ speed = 200 ÷ 340 = 0.59 s. (b) Light travels at 3.0×10^8 m/s, so the smoke is seen by every timekeeper almost instantly, no matter where they stand. The sound travels far more slowly (340 m/s) and would reach timekeepers at different times depending on their distance from the pistol, giving some runners an unfair head start. Using the sight of the smoke removes this difference.

Question 11 (a) $\lambda = c \div f = 3.0 \times 10^8 \div (2.45 \times 10^9) = 0.122 \text{ m} \approx 0.12$ m. (b) The microwaves are absorbed by the water in the food. The absorbed wave energy heats the water, and the hot water then heats the rest of the food.

Question 12 The pulse travels to the aircraft and back, so it covers twice the distance in 0.000 40 s. Total distance: $3.0 \times 10^8 \times 0.000\,40 = 120\,000$ m. The distance to the aircraft is half of this: 120 000 ÷ 2 = 60 000 m = 60 km.

Question 13 (a) X-rays pass through soft material such as skin and muscle but are absorbed by denser material such as bone. This means an X-ray image shows the bones clearly inside the body. Visible light does not pass through the body at all, so it cannot show what is inside. (b) Ultraviolet radiation kills microbes — the tiny living things that can cause disease. Shining ultraviolet through water kills the microbes in it, making the water safe to drink without needing to boil it or add chemicals.

Question 14 (a) X-rays can damage living cells. Standing behind a protective screen and spending less time near the source both reduce the amount of X-ray radiation the worker's body receives over a working day. (b) Any one of: applying sunscreen, staying in the shade, wearing clothing, a hat or sunglasses that block ultraviolet, or avoiding the Sun when the UV level is highest.

Question 15 The statement is wrong because a wave carries energy, not matter, from one place to another. The particles of the rope do not travel from one end to the other. Each particle of the rope oscillates about its fixed position — moving up and down while the wave travels along — and passes the disturbance on to the next particle. Only the disturbance, and the energy it carries, travels the length of the rope.

Question 16 (a) Any two of: both transfer energy from one place to another; both can be described by amplitude, wavelength, frequency and speed; both obey the wave equation $v = f\lambda$. (b) Three differences: 1. Medium: sound is a mechanical wave and needs a medium; light is an electromagnetic wave and can travel through a vacuum. 2. Wave type: sound is longitudinal; light is transverse. 3. Speed: sound travels at about 340 m/s in air; light travels at 3.0×10^8 m/s in a vacuum — almost a million times faster.

Conservation of energy in systems: transfers, transformations and efficiency

Chapter 14 — Physical sciences A: energy transfer and waves (Science, Levels 9 and 10)

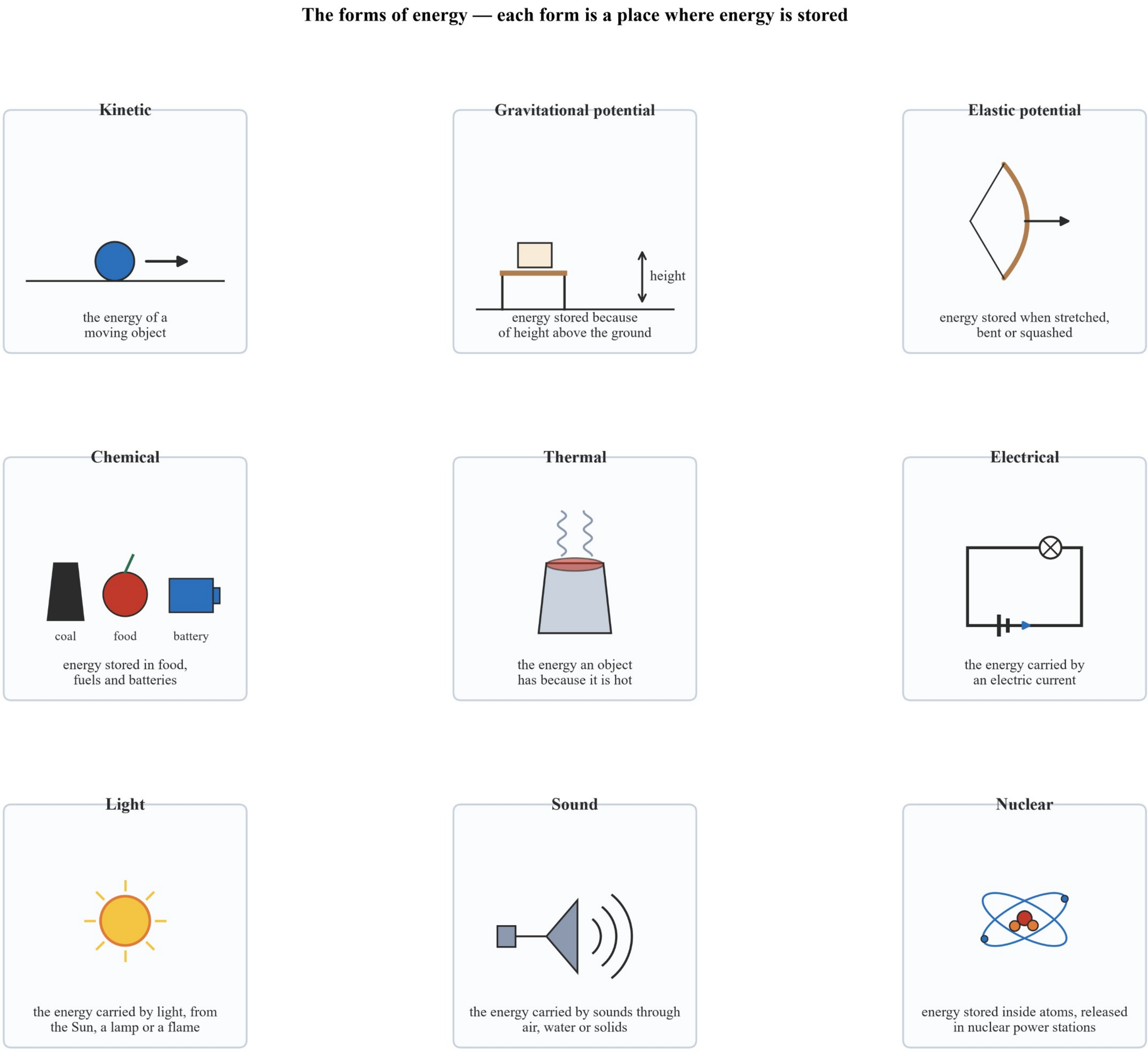
Subtopic 14C · VC2 Science Understanding — Physical sciences

CD code: `VC2S10U15` (delivered whole by this subtopic) **Content description (word for word):** "the Law of Conservation of Energy can be analysed in systems, including Earth systems, by assessing the efficiency of energy inputs, outputs, transfers and transformations" **Elaboration ids drawn on:** `VC2S10U15.E01` · `VC2S10U15.E02` · `VC2S10U15.E03` · `VC2S10U15.E05` · `VC2S10U15.E06` (`VC2S10U15.E04` is withheld under the TOC's D10 ICIP decision and is not taught here.) **Achievement standard (extract served):** "They analyse and represent energy conservation, including efficiency, in systems, and model how different forms of energy are transformed into electrical energy." (The same sentence is quoted by subtopic 15A against its own CD — TOC D14.) **Maths interlock (D11):** `VC2M9M05` — direct proportion, rates, ratio and scale, used here for efficiency ratios and for the proportional widths of Sankey diagrams.

