Physics Units 1 & 2

Chapter 2 — Thermal energy and radiation

Aboriginal and Torres Strait Islander content has been excluded as accuracy cannot be guaranteed, and it is better to be respectful than cover the entire curriculum inaccurately.

Significant effort has been made to ensure this content is legal. Please send any areas of concern to admin@vwx.au with appropriate document/legal references so errors can be verified and changes be made.

Contents

Theory

Temperature and the Celsius scale. Temperature is the quantity that tells us how hot or cold something is. It is measured with a thermometer. A liquid-in-glass thermometer works because the liquid inside expands when it is heated: the higher the temperature, the longer the column of liquid. In everyday life in Australia, temperatures are reported in **degrees Celsius** (symbol °C). On the Celsius scale, $0\,°\text{C}$ is the temperature at which pure water freezes and $100\,°\text{C}$ is the temperature at which it boils, both at normal atmospheric pressure. Temperatures below the freezing point of water are negative on this scale: the inside of a typical domestic freezer is about $-18\,°\text{C}$.

The kelvin scale and absolute zero. The SI unit of temperature is the **kelvin** (symbol K). Note the convention: we say "kelvin", not "degree kelvin", and the symbol is written without a degree sign. The kelvin scale starts at **absolute zero**, $0\,\text{K}$, the lowest temperature that can exist. At absolute zero the particles of matter have the least kinetic energy they can possibly have, and nothing can be cooled below this temperature. Absolute zero corresponds to $-273.15\,°\text{C}$. The two scales are related by

$$T(\text{K}) = T(°\text{C}) + 273.15 \text{ and } T(°\text{C}) = T(\text{K}) - 273.15.$$

A kelvin is the same size as a Celsius degree: a temperature *change* of $1\,\text{K}$ is exactly the same change as a temperature *change* of $1\,°\text{C}$. The two scales have different zero points but equal-sized units. Some useful reference temperatures are listed below.

Situation	Temperature (°C)	Temperature (K)
Absolute zero	-273.15	0
Freezing point of water	0	273.15
Human body (approx.)	37	310
Boiling point of water	100	373.15

Thermal energy. All matter is made of particles — atoms and molecules. These particles are never still: in a solid they vibrate about fixed positions, in a liquid they slide past one another, and in a gas they move freely. Because they are moving, the particles have kinetic energy. The particles also exert forces on one another, so they have potential energy because of their positions relative to each other. The **thermal energy** of a system is the total kinetic and potential energy of all the particles that make up that system. (In physics a **system** is the object or collection of particles we choose to study; everything outside it is the **surroundings**.)

An increase in the temperature of a system corresponds to an increase in its thermal energy. Heating a system makes its particles move faster on average, which raises their average kinetic energy and so raises the temperature. Cooling does the reverse.

Temperature and thermal energy are related but they are not the same thing. Temperature depends on the *average* kinetic energy of the particles, so it does not matter how much matter there is. Thermal energy is the *total* energy of all the particles, so it does depend on how much matter there is. A bathtub of warm water at $40\,°\text{C}$ contains far more thermal energy than a cup of boiling water at $100\,°\text{C}$ — the water in the cup is at a higher temperature, but the bath contains many more particles.

(One more idea to keep for later: energy added to a system does not always raise its temperature. During a change of state, such as melting or boiling, the added energy increases the potential energy of the particles while the temperature stays constant. You will calculate the energy involved in changes of state in 2B.)

Heat. Heat is energy transferred between a system and its surroundings, or between two systems, because of a temperature difference. Like all energy, heat is measured in **joules** (J). Energy transferred as heat always flows naturally from the hotter object to the colder object, never the reverse. When two objects in contact reach the same temperature they are in **thermal equilibrium**, and from then on there is no net transfer of energy between them. Be careful with the word: an object does not "contain heat". Objects contain thermal energy; heat is the name for that energy only while it is being transferred.

Three mechanisms of heat transfer. Thermal energy can be transferred within a system, or between systems, in three ways: conduction, convection and radiation.

Conduction is the transfer of energy through a material without the material itself moving from one place to another. In a hotter region, particles vibrate or move more strongly; as they collide with their neighbours they pass energy along from particle to particle. Conduction happens in solids, liquids and gases but is most effective in solids, where the particles are locked close together. Metals are particularly good conductors: as well as their vibrating atoms, they contain electrons that are free to move through the metal, carrying energy quickly from hotter regions to cooler regions. Materials such as wood, plastic, wool and air are poor conductors; they are called **insulators**. Trapped air is a good insulator, which is why wool jumpers and the air gap in double-glazed windows help keep us warm.

Convection is the transfer of energy by the movement of the material itself — a liquid or a gas (a **fluid**). When a fluid is heated it expands: the same mass of fluid takes up more space, so it becomes less dense (less mass per unit volume). The warmer, less dense fluid rises through the cooler, denser fluid around it, and cooler fluid sinks to take its place. The result is a circulation called a **convection current**, which carries energy through the fluid. Convection happens within fluids — within the water in a pot being heated, or within the air in a room warmed by a heater. It cannot happen in solids, because the particles of a solid are not free to move around.

Radiation is the transfer of energy by electromagnetic waves. Every object emits electromagnetic radiation; at everyday temperatures most of it is infrared radiation, the region of the electromagnetic spectrum just beyond red light (1B). Radiation does not need a medium: it can travel through empty space. This is how energy from the Sun reaches the Earth across the near-vacuum of space. Conduction and convection both need matter; radiation does not. How the temperature of an object affects the radiation it emits is taken up in 2C.

Mechanism	How energy is carried	Medium needed?	Where it happens	Example
Conduction	Particle collisions and vibrations; free electrons in metals	Yes — most effective in solids	Within a material, or between objects in direct contact	A metal spoon becoming hot in a bowl of soup
Convection	Movement of the heated fluid itself	Yes — liquids and gases only	Within a fluid	Warm air rising above a bar heater
Radiation	Electromagnetic waves (mostly infrared)	No — travels through a vacuum	Between objects, even across empty space	Energy from the Sun reaching the Earth

Evaporation and cooling. Evaporation is the escape of particles from the surface of a liquid into the gas state. It happens at any temperature — not only at the boiling point. The simple kinetic energy model explains why evaporation always cools the liquid:

- The particles in a liquid have a *range* of kinetic energies: some move slowly and some move quickly.
- A particle at the surface that is moving fast enough can overcome the attractions of its neighbours and escape from the liquid.
- The particles that escape are the faster ones, so the *average* kinetic energy of the particles left behind decreases.
- A lower average kinetic energy means a lower temperature, so the liquid cools.

The escaping particles carry energy away with them, and that energy comes from the liquid itself and from whatever is in contact with it. When sweat evaporates from your skin, the energy comes from your skin, and your skin cools. Moving air — wind, or a fan — carries the escaped particles away before they can fall back into the liquid, so evaporation is faster and the cooling is faster too. On a humid day the air already holds a lot of water vapour, so evaporation is slower and the cooling is less effective.

Worked examples

Example 1 — scaffolded

Convert the following temperatures.

(a) the boiling point of water, $100\,°\mathrm{C}$, to kelvin

(b) the temperature inside a domestic freezer, $-18\,°\mathrm{C}$, to kelvin

(c) the boiling point of liquid nitrogen, $-196\,°\mathrm{C}$, to kelvin

(d) a comfortable room temperature, $298\,\mathrm{K}$, to degrees Celsius

Working	Comment
$T(\mathrm{K}) = T(°\mathrm{C}) + 273.15$	To convert from Celsius to kelvin, add 273.15.
(a) $T = 100 + 273.15 = 373.15\,\mathrm{K} \approx 373\,\mathrm{K}$	The value is given to the nearest degree, so round the answer to the nearest kelvin.
(b) $T = -18 + 273.15 = 255.15\,\mathrm{K} \approx 255\,\mathrm{K}$	Negative Celsius temperatures are handled in the same way.
(c) $T = -196 + 273.15 = 77.15\,\mathrm{K} \approx 77\,\mathrm{K}$	Liquid nitrogen boils at about $77\,\mathrm{K}$.
(d) $T(°\mathrm{C}) = T(\mathrm{K}) - 273.15 = 298 - 273.15 = 24.85\,°\mathrm{C} \approx 25$	To convert from kelvin to Celsius, subtract 273.15.

Example 2 — scaffolded

A kettle in a Melbourne kitchen heats water from $21\,°\mathrm{C}$ to $100\,°\mathrm{C}$.

(a) Express the initial and final temperatures of the water in kelvin.

(b) Find the temperature change of the water in degrees Celsius and in kelvin. What do you notice?

Working	Comment
Initial: $T_1 = 21 + 273.15 = 294.15\,\mathrm{K} \approx 294\,\mathrm{K}$	Add 273.15 to convert from Celsius to kelvin.
Final: $T_2 = 100 + 273.15 = 373.15\,\mathrm{K} \approx 373\,\mathrm{K}$	Water boils at $100\,°\mathrm{C}$ at normal atmospheric pressure.
$\Delta T = 100 - 21 = 79\,°\mathrm{C}$	The temperature change in degrees Celsius.
$\Delta T = 373.15 - 294.15 = 79\,\mathrm{K}$	The temperature change in kelvin, using the unrounded values.

The change is the same number in both scales. A change of $1\,°\mathrm{C}$ *is* a change of $1\,\mathrm{K}$: the two scales have equal-sized units and differ only in where they place zero.

Example 3 — unscaffolded

A swimmer steps out of an outdoor pool on a warm, dry day and feels cold, even though the air is warmer than the pool water. Use the simple kinetic energy model of evaporation to explain why the swimmer feels cold, and why the feeling is stronger when a breeze picks up.

Water on the swimmer's skin evaporates. The particles in that water have a range of kinetic energies, and the fastest particles at the surface have enough kinetic energy to overcome the attractions of their neighbours and escape into the air. Because the escaping particles are the faster ones, the average kinetic energy of the water left on the skin decreases, so its temperature falls. Energy is then transferred as heat from the swimmer's warmer skin to the cooler water on the skin, and the swimmer feels cold. When a breeze picks up it carries water vapour away from the skin, so fewer escaping particles fall back into the liquid; evaporation is faster, and so the cooling is faster.

Example 4 — unscaffolded

For each situation below, identify the main mechanism of heat transfer and justify your choice.

(a) You hold your hands to the *side* of a campfire and feel warmth.

(b) The metal handle of a saucepan becomes hot while the saucepan sits on a hot cooktop.

(c) Water circulates through a pot as it is heated from below.

(d) **Radiation.** Energy reaches the hands by electromagnetic waves (mostly infrared). The air between the fire and the hands is a poor conductor, and the hot air from the fire rises upward rather than travelling sideways, so neither conduction nor convection can account for the warmth felt at the side.

(e) **Conduction.** Energy travels through the solid metal from the hot end to the cooler end, passed from particle to particle by vibrations (and carried by the metal's free electrons), without the metal itself moving from place to place.

(f) **Convection.** Water heated at the bottom of the pot expands, becomes less dense and rises, while cooler, denser water sinks to take its place. The convection current that results carries energy through the water.

Practice questions

Question 1 Convert the following temperatures to kelvin.

(a) $25\,°\mathrm{C}$, a comfortable room temperature

(b) $-40\,°\mathrm{C}$, a very cold winter's day

(c) $55\,°\mathrm{C}$, hot tap water

Question 2 Convert the following temperatures to degrees Celsius.

(a) $300\,\mathrm{K}$

(b) $265\,\mathrm{K}$, a cold winter's day

(c) $310\,\mathrm{K}$, the human body

Question 3 Copy and complete the table of reference temperatures below.

Situation	Temperature (°C)	Temperature (K)
Absolute zero	…	0
Freezing point of water	0	…
Human body (approx.)	…	310
Boiling point of water	…	373.15

Question 4 The coolant in a car engine warms from $15\,°\mathrm{C}$ to $90\,°\mathrm{C}$ during the first minutes of a trip.

(a) Express both temperatures in kelvin.

(b) Find the temperature change of the coolant in degrees Celsius and in kelvin.

(c) What do you notice about your two answers to part (b)?

Question 5 A saucepan with a metal body and a plastic handle sits on a hot cooktop.

(a) Name the mechanism by which energy is transferred through the metal base of the saucepan.

(b) Explain, in terms of particles, how energy is transferred through the metal.

(c) Explain why the handle is made of plastic rather than metal.

Question 6 (a) Name the mechanism by which energy from the Sun reaches the Earth.

(b) Explain why this energy transfer cannot happen by conduction or by convection.

(c) Takeaway food is often kept warm under a heat lamp. Identify the mechanism by which energy from the lamp reaches the food, and justify your choice.

Question 7 Convert the following temperatures to kelvin.