Theory

Energy — a quick recap. Energy is what is needed for anything to change: to move, to heat up, to light up, to make a sound. Energy is measured in **joules** (J). Larger amounts are measured in megajoules (1 MJ = 1 000 000 J). Energy comes in several forms, and each form can be thought of as a place where energy is stored:

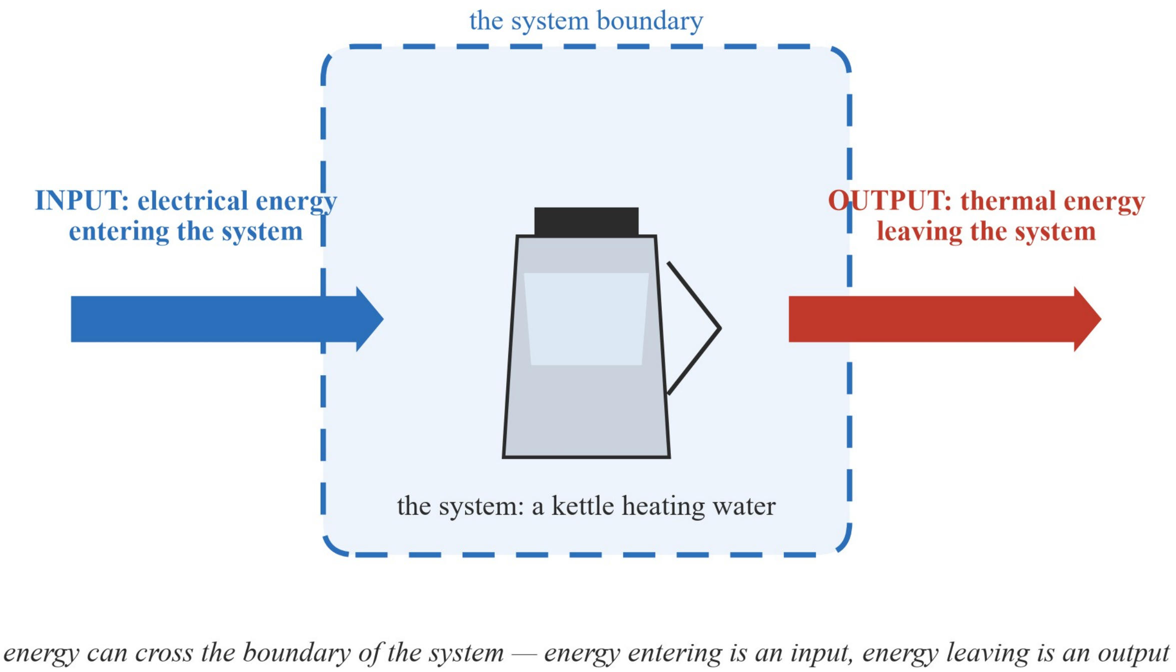
- **Kinetic energy** — the energy of a moving object. A rolling ball, a running athlete and moving air (wind) all have kinetic energy.
- **Gravitational potential energy** — the energy stored in an object because of its height above the ground. The higher the object is, the more gravitational potential energy it has.
- **Elastic potential energy** — the energy stored when an object is stretched, bent or squashed: a drawn bow, a bent pole-vault pole, a compressed spring.
- **Chemical energy** — the energy stored in food, fuels (coal, gas, petrol, wood) and batteries.
- **Thermal energy** — the energy an object has because it is hot. The hotter the object, the more thermal energy it holds.
- **Electrical energy** — the energy carried by an electric current in a circuit.
- **Light energy** — the energy carried by light, from the Sun, a lamp or a flame.
- **Sound energy** — the energy carried by sounds through air, water or solids.
- **Nuclear energy** — the energy stored inside atoms, released in nuclear power stations.



Nine panels, one for each form of energy: kinetic (a rolling ball), gravitational potential (a box held high), elastic potential (a drawn bow), chemical (coal, food and a battery), thermal (a steaming mug), electrical (a simple circuit), light (the Sun), sound (a loudspeaker) and nuclear (inside an atom).

Systems, transfers and transformations. To keep track of energy, first choose a **system**: the part of the world you have decided to watch. A system can be as small as a bouncing ball or as large as the whole Earth. Energy can cross the boundary of the system: energy entering the system is an **input**, and energy leaving it is an **output**.

A system: the part of the world you have decided to watch

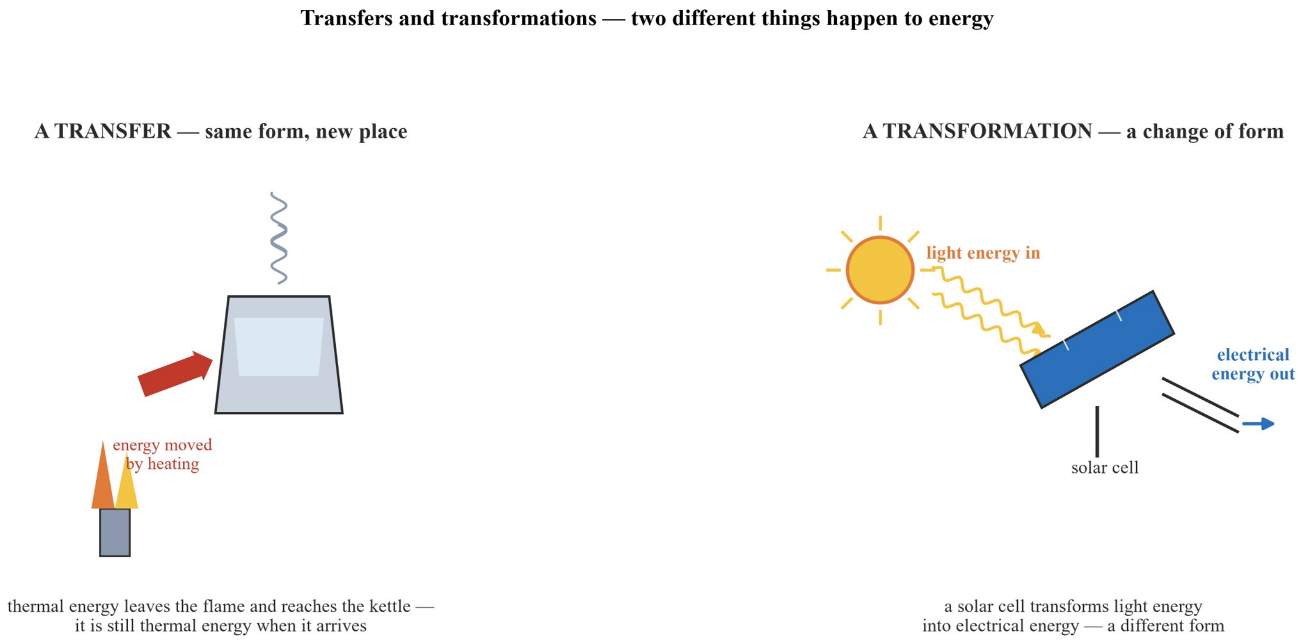


A dashed system boundary around a kettle heating water, with an input arrow of electrical energy crossing in and an output arrow of thermal energy crossing out.

Two things can happen to energy, and they have different names:

- A **transfer** moves energy from one place or object to another *without changing its form*. Energy transferred from a flame to a kettle by heating is still thermal energy. Energy carried along a power line is still electrical energy. Light travelling from the Sun to Earth is a transfer of light energy.
- A **transformation** changes energy *from one form into another*. A solar cell transforms light energy into electrical energy. A stretched bow transforms its stored elastic potential energy into the kinetic energy of an arrow.

Most real devices do both. A torch transfers chemical energy out of its battery as electrical energy, and then transforms that electrical energy into light (and thermal energy) in the bulb.



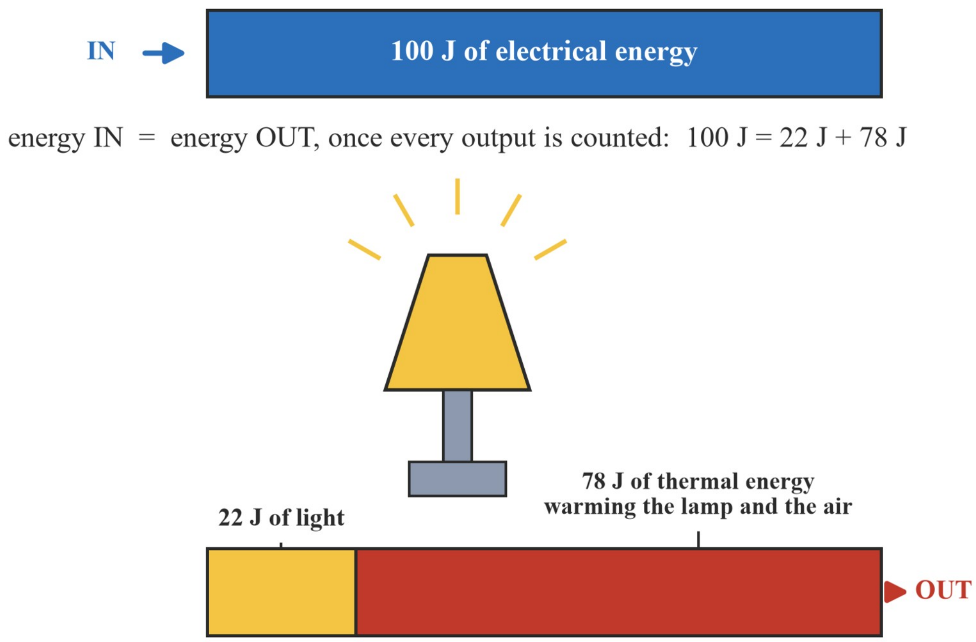
Two panels: a flame heating a kettle shows a transfer (thermal energy arrives still as thermal energy), and light falling on a solar cell shows a transformation (light energy becomes electrical energy).