(a) $4.0\,°\mathrm{C}$, the inside of a refrigerator

(b) $-10\,°\mathrm{C}$, an icy morning

(c) $1000\,°\mathrm{C}$, a candle flame (approximately)

(d) $1064\,°\mathrm{C}$, the melting point of gold

Question 8 Convert the following temperatures to degrees Celsius.

(a) $295\,\mathrm{K}$

(b) $77\,\mathrm{K}$, the boiling point of liquid nitrogen

(c) $373.15\,\mathrm{K}$

(d) $0\,\mathrm{K}$

Question 9 A pizza oven heats from $25\,°\mathrm{C}$ to $300\,°\mathrm{C}$. Express the initial and final temperatures in kelvin, and find the temperature change in kelvin.

Question 10 A cup of tea at $90\,°\mathrm{C}$ is left on a bench, and its temperature falls by $62\,\mathrm{K}$.

(a) What is the final temperature of the tea in degrees Celsius?

(b) What is the final temperature of the tea in kelvin?

Question 11 In each pair, decide which temperature is higher. Show a conversion to justify each answer.

(a) $300\,\mathrm{K}$ or $25\,°\mathrm{C}$

(b) $0\,°\mathrm{C}$ or $260\,\mathrm{K}$

(c) $100\,°\mathrm{C}$ or $373\,\mathrm{K}$

Question 12 (a) Helium boils at $4\,\mathrm{K}$ at normal atmospheric pressure. Convert this temperature to degrees Celsius.

(b) Iron melts at about $1500\,°\mathrm{C}$ in a steelworks furnace. Convert this temperature to kelvin.

Question 13 (a) State the temperature of absolute zero in kelvin and in degrees Celsius.

(b) A sample of gas is cooled from $27\,°\mathrm{C}$ to $-73\,°\mathrm{C}$. Find the temperature change of the gas in kelvin.

Question 14 On a hot, dry day, a student wraps a damp towel around a water bottle, and the water in the bottle stays cool. Use the simple kinetic energy model of evaporation to explain why.

Question 15 Sweating cools the body during exercise. Explain why a fan makes a person feel much cooler on a hot, dry day, but does not help nearly as much on a hot, humid day.

Question 16 On a cold morning, the metal rail of a fence feels colder to the touch than the wooden post beside it, even though both have been outside all night and are at the same temperature. Explain why the rail feels colder.

Question 17 The freezer compartment of a refrigerator is at the top of the cabinet. Use the idea of density to explain how this arrangement cools the whole cabinet.

Question 18 Energy from the Sun reaches the Earth across space, which is almost a vacuum. Explain why this tells you the transfer is by radiation rather than by conduction or convection.

Question 19 A bathtub of water at $40\,°\mathrm{C}$ has more thermal energy than a cup of water at $100\,°\mathrm{C}$, even though the water in the cup is at a higher temperature. Explain how this can be.

Question 20 A vacuum flask has double walls with a vacuum between them, shiny silvered inner surfaces, and a plastic stopper. For each of these three features, identify the mechanism (or mechanisms) of heat transfer it mainly reduces, and explain how.

Answers

Question 1 (a) $298\,\mathrm{K}$; (b) $233\,\mathrm{K}$; (c) $328\,\mathrm{K}$.

Question 2 (a) $27\,°\mathrm{C}$; (b) $-8\,°\mathrm{C}$; (c) $37\,°\mathrm{C}$.

Question 3 Absolute zero $-273.15\,°\mathrm{C}$; freezing point of water $273.15\,\mathrm{K}$; human body $37\,°\mathrm{C}$; boiling point of water $100\,°\mathrm{C}$.

Question 4 (a) $288\,\mathrm{K}$ and $363\,\mathrm{K}$; (b) $75\,°\mathrm{C}$ and $75\,\mathrm{K}$; (c) the two changes are equal.

Question 5 (a) conduction; (b) particles in the hot region vibrate more strongly and pass energy to neighbouring particles in collisions; (c) plastic is an insulator (a poor conductor), so little energy is conducted to the hand.

Question 6 (a) radiation; (b) space is almost a vacuum, and conduction and convection both need a medium; (c) radiation — energy travels by electromagnetic waves; the air is a poor conductor and the lamp is above the food, so heated air rises away from the food rather than toward it.

Question 7 (a) $277\,\mathrm{K}$; (b) $263\,\mathrm{K}$; (c) $1273\,\mathrm{K}$; (d) $1337\,\mathrm{K}$.

Question 8 (a) $22\,°\mathrm{C}$; (b) $-196\,°\mathrm{C}$; (c) $100\,°\mathrm{C}$; (d) $-273.15\,°\mathrm{C}$.

Question 9 $298\,\mathrm{K}$; $573\,\mathrm{K}$; change $275\,\mathrm{K}$.

Question 10 (a) $28\,°\mathrm{C}$; (b) $301\,\mathrm{K}$.

Question 11 (a) $300\,\mathrm{K}$; (b) $0\,°\mathrm{C}$; (c) $100\,°\mathrm{C}$.

Question 12 (a) $-269\,°\mathrm{C}$; (b) about $1773\,\mathrm{K}$.

Question 13 (a) $0\,\mathrm{K}$, $-273.15\,°\mathrm{C}$; (b) a fall of $100\,\mathrm{K}$.

Question 14 The fastest water particles escape from the damp towel, lowering the average kinetic energy (and temperature) of the water left behind; the energy the escaping particles carry away comes from the towel and the water in the bottle, so the bottle's water cools.

Question 15 The fan carries water vapour away from the skin, so sweat evaporates faster and cooling is faster; on a humid day the air already holds much water vapour, so evaporation is slow and the fan makes little difference.

Question 16 Metal is a better conductor than wood, so it conducts energy away from the warm hand faster; the hand loses energy at a greater rate and the rail feels colder.

Question 17 Air cooled by the freezer compartment becomes denser and sinks through the cabinet, while warmer, less dense air rises to be cooled, setting up a convection current.

Question 18 Space is almost a vacuum, so there is no medium; conduction and convection both need matter, so only radiation can carry the energy across.

Question 19 Thermal energy is the total energy of all the particles; the bath contains far more particles, and its greater amount of matter more than makes up for its lower temperature.

Question 20 Vacuum: stops conduction and convection (no particles to carry energy). Silvered surfaces: reduce radiation (they reflect infrared radiation). Plastic stopper: reduces conduction (plastic is a poor conductor) and blocks convection currents and evaporation through the neck.