The Law of Conservation of Energy. All of these changes obey one rule, called the Law of Conservation of Energy (elaboration `VC2S10U15.E01`):

> Energy cannot be created or destroyed. It can only be transferred from one place to another or transformed from one form into another. The total amount of energy stays the same.

This means the energy input into a system always equals the energy output, once every output is counted. If a lamp receives 100 J of electrical energy, exactly 100 J of energy leaves it — some as light, the rest as thermal energy warming the lamp and the air around it. Energy never vanishes, and no device can ever give out more energy than it takes in.

The Law of Conservation of Energy — the lamp accounts for every joule



energy cannot be created or destroyed — the two bars are the same total width because no energy is lost, and none appears

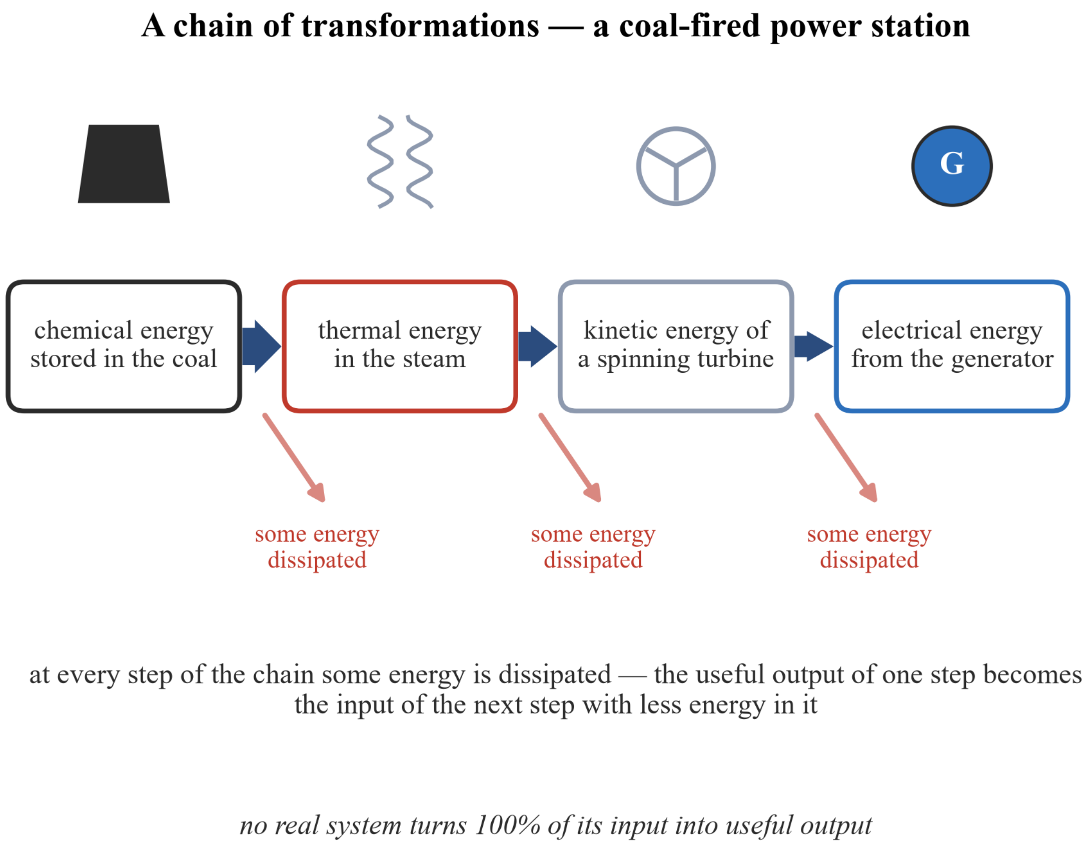
A lamp between two bars of the same total width: the top bar is 100 J of electrical energy in, and the bottom bar splits into 22 J of light and 78 J of thermal energy out.

When people say a device "uses up" energy, or a bouncing ball "loses" energy, the energy has not been destroyed. Something more subtle has happened, and it is the key idea of this subtopic.

Useful energy and dissipation. What really matters about a device is not just how much energy passes through it, but how much of that energy ends up *where you want it, in the form you want it*. This is the **useful energy output**. A lamp is bought to give light, so its light is its useful output. A kettle is bought to heat water, so the thermal energy that goes into the water is its useful output — for a kettle, heating things is the point.

In every real device, some of the input energy ends up somewhere unhelpful: it becomes thermal energy that warms the device itself and the surroundings. This energy is said to be **dissipated** — spread out into the environment where it cannot easily be used for the job in hand. Dissipated energy has not been destroyed (the total still adds up), but it is no longer available to do what you wanted.

Energy transformations also happen in **chains of several steps** (elaboration `VC2S10U15.E02`). In a coal-fired power station, for example, chemical energy in the coal becomes thermal energy in steam, then kinetic energy in a spinning turbine, then electrical energy in a generator. At every step of the chain some energy is dissipated, so the useful output of one step becomes the input of the next step with less energy in it. Step by step, the amount of usable energy gets smaller. No real system turns 100% of its input into useful output.



The transformation chain of a coal-fired power station: chemical energy in the coal, thermal energy in the steam, kinetic energy of a spinning turbine, electrical energy from the generator, with some energy dissipated at every step.

Efficiency. The **efficiency** of a system measures how much of the input energy comes out as useful output:

$$\text{efficiency} = \frac{\text{useful energy output}}{\text{total energy input}}$$

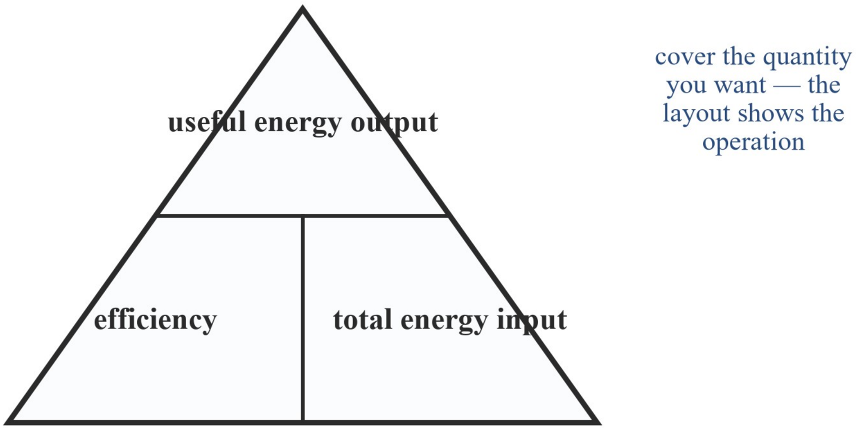
Both quantities are measured in joules, so the same unit appears on the top and the bottom of the ratio and the efficiency is just a number. It is usually written as a decimal or a fraction, or multiplied by 100 and written as a percentage. A lamp with an efficiency of 0.22 (22%) turns 22 J of every 100 J it receives into light; the other 78 J is dissipated.

The formula can be rearranged to find any one of the three quantities:

$$\text{useful energy output} = \text{efficiency} \times \text{total energy input}$$

$$\text{total energy input} = \frac{\text{useful energy output}}{\text{efficiency}}$$

The efficiency triangle — cover the quantity you want



efficiency = useful energy output ÷ total energy input

useful energy output = efficiency × total energy input

total energy input = useful energy output ÷ efficiency

both energy quantities are measured in joules, so efficiency is just a number — often written as a percentage

The efficiency triangle: useful energy output on top, efficiency and total energy input along the bottom, with the three rearranged forms of the formula written out below.

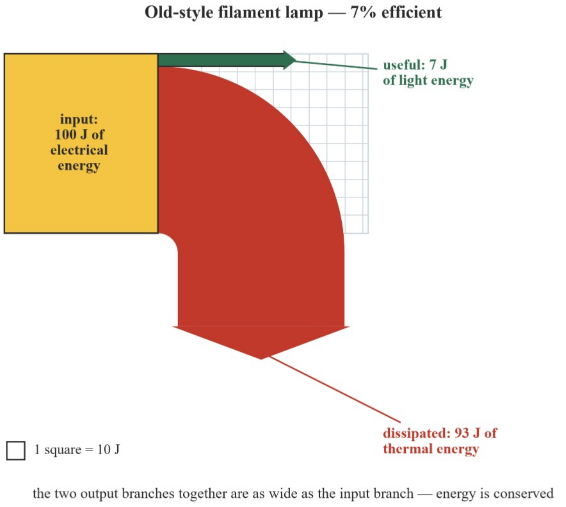
Because energy cannot be created, the useful output can never be greater than the input, so an efficiency can never be greater than 1 (greater than 100%). Any claim that a device gives out more energy than it takes in breaks the Law of Conservation of Energy.