Fully-worked solutions

Question 1 Use $T(\mathrm{K}) = T(°\mathrm{C}) + 273.15$, rounding to the same precision as the given value. (a) $T = 25 + 273.15 = 298.15\,\mathrm{K} \approx 298\,\mathrm{K}$. (b) $T = -40 + 273.15 = 233.15\,\mathrm{K} \approx 233\,\mathrm{K}$. (c) $T = 55 + 273.15 = 328.15\,\mathrm{K} \approx 328\,\mathrm{K}$.

Question 2 Use $T(°C) = T(K) - 273.15$. (a) $T = 300 - 273.15 = 26.85\,°C \approx 27\,°C$. (b) $T = 265 - 273.15 = -8.15\,°C \approx -8\,°C$. (c) $T = 310 - 273.15 = 36.85\,°C \approx 37\,°C$.

Question 3 Absolute zero is $0\,K = -273.15\,°C$. Water freezes at $0\,°C = 273.15\,K$. The human body is about $37\,°C$, and $37 + 273.15 = 310.15\,K \approx 310\,K$. Water boils at $373.15\,K - 273.15 = 100\,°C$.

Question 4 (a) $T_1 = 15 + 273.15 = 288.15\,K \approx 288\,K$; $T_2 = 90 + 273.15 = 363.15\,K \approx 363\,K$. (b) In Celsius: $\Delta T = 90 - 15 = 75\,°C$. In kelvin: $\Delta T = 363.15 - 288.15 = 75\,K$. (c) The two changes are equal. A change of $1\,°C$ is a change of $1\,K$, so a temperature change has the same numerical value in both scales.

Question 5 (a) Conduction. (b) The particles in the hot region of the metal vibrate more strongly. As they collide with their neighbours they pass energy along from particle to particle, and the metal's free electrons also move through the metal carrying energy. Energy is transferred through the base without the metal itself moving. (c) Plastic is an insulator — a poor conductor of heat. Very little energy is conducted from the hot body of the pan to the handle, so the handle stays cool enough to hold.

Question 6 (a) Radiation. (b) The space between the Sun and the Earth is almost a vacuum — it contains almost no matter. Conduction needs particles in contact, and convection needs the movement of a fluid, so neither can operate across empty space. Radiation needs no medium. (c) Radiation. The lamp emits electromagnetic waves (mostly infrared) that travel down to the food through the air. The air is a poor conductor, so conduction is negligible, and the lamp is above the food: any air heated by the lamp rises away from the food rather than toward it, so convection cannot deliver the energy either.

Question 7 Use $T(K) = T(°C) + 273.15$. (a) $T = 4.0 + 273.15 = 277.15\,K \approx 277\,K$. (b) $T = -10 + 273.15 = 263.15\,K \approx 263\,K$. (c) $T = 1000 + 273.15 = 1273.15\,K \approx 1273\,K$. (d) $T = 1064 + 273.15 = 1337.15\,K \approx 1337\,K$.

Question 8 Use $T(°C) = T(K) - 273.15$. (a) $T = 295 - 273.15 = 21.85\,°C \approx 22\,°C$. (b) $T = 77 - 273.15 = -196.15\,°C \approx -196\,°C$. (c) $T = 373.15 - 273.15 = 100\,°C$. (d) $T = 0 - 273.15 = -273.15\,°C$. This is absolute zero, the lowest possible temperature.

Question 9 Initial: $T_1 = 25 + 273.15 = 298.15\,K \approx 298\,K$. Final: $T_2 = 300 + 273.15 = 573.15\,K \approx 573\,K$. The change is $\Delta T = 300 - 25 = 275\,°C$, which is the same change in kelvin: $\Delta T = 275\,K$ (check: $573.15 - 298.15 = 275$).

Question 10 A fall of $62\,K$ is the same change as a fall of $62\,°C$. (a) $T = 90 - 62 = 28\,°C$. (b) $T = 28 + 273.15 = 301.15\,K \approx 301\,K$ (check: $363.15 - 62 = 301.15\,K$).

Question 11 Convert each pair to one scale, then compare. (a) $25\,°C = 25 + 273.15 = 298.15\,K$. Since $300\,K > 298.15\,K$, $300\,K$ **is higher**. (b) $0\,°C = 273.15\,K$. Since $273.15\,K > 260\,K$, $0\,°C$ **is higher**. (c) $373\,K = 373 - 273.15 = 99.85\,°C$. Since $100\,°C > 99.85\,°C$, $100\,°C$ **is higher**.

Question 12 (a) $T = 4 - 273.15 = -269.15\,°C \approx -269\,°C$. (b) $T = 1500 + 273.15 = 1773.15\,K$, about $1773\,K$.

Question 13 (a) Absolute zero is $0\,K$, which equals $-273.15\,°C$. (b) The change in Celsius is $\Delta T = -73 - 27 = -100\,°C$. A change of $1\,°C$ is a change of $1\,K$, so the temperature change is a fall of $100\,K$.

Question 14 Model answer. The water in the damp towel evaporates. The particles in the water have a range of kinetic energies; the fastest particles at the surface escape into the air, taking their energy with them. The particles left behind therefore have a lower average kinetic energy, so the temperature of the remaining water falls. The energy carried off by the escaping particles comes from the towel and its surroundings — including the bottle — so energy is transferred from the water in the bottle to the evaporating water, and the bottle's water cools. On a dry day the air holds little water vapour, so evaporation is fast and the cooling effect is strong.

Question 15 Model answer. Sweat evaporating from the skin cools the body, because the fastest water particles escape and the energy they carry away comes from the skin. On a hot, dry day a fan carries the water vapour away from the skin, so fewer escaping particles fall back into the sweat; evaporation is faster, and so the cooling is faster and the person feels much cooler. On a humid day the air already holds a lot of water vapour, so particles return to the liquid almost as fast as they escape; net evaporation is slow, and speeding up the air movement with a fan makes little difference to the cooling.

Question 16 Model answer. Energy is transferred as heat from the warm hand to the colder rail or post. Metal is a much better conductor than wood, so the metal rail conducts energy away from the hand at a greater rate. The hand loses energy faster to the rail than to the post, so the rail feels colder even though both are at the same temperature. (The feeling of "cold" depends on the rate of energy loss from the skin, not on the temperature of the object alone.)

Question 17 Model answer. Air in contact with the freezer compartment at the top is cooled. Cooled air contracts, becomes denser, and sinks down through the cabinet, while warmer, less dense air from lower down rises to the top, where it is cooled in turn. This convection current circulates cold air through the whole cabinet, cooling all of the food inside.