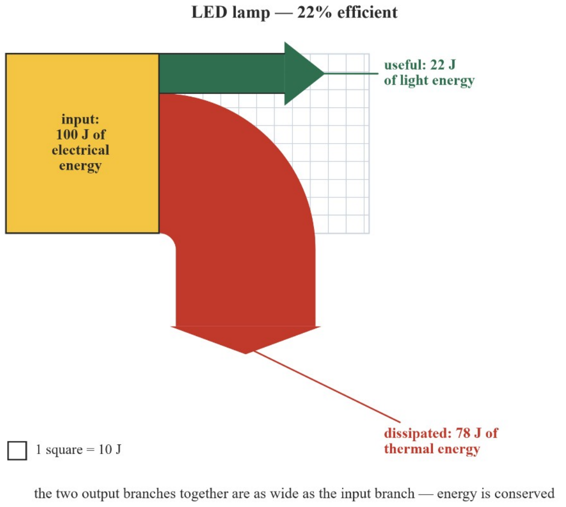
Sankey diagrams. A **Sankey diagram** is a way of drawing the energy flow through a system so that the conservation of energy can be seen at a glance. The rules are:

- One arrow brings the total energy input into the system.
- The system's outputs are drawn as arrows leaving it — usually the useful output goes straight on, and the dissipated energy bends down and away.
- The **width of each arrow is proportional to the amount of energy** it carries, using a scale you choose (for example, 1 cm = 10 J).
- The total width of the arrows leaving equals the width of the arrow coming in, because energy is conserved.

Reading a Sankey diagram is a proportional-reasoning task (`VC2M9M05`): a branch that is half as wide carries half the energy. Drawing one forces you to account for every joule — if the widths do not add up, some energy has gone missing from your diagram.

Sankey diagrams — the width of each arrow is proportional to the energy it carries



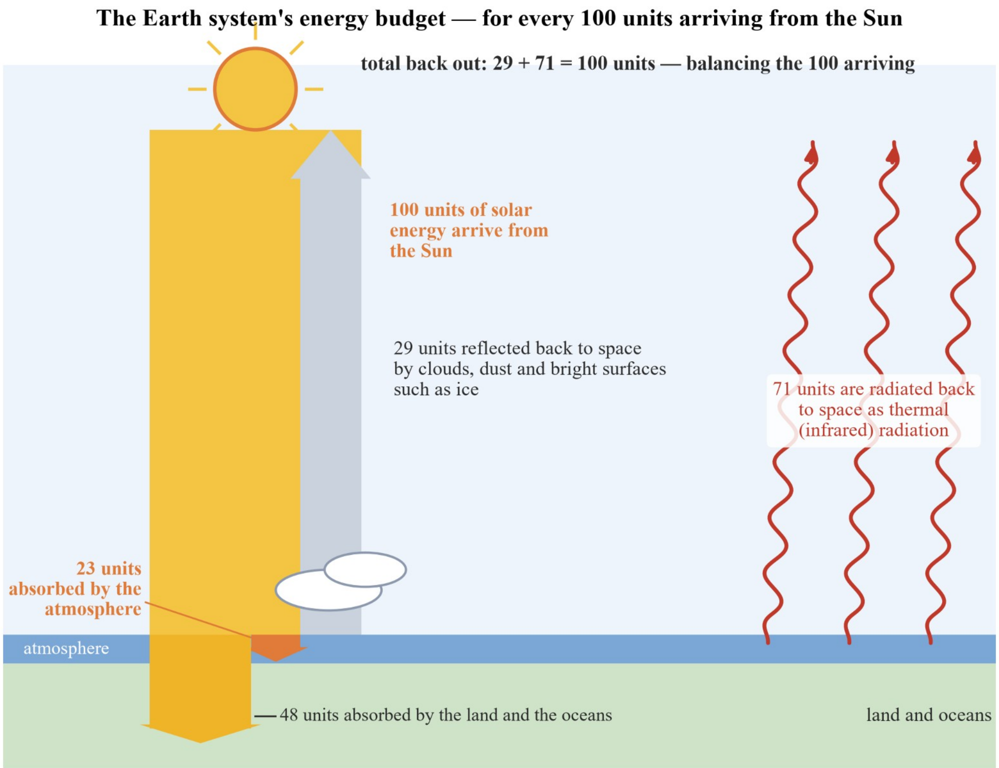


Two Sankey diagrams drawn to scale on squared paper (1 square = 10 J): a filament lamp with a very thin useful branch (7 J of light) and a wide dissipated branch (93 J of thermal), and an LED lamp with a wider useful branch (22 J) and a narrower dissipated branch (78 J).

The Earth as a system. The biggest system you can analyse is the Earth itself — the CD asks for systems *including Earth systems*. The Earth system's main input is light energy arriving from the Sun, and its main output is thermal (infrared) radiation leaving the Earth and heading back out to space.

Measurements from satellites show roughly what happens to every 100 units of solar energy that arrives at the top of the atmosphere:

- about **29 units** are reflected straight back to space by clouds, dust and bright surfaces such as ice;
- about **23 units** are absorbed by the atmosphere;
- about **48 units** pass through the atmosphere and are absorbed by the land and the oceans.



values are the section's rounded NASA Earth Observatory figures — band widths are proportional to the units; the detailed study of this balance belongs to subtopic 12C

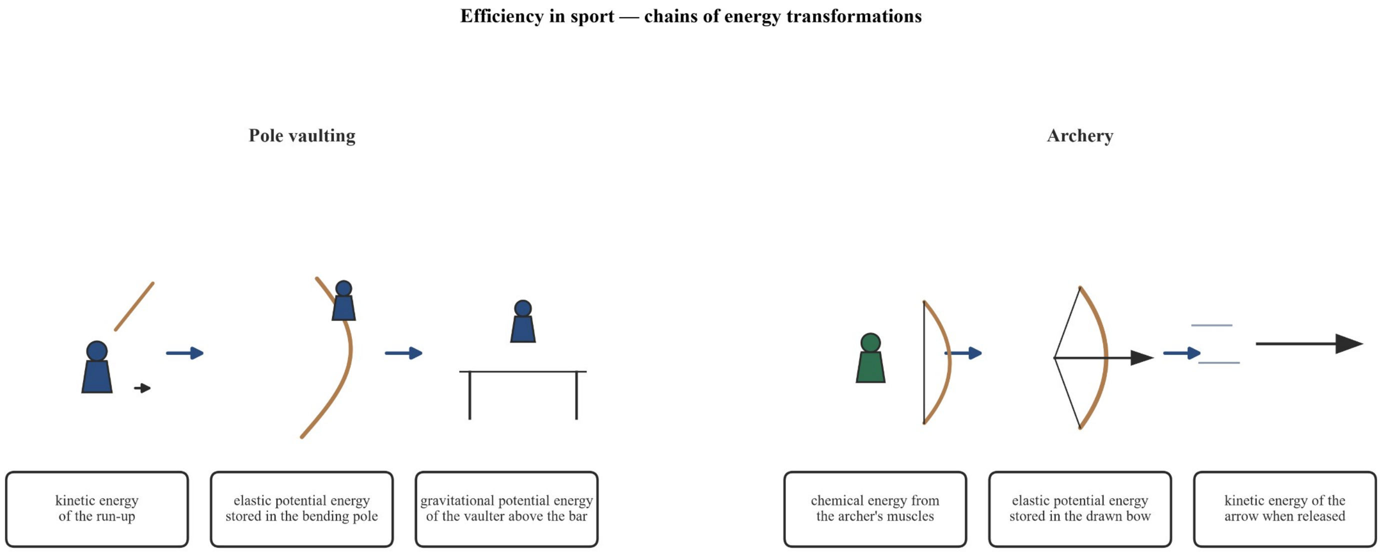
The Earth system's energy budget: of every 100 units arriving from the Sun, 29 units are reflected back to space, 23 units are absorbed by the atmosphere and 48 units are absorbed by the land and the oceans, while 71 units are radiated back to space as thermal (infrared) radiation.

So about 71 units in every 100 are absorbed by the Earth system. This absorbed energy is what drives the weather, the winds, the ocean currents, the water cycle and photosynthesis — it is the input that keeps Earth's systems moving. Meanwhile the Earth radiates energy back to space. When the total energy arriving from the Sun is balanced by the total energy radiated back out, Earth's average temperature stays roughly steady. If the balance changes — if the Earth absorbs a little more than it radiates, or a little less — the average temperature changes with it. (The detailed study of that balance, and how human activity is changing it, belongs to subtopic 12C.)

Source: NASA Earth Observatory, "Climate and Earth's Energy Budget", 2009 (updated 18 September 2025). https://science.nasa.gov/earth/earth-observatory/climate-and-earths-energy-budget — retrieved 2026-08-19.

Efficiency in sport. The same ideas apply on the sporting field (elaboration `VC2S10U15.E05`).

- **Pole vaulting.** The transformation chain is: kinetic energy of the run-up → elastic potential energy stored in the bending pole → gravitational potential energy of the vaulter high above the bar. Early vaulters used stiff bamboo or metal poles that stored little energy. Modern flexible poles bend much further, store more of the vaulter's kinetic energy, and return more of it, so a larger share of the run-up energy ends up lifting the vaulter. For the same run-up speed, a more efficient pole means a higher vault.
- **Archery.** The chain is: chemical energy from the archer's muscles → elastic potential energy stored in the drawn bow → kinetic energy of the arrow when the string is released. A bow that returns a larger share of its stored energy gives the arrow more kinetic energy, so the arrow leaves the bow faster for the same draw. Improving the efficiency of the energy transformation is one way modern equipment improves athletic performance.



Two chains of transformations on the sporting field: pole vaulting (kinetic energy of the run-up, elastic potential energy in the bending pole, gravitational potential energy of the vaulter above the bar) and archery (chemical energy from the archer's muscles, elastic potential energy in the drawn bow, kinetic energy of the arrow).

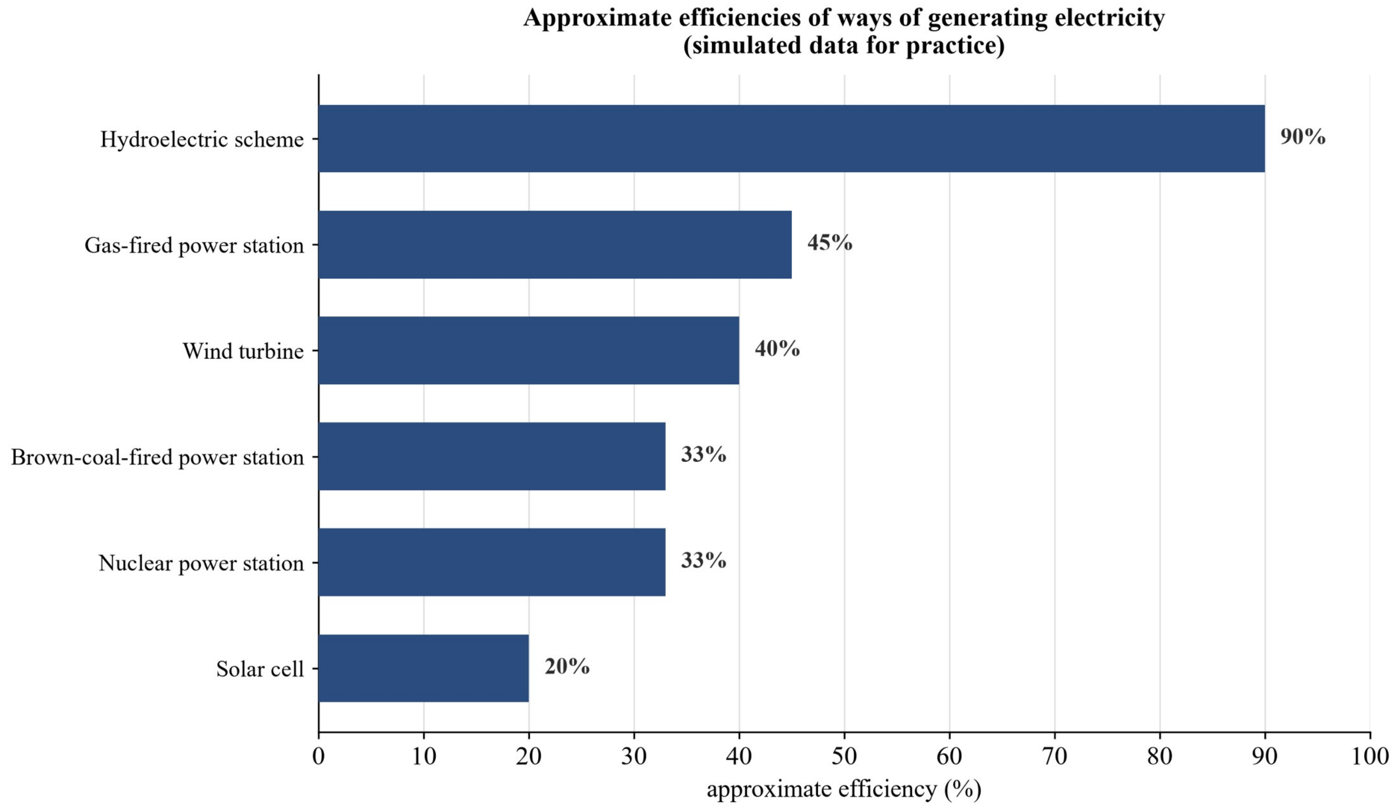
Efficiency of electricity generation. Different ways of generating electricity have very different efficiencies (elaboration `VC2S10U15.E06`), because their transformation chains are different.

- Power stations that burn fuel (brown coal, black coal or gas) and nuclear power stations all follow the same chain: stored energy in the fuel → thermal energy to make steam → kinetic energy of a spinning turbine → electrical energy from a generator. The heating step is where most of the energy is dissipated into the surroundings, so these stations turn only part of the fuel's energy into electricity.
- A hydroelectric scheme uses falling water: gravitational potential energy of the stored water → kinetic energy of the falling water → kinetic energy of the turbine → electrical energy. There is no burning and no steam step, so far less energy is dissipated.
- A wind turbine takes kinetic energy straight from moving air to a spinning generator.
- A solar cell transforms light energy directly into electrical energy, with no moving parts — though most of the light energy falling on the cell still ends up as thermal energy in the panel.

Table 1 gives a set of approximate efficiencies to practise with in this subtopic. They are rounded values for classroom use (simulated data for practice); real values differ from station to station and change over time.

Method of generating electricity	Input energy	Approximate efficiency
Brown-coal-fired power station	chemical energy in coal	33%
Gas-fired power station	chemical energy in gas	45%
Nuclear power station	nuclear energy in the fuel	33%
Hydroelectric scheme	energy of falling water	90%
Wind turbine	kinetic energy of moving air	40%
Solar cell	light from the Sun	20%

Table 1. Approximate efficiencies of electricity generation methods (simulated data for practice).

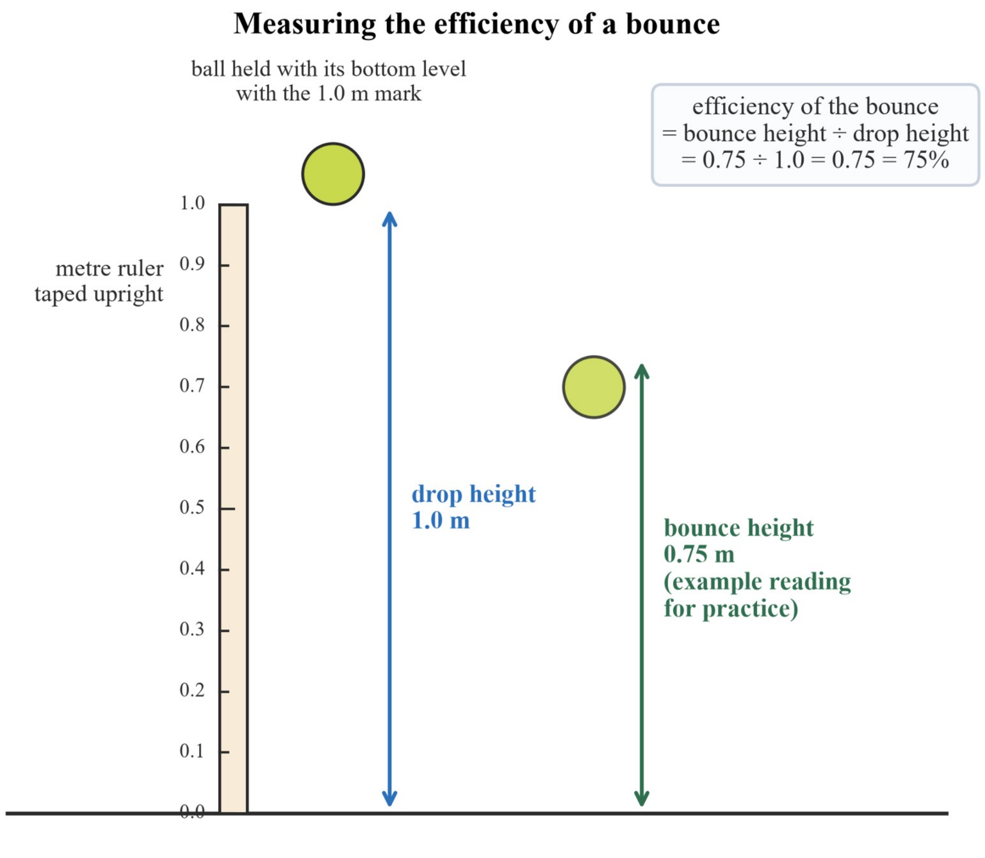


A bar chart of the approximate efficiencies from Table 1: hydroelectric scheme 90%, gas-fired power station 45%, wind turbine 40%, brown-coal-fired power station 33%, nuclear power station 33%, solar cell 20%.