Question 18 Model answer. Conduction transfers energy through collisions between particles, and convection transfers energy by the movement of a fluid; both mechanisms need matter. The space between the Sun and the Earth is almost a vacuum — it contains almost no particles — so neither conduction nor convection can carry energy across it. Radiation needs no medium: it is the transfer of energy by electromagnetic waves, which can travel through a vacuum. The fact that the Sun's energy reaches the Earth across empty space therefore shows the transfer is by radiation.

Question 19 Model answer. Temperature depends on the *average* kinetic energy of the particles, but thermal energy is the *total* kinetic and potential energy of all the particles in the system. The cup of water is at a higher temperature ($100\,°\mathrm{C}$ against $40\,°\mathrm{C}$), so its particles have a higher average kinetic energy. But the bathtub contains far more water — many more particles — and the total energy of all those particles is greater than the total energy of the much smaller number of particles in the cup. The bath therefore has more thermal energy despite its lower temperature.

Question 20 Model answer. *Vacuum between the walls:* conduction needs particles in contact and convection needs the movement of a fluid, and a vacuum contains no particles, so the vacuum stops energy transfer by both conduction and convection between the inner and outer walls. *Shiny silvered surfaces:* shiny surfaces are poor emitters and good reflectors of infrared radiation, so the silvered walls reduce energy transfer by radiation (keeping radiation from hot contents in, and outside radiation out). *Plastic stopper:* plastic is a poor conductor, so the stopper reduces conduction through the neck; it also closes the neck, blocking convection currents and evaporation through the opening.

Theory

Section 2A showed that an increase in the temperature of a system corresponds to an increase in its thermal energy — the total kinetic and potential energy of its particles — and that energy can be transferred between a system and its surroundings. This section makes those energy transfers quantitative. Two situations are considered: energy transferred **without** a change of state, which changes the temperature, and energy transferred **during** a change of state, which does not.

One point of language first. In this section Q stands for an amount of energy transferred to or from a system, measured in **joules** (J). The word *heat* is often used for energy that is in transit because of a temperature difference. A system does not "contain heat"; it contains thermal energy. When energy is transferred to a system we take Q as positive; when energy leaves a system, Q is negative. In most of what follows we work with the magnitude of Q and state the direction of the transfer in words.

Specific heat capacity. The energy needed to raise the temperature of a substance depends on three things: how much of it there is (the mass m), how much the temperature changes (ΔT), and what the substance is. The **specific heat capacity** c of a substance is defined as the energy required to raise the temperature of $1\,\mathrm{kg}$ of the substance by $1\,\mathrm{K}$ (the same as a change of $1\,°\mathrm{C}$ — Section 2A covers the Celsius and kelvin scales). Its unit is $\mathrm{J\,kg^{-1}\,K^{-1}}$.

The energy Q required to change the temperature of a mass m by ΔT is

$$Q = mc\Delta T$$

where $\Delta T = T_{\text{final}} - T_{\text{initial}}$. Because a change of $1\,°\mathrm{C}$ is the same size as a change of $1\,\mathrm{K}$, ΔT has the same numerical value in either unit. When a substance cools, ΔT is negative: $Q = mc\Delta T$ then gives the energy removed.

Specific heat capacities vary widely between substances. Some approximate values, treated as constants in this section, are:

Substance	Specific heat capacity ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
water (liquid)	4180
ethanol	2440
ice	2100
aluminium	900
iron	450
copper	385
lead	130

Water's specific heat capacity is unusually large — roughly five times that of sand or rock, and ten times that of many metals. For the same mass and the same energy input, water's temperature rises much less than most materials' would; and when it cools, it releases much more energy per degree of temperature drop. This is why hot-water bottles and hot-water heating systems work well, and why large bodies of water warm up and cool down slowly, keeping nearby coastal areas at more even temperatures than inland areas (an idea that returns in Section 2D, where energy transfers are applied to climate).

Changes of state. Matter commonly exists in three states: solid, liquid and gas. The changes between them have names: melting (solid to liquid), freezing (liquid to solid), vaporisation (liquid to gas), condensation (gas to liquid). Evaporation is vaporisation from the surface of a liquid below its boiling point; Section 2A explains the cooling it causes.

When a pure substance changes state at normal atmospheric pressure, its temperature stays constant while energy continues to be transferred. The energy does not increase the average kinetic energy of the particles — which is what temperature measures — but instead works against the attractive forces between particles, changing the potential-energy part of the thermal energy (Section 2A). This "hidden" energy is called **latent heat**.

The **specific latent heat** L of a substance is the energy required to change the state of $1\,\mathrm{kg}$ of the substance at constant temperature. Its unit is $\mathrm{J\ kg^{-1}}$. The energy Q for a change of state of a mass m is

$$Q = m\,L$$

Water has two specific latent heats you will use repeatedly:

- specific latent heat of fusion (melting/freezing at $0\,°\mathrm{C}$): $L_f = 3.34\times10^5\ \mathrm{J\ kg^{-1}}$;
- specific latent heat of vaporisation (boiling/condensing at $100\,°\mathrm{C}$): $L_v = 2.26\times10^6\ \mathrm{J\ kg^{-1}}$.

The reverse change releases exactly the energy the forward change absorbs: freezing $1\,\mathrm{kg}$ of water at $0\,°\mathrm{C}$ releases $3.34\times10^5\ \mathrm{J}$, and condensing $1\,\mathrm{kg}$ of steam at $100\,°\mathrm{C}$ releases $2.26\times10^6\ \mathrm{J}$. Notice that L_v is much larger than L_f: separating particles completely into a gas takes far more energy than loosening them from a solid into a liquid.

The heating curve for water. Suppose a sample of ice below $0\,°\mathrm{C}$ is heated steadily until it becomes steam above $100\,°\mathrm{C}$. The temperature does not simply climb in one straight line; it rises in stages, with flat plateaus at each change of state:

Stage	What happens	Temperature	Energy calculation
1	ice warms up	rising, up to $0\,°\mathrm{C}$	$Q = m\,c\,\Delta T$ with $c = 2100\ \mathrm{J\ kg^{-1}K^{-1}}$ (ice)
2	ice melts	constant at $0\,°\mathrm{C}$	$Q = m\,L_f$
3	water warms up	rising, $0\,°\mathrm{C}$ to $100\,°\mathrm{C}$	$Q = m\,c\,\Delta T$ with $c = 4180\ \mathrm{J\ kg^{-1}K^{-1}}$ (water)
4	water boils	constant at $100\,°\mathrm{C}$	$Q = m\,L_v$
5	steam warms up	rising above $100\,°\mathrm{C}$	$Q = m\,c\,\Delta T$ (steam)

On a temperature–energy graph this appears as rising sections (where $Q = m\,c\,\Delta T$ applies) separated by flat sections (where $Q = m\,L$ applies). The melting and boiling temperatures depend on pressure; this section assumes normal atmospheric pressure.

Measuring c and L practically. The specific heat capacity of a substance can be measured by supplying a known amount of energy to a known mass and measuring the temperature rise, then rearranging $Q = m\,c\,\Delta T$ to $c = \dfrac{Q}{m\,\Delta T}$. In school laboratories the energy is often measured directly with a joulemeter, which reads the energy supplied in joules. A similar method measures a specific latent heat: supply a known energy to melt (or boil) a known mass at constant temperature, and use $L = \dfrac{Q}{m}$.

In any real measurement, some of the supplied energy is transferred to the container and to the surroundings rather than to the sample. Because the calculation treats *all* of the supplied energy as having gone into the sample, the measured value of c or L is usually larger than the accepted value. Insulating the container, using a lid, and keeping the temperature rise moderate all reduce this loss. When you carry out such an investigation, record the mass, the temperatures, the energy supplied and your evaluation of the energy losses in your logbook.

Mixing and conservation of energy. When a hot object and a cold object are placed in contact inside an insulated container, energy transfers from the hotter to the colder until both reach one common final temperature; the two are then in **thermal equilibrium** with each other. If the container is well insulated, energy is conserved, so

$$\text{energy lost by the hotter object} = \text{energy gained by the colder object}.$$

Each side is calculated with $Q = m c \Delta T$ (or $Q = m L$ if a change of state occurs). This *method of mixtures* is used in Worked Example 3.

Throughout this section, specific heat capacities and specific latent heats are treated as constants, and the system is assumed to be a pure substance at normal atmospheric pressure.

Worked examples

Example 1 — scaffolded

A $1.7\,\mathrm{L}$ electric kettle is filled with water at $20\,°\mathrm{C}$ and switched on. Calculate the energy required to raise the temperature of the water to $100\,°\mathrm{C}$, assuming all of the energy goes into the water. (Specific heat capacity of water $= 4180\,\mathrm{J\,kg^{-1}\,K^{-1}}$; $1\,\mathrm{L}$ of water has a mass of $1\,\mathrm{kg}$.)

Working	Comment
$m = 1.7\,\mathrm{kg}$; $c = 4180\,\mathrm{J\,kg^{-1}\,K^{-1}}$; $\Delta T = 100 - 20 = 80\,°\mathrm{C}$.	List the data. Convert the volume of water to a mass, and find the temperature change.
$Q = m c \Delta T = 1.7 \times 4180 \times 80 = 568\,480\,\mathrm{J}$.	There is no change of state, so use $Q = m c \Delta T$.
$Q = 5.7 \times 10^5\,\mathrm{J}$.	Round to two significant figures — the least number in the data ($1.7\,\mathrm{kg}$, $80\,°\mathrm{C}$ rise).

Note that in a real kettle some energy warms the kettle body itself and is transferred to the surrounding air, so the electrical energy drawn from the wall is greater than $5.7 \times 10^5\,\mathrm{J}$.

Example 2 — scaffolded

After training, a player ices a sore ankle with a $2.0\,\mathrm{kg}$ ice pack at $0\,°\mathrm{C}$. Calculate the energy absorbed by the ice as it all melts. Assume the ice stays at $0\,°\mathrm{C}$ while it melts. (Specific latent heat of fusion of water $= 3.34 \times 10^5\,\mathrm{J\,kg^{-1}}$.)

Working	Comment
$m = 2.0\,\mathrm{kg}$; $L = L_f = 3.34 \times 10^5\,\mathrm{J\,kg^{-1}}$.	Melting happens at constant temperature, so this is a latent-heat calculation, not a $Q = m c \Delta T$ calculation.
$Q = m L = 2.0 \times 3.34 \times 10^5 = 6.68 \times 10^5\,\mathrm{J}$.	Use $Q = m L$ with the specific latent heat of fusion.
$Q = 6.7 \times 10^5\,\mathrm{J}$.	Round to two significant figures. The energy is transferred from the ankle to the ice.

Example 3 — unscaffolded

In a school laboratory, a $0.45\,\mathrm{kg}$ aluminium block heated to $95\,°\mathrm{C}$ is quickly transferred into an insulated container holding $1.0\,\mathrm{kg}$ of water at $20.0\,°\mathrm{C}$. Calculate the final temperature of the water once the block and the water reach thermal equilibrium. Assume no energy is transferred to the container or to the surroundings. (Specific heat capacity of aluminium $= 900\,\mathrm{J\,kg^{-1}\,K^{-1}}$; specific heat capacity of water $= 4180\,\mathrm{J\,kg^{-1}\,K^{-1}}$.)

Let the final temperature be T. The aluminium block cools from $95\,°\mathrm{C}$ to T, releasing energy $Q = m c \Delta T = 0.45 \times 900 \times (95 - T)$, and the water warms from $20.0\,°\mathrm{C}$ to T, gaining energy $Q = 1.0 \times 4180 \times (T - 20)$. Since the container is insulated, conservation of energy gives

$$0.45 \times 900 \times (95 - T) = 1.0 \times 4180 \times (T - 20)$$

$$405(95 - T) = 4180(T - 20)$$

$$38\,475 - 405T = 4180T - 83\,600$$

$$122\,075 = 4585T$$

$$T = \frac{122\,075}{4585} = 26.6\,°C.$$

(Check: the aluminium loses $405 \times 68.4 \approx 2.8 \times 10^4$ J and the water gains $4180 \times 6.6 \approx 2.8 \times 10^4$ J. The two agree, so energy is conserved.)

∴ the final temperature is $26.6\,°C$. Notice how little the water's temperature changes: water's large specific heat capacity means it absorbs a great deal of energy for only a small rise in temperature.

Example 4 — unscaffolded

A $0.500\,\text{kg}$ block of ice at $-10.0\,°C$ is taken from a freezer and heated until it has all become steam at $100\,°C$. Calculate the total energy transferred to the water. (Specific heat capacity of ice $= 2100\,\text{J kg}^{-1}\text{K}^{-1}$; specific heat capacity of water $= 4180\,\text{J kg}^{-1}\text{K}^{-1}$; $L_f = 3.34 \times 10^5\,\text{J kg}^{-1}$; $L_v = 2.26 \times 10^6\,\text{J kg}^{-1}$.)

This follows the heating curve of the Theory section: two warming stages (each $Q = m\,c\,\Delta T$) and two changes of state (each $Q = m\,L$), added in order.