Notice that "input energy" means something different for each method — the chemical energy stored in a fuel, the energy of falling water, the kinetic energy of wind, or the light falling on a cell. The efficiency ratio always compares the useful electrical energy output with the input for that particular method.

Activities

Activity 1 — The efficiency of a bouncing ball. Tape a metre ruler upright beside a smooth floor. Hold a tennis ball with its bottom level with the 1.0 m mark and drop it. Watch the top of the bounce and record the bounce height. Repeat three times and average the bounce heights. Because the ball's gravitational potential energy grows with height, the fraction (bounce height ÷ drop height) is a good guide to the fraction of energy returned in the bounce — the efficiency of the bounce. Try the same drop with other balls (a basketball, a rubber ball) and compare their efficiencies. Where is the "missing" energy going?



the higher the bounce, the larger the share of energy returned — the rest warms the ball, the floor and the air, or is transferred as sound

A ball held with its bottom level with the 1.0 m mark of a metre ruler taped upright, and a bounce height of 0.75 m marked as an example reading; the efficiency of the bounce is 0.75 divided by 1.0, or 75%.

Activity 2 — Drawing a Sankey diagram. An old-style filament lamp receives 100 J of electrical energy and transfers 7 J as light energy; the rest is dissipated as thermal energy. On squared paper, choose a scale (1 square = 10 J is a good start) and draw the Sankey diagram for the lamp: an input arrow 10 squares wide, a straight useful branch 0.7 of a square wide, and a downward dissipated branch carrying the rest. Check that the two output branches add up to the input width. Now draw the matching diagram for an LED lamp of efficiency 22% receiving 100 J. Which lamp keeps more of its input useful?

Activity 3 — Slowing down dissipation. Pour the same volume of warm (not boiling) water into four cups made of different materials — for example paper, plastic, metal, and one wrapped in a cloth sleeve. Record the starting temperature of each. After ten minutes, record the temperatures again. Rank the cups by how much thermal energy their water has dissipated to the surroundings. Which material slowed the dissipation most, and how can you tell? Take care with warm water and wipe up spills at once.

Worked examples

All data in this section are given to two significant figures, so final answers are also given to two significant figures unless the arithmetic is exact.

Example 1 — scaffolded

An LED lamp receives 250 J of electrical energy. Of this, 55 J is transferred as light energy and the rest is dissipated as thermal energy. (a) Calculate the efficiency of the lamp. (b) Calculate the energy dissipated.

Working	Comment
Total energy input = 250 J, useful energy output = 55 J	List the known quantities. Light is the useful output of a lamp.

Working	Comment
efficiency = useful energy output ÷ total energy input	The definition of efficiency.
efficiency = 55 ÷ 250 = 0.22	Both quantities are in joules, so the units cancel.
0.22 × 100 = 22%	Multiply by 100 to write the efficiency as a percentage.
(b) dissipated energy = 250 − 55 = 195 J	By conservation of energy, input = useful output + dissipated energy.

The lamp is 22% efficient: it turns 22 J of every 100 J it receives into light, and dissipates 195 J of the 250 J input as thermal energy.

Example 2 — scaffolded

An electric motor receives 400 J of electrical energy while lifting a load. The load gains 300 J of gravitational potential energy. (a) Calculate the efficiency of the motor. (b) Calculate the energy dissipated, and say where it goes.

Working	Comment
Total energy input = 400 J, useful energy output = 300 J	The useful output is the gravitational potential energy gained by the load.
efficiency = 300 ÷ 400 = 0.75	Useful output ÷ total input.
0.75 × 100 = 75%	The motor is 75% efficient.
(b) dissipated energy = 400 − 300 = 100 J	Input − useful output.

The dissipated 100 J warms the motor, the load, the string and the surrounding air, and a little is transferred as sound.

Example 3 — unscaffolded

At a hydroelectric scheme, falling water transfers 1.2 MJ of energy to the turbines and generators. The scheme is 85% efficient. Calculate the electrical energy output and the energy dissipated.

The useful output is the efficiency multiplied by the total input:

$$\text{useful output} = 0.85 \times 1.2 = 1.02\,\text{MJ} \approx 1.0\,\text{MJ (to two significant figures).}$$

By conservation of energy, the rest of the input is dissipated:

$$\text{dissipated energy} = 1.2 - 1.02 = 0.18\,\text{MJ}.$$

The scheme delivers 1.02 MJ of electrical energy and dissipates 0.18 MJ, mostly as thermal energy in the machinery and the water below the turbines.

Example 4 — unscaffolded

A gas-fired power station is 50% efficient. It receives 5.0 MJ of chemical energy from burning gas. The electrical energy it produces travels along power lines to a town, and the lines deliver 94% of the energy they carry. Calculate the energy that reaches the town, and the overall efficiency of the whole chain.

Step 1 — the power station: the useful electrical output is

$$0.50 \times 5.0 = 2.5\,\text{MJ}.$$

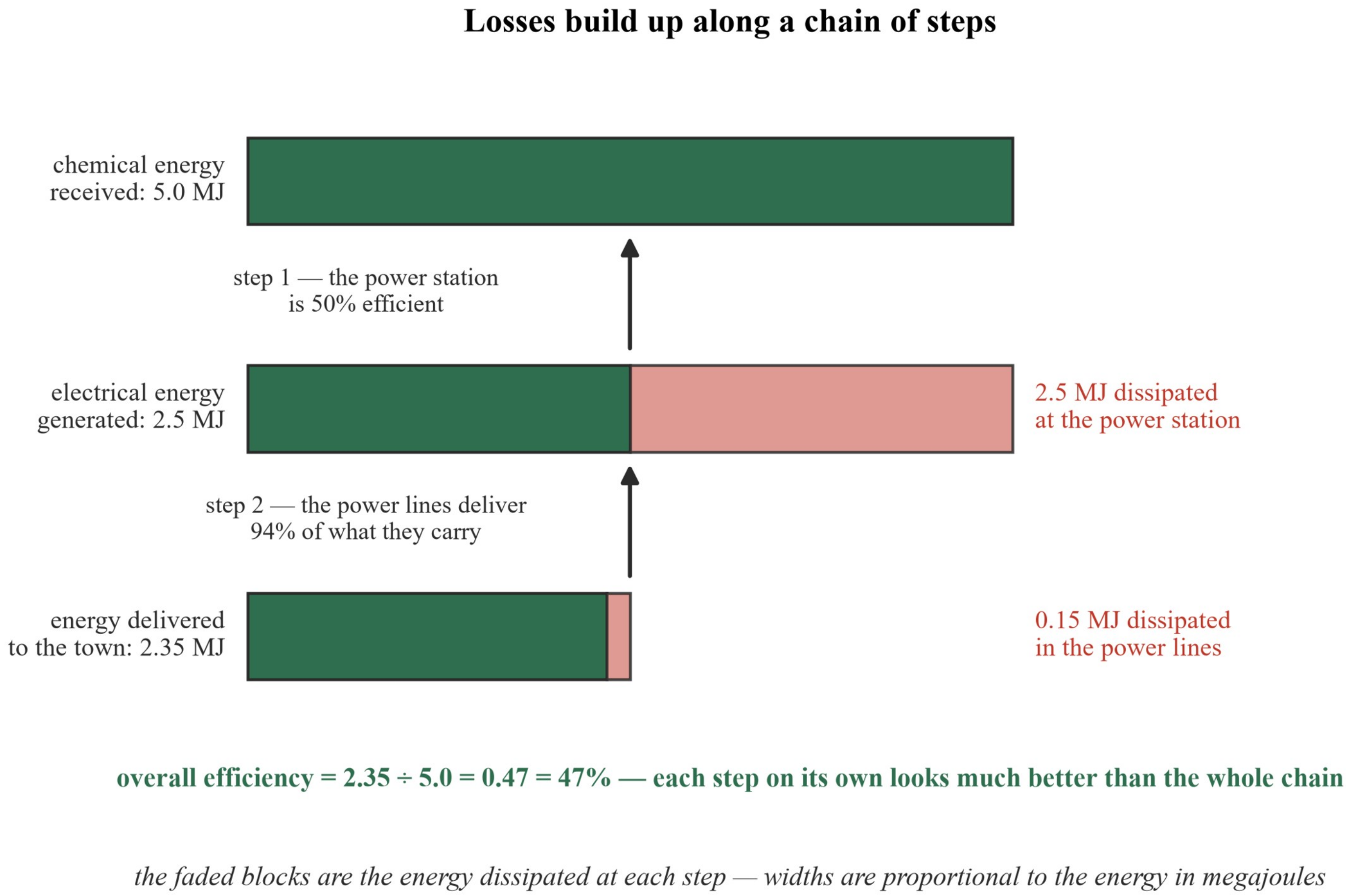
Step 2 — the power lines: the useful output of the first step is the input of the second step. The lines deliver