Stage 1 — warming the ice from $-10.0\,°C$ to $0\,°C$:

$$Q_1 = m\,c\,\Delta T = 0.500 \times 2100 \times 10.0 = 10\,500\,\text{J}.$$

Stage 2 — melting the ice at $0\,°C$:

$$Q_2 = m\,L_f = 0.500 \times 3.34 \times 10^5 = 167\,000\,\text{J}.$$

Stage 3 — warming the water from $0\,°C$ to $100\,°C$:

$$Q_3 = m\,c\,\Delta T = 0.500 \times 4180 \times 100 = 209\,000\,\text{J}.$$

Stage 4 — vaporising the water at $100\,°C$:

$$Q_4 = m\,L_v = 0.500 \times 2.26 \times 10^6 = 1\,130\,000\,\text{J}.$$

The total is

$$Q = Q_1 + Q_2 + Q_3 + Q_4 = 10\,500 + 167\,000 + 209\,000 + 1\,130\,000 = 1\,516\,500\,\text{J}.$$

∴ the total energy transferred is 1.52×10^6 J (about $1.5\,\text{MJ}$).

The largest contribution by far is the vaporisation stage — roughly three-quarters of the total — even though boiling happens at a single temperature. This is why a pot of water takes so long to boil dry, and why steam carries so much energy.

Practice questions

Unless stated otherwise, use: specific heat capacity of water $= 4180\,\text{J kg}^{-1}\text{K}^{-1}$; specific heat capacity of ice $= 2100\,\text{J kg}^{-1}\text{K}^{-1}$; L_f for water $= 3.34 \times 10^5\,\text{J kg}^{-1}$; L_v for water $= 2.26 \times 10^6\,\text{J kg}^{-1}$; $1\,\text{L}$ of water has a mass of $1\,\text{kg}$.

Question 1 A student on a camping trip heats $2.0\,\text{kg}$ of water from $20\,°C$ to $90\,°C$ on a stove to make hot drinks. (a) Write the relationship between the energy Q, the mass m, the specific heat capacity c and the temperature change ΔT. (b) Calculate the temperature change of the water. (c) Calculate the energy transferred to the water.

Question 2 In a school laboratory, a $0.50\,\text{kg}$ block of an unknown metal absorbs $4.5\,\text{kJ}$ of energy and its temperature rises from $20\,°C$ to $40\,°C$. (a) Rearrange $Q = m\,c\,\Delta T$ to make c the subject. (b) Calculate the specific heat capacity of the metal. (c) Using the table of specific heat capacities in the Theory section, identify the most likely metal.

Question 3 A household storage hot-water system holds $125\,\mathrm{L}$ of water and heats it from $15\,°\mathrm{C}$ to $60\,°\mathrm{C}$. (a) State the mass of the water and the temperature change. (b) Calculate the energy required. (c) With reference to the specific heat capacity of water, explain why heating water is such a large part of a household's energy use.

Question 4 A $0.200\,\mathrm{kg}$ ice cube at $0\,°\mathrm{C}$ is added to a drink and melts completely, staying at $0\,°\mathrm{C}$ as it melts. (a) Name the change of state that occurs, and state the temperature at which it happens for pure water at normal atmospheric pressure. (b) Calculate the energy absorbed by the ice as it melts. (c) State what happens to the temperature of the ice while it is melting, and explain where the absorbed energy goes.

Question 5 A steam iron converts $0.30\,\mathrm{kg}$ of water at $100\,°\mathrm{C}$ entirely into steam at $100\,°\mathrm{C}$. (a) Calculate the energy required. (b) Calculate the energy the same $0.30\,\mathrm{kg}$ of water would absorb if it were simply warmed from $20\,°\mathrm{C}$ to $100\,°\mathrm{C}$ instead. (c) Compare your answers to (a) and (b), and comment on what this says about changes of state.

Question 6 A $1.5\,\mathrm{kg}$ bottle of water at $25\,°\mathrm{C}$ is placed in an insulated cooler and cools to $5\,°\mathrm{C}$. (a) Calculate the magnitude of the energy removed from the water. (b) State the direction of the energy transfer during the cooling. (c) An equal mass of cooking oil (specific heat capacity $\approx 2000\,\mathrm{J\,kg^{-1}\,K^{-1}}$) is cooled through the same temperature change. Would this require more or less energy than for the water? Justify your answer with a calculation.

Question 7 A $1.2\,\mathrm{kg}$ cast-iron cooking pot is heated on a stove from $22\,°\mathrm{C}$ to $180\,°\mathrm{C}$. The specific heat capacity of iron is $450\,\mathrm{J\,kg^{-1}\,K^{-1}}$. Calculate the energy absorbed by the pot.

Question 8 On a sunny day, a solar hot-water system transfers $62.7\,\mathrm{kJ}$ of energy to some water, raising its temperature from $18\,°\mathrm{C}$ to $38\,°\mathrm{C}$. Calculate the mass of water that was heated.

Question 9 A $0.100\,\mathrm{kg}$ ice cube at $0\,°\mathrm{C}$ melts completely and the resulting water then warms to $25\,°\mathrm{C}$. Calculate the total energy absorbed.

Question 10 A $0.30\,\mathrm{kg}$ piece of copper at $80\,°\mathrm{C}$ is placed into an insulated container holding $0.60\,\mathrm{kg}$ of water at $20\,°\mathrm{C}$. Calculate the final temperature once the copper and the water reach thermal equilibrium. The specific heat capacity of copper is $385\,\mathrm{J\,kg^{-1}\,K^{-1}}$. Assume no energy is transferred to the container or the surroundings.

Question 11 Steam from a kettle condenses on a cold window. For $0.050\,\mathrm{kg}$ of steam at $100\,°\mathrm{C}$ that condenses to water at $100\,°\mathrm{C}$ and then cools to $40\,°\mathrm{C}$, calculate the total energy released.

Question 12 In an experiment to measure the specific latent heat of fusion of water, a student supplies $25.05\,\mathrm{kJ}$ of energy to a sample of ice at $0\,°\mathrm{C}$ and finds that $0.0750\,\mathrm{kg}$ of ice melts. Determine the specific latent heat of fusion from the student's data.

Question 13 When a pot of water boils at $100\,°\mathrm{C}$, energy continues to be supplied, yet the temperature stays at $100\,°\mathrm{C}$. With reference to the particles of the water, explain why the temperature does not rise during boiling.