$$0.94 \times 2.5 = 2.35\,\text{MJ} \approx 2.4\,\text{MJ (to two significant figures).}$$

The overall efficiency compares the energy that finally arrives with the original input to the chain:

$$\text{overall efficiency} = \frac{2.35}{5.0} = 0.47 = 47\,\%.$$

The chain is only 47% efficient overall, even though each step on its own looks much better. This is the pattern with chains of transformations: every step dissipates some energy, so each step's output is smaller than its input, and the losses build up (elaboration `VC2S10U15.E02`).



Three bars drawn to scale: 5.0 MJ of chemical energy received, 2.5 MJ of electrical energy generated with 2.5 MJ dissipated at the power station, and 2.35 MJ delivered to the town with 0.15 MJ dissipated in the power lines — an overall efficiency of 47%.

Practice questions

Scaffolded questions

Question 1 An old-style filament lamp receives 100 J of electrical energy. It transfers 7 J as light energy and 93 J as thermal energy. (a) Identify the useful energy output and the dissipated energy. (b) Calculate the efficiency of the lamp. (c) State the Law of Conservation of Energy, and show that the energy values for this lamp agree with it.

Question 2 An electric kettle receives 150 000 J of electrical energy while boiling water. Of this, 135 000 J becomes thermal energy in the water. (a) Calculate the efficiency of the kettle. (b) Calculate the energy dissipated. (c) Name two places the dissipated energy goes.

Question 3 A ball is dropped from a height of 1.2 m and bounces back up to a height of 0.90 m. (a) Explain why comparing the heights is a fair way to compare the energies. (b) Calculate the efficiency of the bounce. (c) Name two places the "missing" energy goes.

Question 4 The blades of a wind turbine receive 50 000 J of kinetic energy from the wind, and the turbine generates 17 500 J of electrical energy. (a) Calculate the efficiency of the turbine. (b) Calculate the energy dissipated. (c) Draw a Sankey diagram for the turbine, using a scale of 1 cm = 5 000 J. Label the input, the useful output and the dissipated energy, and give the width of each arrow.

Question 5 A solar cell is 22% efficient. Light energy totalling 5 000 J falls on the cell. (a) Calculate the electrical energy the cell produces. (b) Calculate the energy dissipated by the cell. (c) Calculate the light energy that must fall on the cell to produce 1 100 J of electrical energy.

Question 6 Of every 100 units of solar energy arriving at the top of Earth's atmosphere, about 29 units are reflected back to space, 23 units are absorbed by the atmosphere and 48 units are absorbed by the land and the oceans. (a) Show that these values agree with the Law of Conservation of Energy. (b) Calculate the fraction of the arriving energy that is absorbed by the Earth system as a whole. (c) Earth's average temperature is roughly steady over time. What does this tell you about the total energy Earth sends back to space compared with the total energy arriving from the Sun?

Unscaffolded questions

Question 7 A toaster receives 80 000 J of electrical energy. Of this, 64 000 J becomes thermal energy in the bread, and the rest warms the toaster and the surrounding air. Calculate the efficiency of the toaster. (Hint: think about what the toaster is for.)

Question 8 At a hydroelectric scheme, falling water transfers 2.4 MJ of energy to the turbines and generators, which are 90% efficient. Calculate the electrical energy output and the energy dissipated.

Question 9 A gas-fired power station is 40% efficient and receives 8.0 MJ of chemical energy from burning gas. The electricity travels along power lines that deliver 90% of the energy they carry. (a) Calculate the electrical energy generated. (b) Calculate the energy delivered at the end of the lines. (c) Calculate the overall efficiency of the whole chain.

Question 10 An archer draws a bow, storing 90 J of elastic potential energy in it. When the string is released, the bow transfers 70% of the stored energy into the kinetic energy of the arrow. (a) Calculate the kinetic energy of the arrow as it leaves the bow. (b) Calculate the energy that is not transferred to the arrow, and name one place it goes. (c) Explain why a bow of greater efficiency shoots the arrow faster, for the same draw.

Question 11 A pole vaulter's run-up gives her 800 J of kinetic energy. Her pole stores and returns energy so that she gains 480 J of gravitational potential energy at the top of the vault. (a) State the useful energy output of the vault. (b) Calculate the overall efficiency of transforming her run-up energy into gravitational potential energy. (c) Account for the rest of the run-up energy.

Question 12 Table 1 gives approximate efficiencies (simulated data for practice) for several methods of generating electricity. (a) Which method transfers the largest fraction of its input energy into electrical energy? (b) Explain why brown-coal-fired and nuclear power stations dissipate such a large share of their input energy. (c) A brown-coal-fired power station and a hydroelectric scheme each receive 10 MJ of input energy. Calculate the electrical energy output of each, using the values in Table 1.

Question 13 A filament lamp is 8% efficient and an LED lamp is 25% efficient. Each lamp is used to produce 20 J of light energy. (a) Calculate the electrical energy each lamp must receive. (b) Calculate the energy each lamp dissipates. (c) State which lamp is the better choice for lighting a room, and justify your answer using your results.

Question 14 A battery charger receives 600 J of electrical energy from the mains. The battery stores 480 J of chemical energy. Calculate the efficiency of the charging process and the energy dissipated, and name one place the dissipated energy goes.

Question 15 On a certain day, a region of Earth receives 50 MJ of solar energy. About 30% of it is reflected back to space and the rest is absorbed. (a) Calculate the energy reflected. (b) Calculate the energy absorbed by the region. (c) The region's average temperature does not change during the day. Use the Law of Conservation of Energy to state the total energy the region sends back to space over the whole day, and explain your reasoning.

Question 16 An appliance receives 2 000 J of electrical energy and dissipates 1 500 J of it as thermal energy. (a) Calculate the useful energy output and the efficiency of the appliance. (b) Draw a Sankey diagram for the appliance, using a scale of 1 cm = 250 J. State the width of each arrow. (c) A salesperson claims that a different model "returns more energy than it receives, so it saves you money forever". Evaluate this claim using the Law of Conservation of Energy.

Answers

Question 1 (a) useful output 7 J (light), dissipated 93 J (thermal); (b) 7%; (c) see solution. **Question 2** (a) 90%; (b) 15 000 J; (c) the kettle body, the surrounding air. **Question 3** (a) see solution; (b) 75%; (c) thermal energy of the ball, floor and air; sound. **Question 4** (a) 35%; (b) 32 500 J; (c) input 10 cm, useful 3.5 cm, dissipated 6.5 cm. **Question 5** (a) 1 100 J; (b) 3 900 J; (c) 5 000 J. **Question 6** (a) 29 + 23 + 48 = 100; (b) 71%; (c) the same total as arrives from the Sun. **Question 7** 80%. **Question 8** 2.16 MJ ≈ 2.2 MJ; dissipated 0.24 MJ. **Question 9** (a) 3.2 MJ; (b) 2.88 MJ ≈ 2.9 MJ; (c) 36%. **Question 10** (a) 63 J; (b) 27 J; (c) see solution. **Question 11** (a) 480 J; (b) 60%; (c) see solution. **Question 12** (a) hydroelectric scheme; (b) see solution; (c) coal: 3.3 MJ; hydro: 9.0 MJ. **Question 13** (a) filament 250 J, LED 80 J; (b) filament 230 J, LED 60 J; (c) see solution. **Question 14** 80%; 120 J. **Question 15** (a) 15 MJ; (b) 35 MJ; (c) 50 MJ. **Question 16** (a) 500 J, 25%; (b) input 8 cm, useful 2 cm, dissipated 6 cm; (c) see solution.

Fully-worked solutions

Question 1 Total energy input = 100 J. (a) The lamp is bought to give light, so the useful energy output is the 7 J of light energy. The 93 J of thermal energy that warms the lamp and the air is the dissipated energy. (b) efficiency = useful energy output ÷ total energy input = 7 ÷ 100 = 0.07, which is **7%**. (c) The Law of Conservation of Energy says energy cannot be created or destroyed — only transferred or transformed — so the total energy input must equal the total energy output. Here: 7 J + 93 J = 100 J, which equals the 100 J input, so the values agree with the law.

Question 2 Total energy input = 150 000 J, useful output = 135 000 J. (a) efficiency = 135 000 ÷ 150 000 = 0.90 = **90%**. (Heating water is the point of a kettle, so the thermal energy in the water counts as useful.) (b) dissipated energy = 150 000 − 135 000 = **15 000 J**. (c) The dissipated energy warms the kettle itself and the air around it (the heating element, the kettle's body and the nearby bench also warm up).

Question 3 (a) The ball's gravitational potential energy grows with its height above the ground. Comparing the bounce height with the drop height therefore compares the energy the ball has after the bounce with the energy it had before it, so the height ratio is a fair guide to the energy ratio. (b) efficiency = bounce height ÷ drop height = 0.90 ÷ 1.2 = 0.75 = **75%**. (c) The missing 25% of the energy becomes thermal energy of the ball, the floor and the air, and some is transferred as the sound of the bounce.

Question 4 Total energy input = 50 000 J, useful output = 17 500 J. (a) efficiency = 17 500 ÷ 50 000 = 0.35 = **35%**. (b) dissipated energy = 50 000 − 17 500 = **32 500 J**. (c) With a scale of 1 cm = 5 000 J: the input arrow is 50 000 ÷ 5 000 = **10 cm** wide; the useful output arrow is 17 500 ÷ 5 000 = **3.5 cm** wide, drawn straight on; the dissipated arrow is 32 500 ÷ 5 000 = **6.5 cm** wide, drawn bending down and away. The two output widths (3.5 cm + 6.5 cm = 10 cm) add up to the input width, showing conservation of energy.

Question 5 efficiency = 22% = 0.22, total energy input = 5 000 J. (a) useful output = efficiency × input = 0.22 × 5 000 = **1 100 J**. (b) dissipated energy = 5 000 − 1 100 = **3 900 J**. (c) Rearrange: total energy input = useful output ÷ efficiency = 1 100 ÷ 0.22 = **5 000 J**.

Question 6 (a) The three outputs are 29 + 23 + 48 = 100 units, which equals the 100 units arriving. The input equals the total output, so the values agree with the Law of Conservation of Energy. (b) The energy absorbed by the Earth system is the part absorbed by the atmosphere plus the part absorbed by the land and oceans: 23 + 48 = 71 units out of 100, which is **71%**. (c) A roughly steady average temperature means the Earth system is not storing extra energy, so the total energy sent back to space must equal the total energy arriving from the Sun: about 100 units out for every 100 units in.

Question 7 The toaster's purpose is to heat the bread, so the 64 000 J of thermal energy in the bread is the useful output. efficiency = 64 000 ÷ 80 000 = 0.80 = **80%**.

Question 8 Total energy input = 2.4 MJ, efficiency = 90% = 0.90. Useful output = 0.90 × 2.4 = **2.16 MJ ≈ 2.2 MJ** (to two significant figures). Dissipated energy = 2.4 − 2.16 = **0.24 MJ**.

Question 9 Chemical energy input = 8.0 MJ. (a) electrical energy generated = 0.40 × 8.0 = **3.2 MJ**. (b) energy delivered = 0.90 × 3.2 = **2.88 MJ ≈ 2.9 MJ** (to two significant figures). (c) overall efficiency = energy delivered ÷ original input = 2.88 ÷ 8.0 = 0.36 = **36%**.

Question 10 Stored energy = 90 J, share transferred to the arrow = 70% = 0.70. (a) kinetic energy of the arrow = 0.70 × 90 = **63 J**. (b) energy not transferred to the arrow = 90 − 63 = **27 J**. This energy warms the bow and the string and the air, and some is transferred as the sound of the release. (c) A bow of greater efficiency transfers a larger share of the stored elastic potential energy into the kinetic energy of the arrow. More kinetic energy means the arrow leaves the bow moving faster, for the same draw and the same arrow.

Question 11 Run-up kinetic energy = 800 J. (a) The purpose of the vault is to raise the vaulter, so the useful energy output is the gravitational potential energy gained: **480 J**. (b) efficiency = 480 ÷ 800 = 0.60 = **60%**. (c) The remaining 320 J is dissipated: it warms the pole, the vaulter, the ground and the air, some is transferred as sound, and a little remains as kinetic energy because the vaulter is still moving slightly at the top of the vault.

Question 12 (a) From Table 1, the **hydroelectric scheme** has the largest efficiency (90%), so it transfers the largest fraction of its input energy into electrical energy. (b) Brown-coal-fired and nuclear power stations must first turn their stored energy into thermal energy to make steam, and use that steam to spin a turbine. At the heating step, most of the input energy is dissipated into the surroundings rather than becoming electrical energy, so these stations have much lower efficiencies than methods without a burning and steam step. (c) Brown-coal-fired station: 33% of 10 MJ = 0.33 × 10 = **3.3 MJ**. Hydroelectric scheme: 90% of 10 MJ = 0.90 × 10 = **9.0 MJ**.

Question 13 Useful light output = 20 J for each lamp. (a) Filament lamp: total energy input = useful output ÷ efficiency = 20 ÷ 0.08 = **250 J**. LED lamp: 20 ÷ 0.25 = **80 J**. (b) Filament lamp: 250 − 20 = **230 J** dissipated. LED lamp: 80 − 20 = **60 J** dissipated. (c) The **LED lamp** is the better choice for lighting a room. To produce the same 20 J of light it needs only 80 J of electrical energy instead of 250 J, and it dissipates 60 J instead of 230 J. Less input energy means less energy must be generated for the same light, and less dissipated energy means the room heats up less.

Question 14 Total energy input = 600 J, useful output = 480 J (chemical energy stored in the battery). efficiency = 480 ÷ 600 = 0.80 = **80%**. Dissipated energy = 600 − 480 = **120 J**. It warms the battery, the charger and the surrounding air.

Question 15 Total solar energy received = 50 MJ. (a) energy reflected = 30% of 50 MJ = 0.30 × 50 = **15 MJ**. (b) energy absorbed = 50 − 15 = **35 MJ** (or 70% of 50 MJ). (c) The region's temperature does not change, so the region is not storing extra energy overall. By the Law of Conservation of Energy, the total energy leaving the region must equal the total energy arriving: the region sends **50 MJ** back to space over the whole day (15 MJ reflected directly, and 35 MJ radiated after being absorbed).

Question 16 Total energy input = 2 000 J, dissipated energy = 1 500 J. (a) useful energy output = 2 000 − 1 500 = **500 J**. efficiency = 500 ÷ 2 000 = 0.25 = **25%**. (b) With a scale of 1 cm = 250 J: the input arrow is 2 000 ÷ 250 = **8 cm** wide; the useful output arrow is 500 ÷ 250 = **2 cm** wide, drawn straight on; the dissipated arrow is 1 500 ÷ 250 = **6 cm** wide, drawn bending down and away. The output widths (2 cm + 6 cm = 8 cm) add up to the input width. (c) The claim breaks the Law of Conservation of Energy, which says energy cannot be created. A device's energy output can never be greater than its energy input — the most a device could ever do is return all of the energy it receives, and every real device dissipates some. The salesperson's claim cannot be true.

Where this leads: this subtopic is assumed by VCE Physics Units 1 and 2, Area of Study 1 ("How are light and heat explained?") and Area of Study 3 ("How can electricity be used to transfer energy?"), where efficiency and Sankey reasoning recur throughout — reference-only for this book (TOC D12). The machinery of electricity generation itself — alternating current from magnets and turbines, direct current from solar cells and batteries — is taught in subtopic 15A, and the detailed treatment of Earth's energy balance and climate belongs to subtopic 12C. No VCE content is pre-taught here (TOC D9).