Question 14 Coastal cities such as Melbourne usually have smaller day-to-night temperature ranges than inland cities such as Mildura. With reference to specific heat capacity, explain why.

Question 15 A burn from steam at $100\,°\mathrm{C}$ is usually much worse than a burn from the same mass of boiling water at $100\,°\mathrm{C}$. With reference to latent heat, explain why.

Question 16 A student measures the specific heat capacity of water using a joulemeter to supply a measured amount of energy to a beaker of water, measuring the mass of the water and its temperature rise, then calculating $c = \frac{Q}{m\Delta T}$. Her result is higher than the accepted value of $4180\,\mathrm{J\,kg^{-1}\,K^{-1}}$. (a) Explain why her calculated value is too high. (b) Suggest one improvement to her method that would bring her value closer to the accepted one, and explain why it helps.

Question 17 A hot-water bottle — a sealed rubber bag filled with hot water — is used to warm a bed. The specific heat capacity of sand is about $830\,\mathrm{J\,kg^{-1}\,K^{-1}}$. With reference to specific heat capacity, justify why water is a better filling than the same mass of hot sand.

Question 18 Two identical glasses hold the same amount of the same warm drink. Into one glass, $10\,\mathrm{g}$ of water at $0\,°\mathrm{C}$ is poured; into the other, $10\,\mathrm{g}$ of ice at $0\,°\mathrm{C}$ is added. Explain which drink ends up cooler once everything added has reached the drink's final temperature.

Answers

Question 1 (a) $Q = m c \Delta T$; (b) $70\,°C$; (c) $5.9 \times 10^5\,J$. **Question 2** (a) $c = \frac{Q}{m \Delta T}$; (b) $450\,J\,kg^{-1}\,K^{-1}$; (c) iron. **Question 3** (a) $125\,kg$, $45\,°C$; (b) $2.4 \times 10^7\,J$; (c) see solutions. **Question 4** (a) melting, $0\,°C$; (b) $6.68 \times 10^4\,J$; (c) see solutions. **Question 5** (a) $6.8 \times 10^5\,J$; (b) $1.0 \times 10^5\,J$; (c) see solutions. **Question 6** (a) $1.3 \times 10^5\,J$; (b) from the water to the surroundings; (c) less, $6.0 \times 10^4\,J$. **Question 7** $8.5 \times 10^4\,J$. **Question 8** $0.75\,kg$. **Question 9** $4.4 \times 10^4\,J$. **Question 10** $22.6\,°C$. **Question 11** $1.3 \times 10^5\,J$. **Question 12** $3.34 \times 10^5\,J\,kg^{-1}$. **Question 13** The energy goes into separating the particles, not into increasing their average kinetic energy. **Question 14** Water's much larger specific heat capacity means the sea changes temperature far less than the land for the same energy transfer. **Question 15** Condensing steam releases its latent heat of vaporisation before the hot water then cools, so far more energy reaches the skin. **Question 16** (a) some supplied energy goes to the beaker and surroundings; (b) see solutions. **Question 17** Water releases about five times more energy than the same mass of sand for the same temperature drop. **Question 18** The drink with the ice: melting the ice absorbs extra latent heat from the drink.

Fully-worked solutions

Question 1 $m = 2.0\,kg$, initial temperature $20\,°C$, final temperature $90\,°C$, $c = 4180\,J\,kg^{-1}\,K^{-1}$. (a) The relationship is $Q = m c \Delta T$. (b) $\Delta T = 90 - 20 = 70\,°C$. (c) $Q = m c \Delta T = 2.0 \times 4180 \times 70 = 585\,200\,J = 5.9 \times 10^5\,J$ (to two significant figures).

Question 2 $m = 0.50\,kg$, $Q = 4.5\,kJ = 4500\,J$, $\Delta T = 40 - 20 = 20\,°C$. (a) Rearranging $Q = m c \Delta T$ gives $c = \frac{Q}{m \Delta T}$. (b) $c = \frac{4500}{0.50 \times 20} = \frac{4500}{10} = 450\,J\,kg^{-1}\,K^{-1}$. (c) The table in the Theory section gives $450\,J\,kg^{-1}\,K^{-1}$ for iron, so the block is most likely iron.

Question 3 Volume $= 125\,L$, so $m = 125\,kg$; $\Delta T = 60 - 15 = 45\,°C$. (a) Mass $125\,kg$; temperature change $45\,°C$. (b) $Q = m c \Delta T = 125 \times 4180 \times 45 = 23\,512\,500\,J = 2.4 \times 10^7\,J$ (to two significant figures) — about $24\,MJ$. (c) Water's specific heat capacity is very large, so even a moderate mass of water needs a great deal of energy for a modest temperature rise ($Q = m c \Delta T$ with a large c). Storing enough hot water for showers and washing therefore takes tens of megajoules per day, which is why water heating is one of the biggest energy uses in a home.

Question 4 $m = 0.200\,kg$, melting at $0\,°C$, $L_f = 3.34 \times 10^5\,J\,kg^{-1}$. (a) The change of state is **melting**, and for pure water at normal atmospheric pressure it occurs at $0\,°C$. (b) $Q = m L_f = 0.200 \times 3.34 \times 10^5 = 66\,800\,J = 6.68 \times 10^4\,J$. (c) The temperature stays constant at $0\,°C$ throughout the melting. The absorbed energy does not increase the particles' average kinetic energy; it works against the forces between the particles, increasing the potential-energy part of the thermal energy as the solid becomes a liquid.

Question 5 $m = 0.30\,kg$. (a) Vaporisation at constant temperature: $Q = m L_v = 0.30 \times 2.26 \times 10^6 = 678\,000\,J = 6.8 \times 10^5\,J$ (to two significant figures). (b) Warming from $20\,°C$ to $100\,°C$: $\Delta T = 80\,°C$, so $Q = m c \Delta T = 0.30 \times 4180 \times 80 = 100\,320\,J = 1.0 \times 10^5\,J$ (to two significant figures). (c) Vaporising the water needs about seven times more energy than warming the same water through $80\,°C$ ($678\,000\,J$ compared with $100\,320\,J$). Changes of state involve large energy transfers at constant temperature because the energy must separate the particles, not merely warm them.

Question 6 $m = 1.5\,kg$, $\Delta T = 25 - 5 = 20\,°C$, $c = 4180\,J\,kg^{-1}\,K^{-1}$. (a) $|Q| = m c \Delta T = 1.5 \times 4180 \times 20 = 125\,400\,J = 1.3 \times 10^5\,J$ (to two significant figures). (b) Energy transfers from the water (the warmer system) to the cooler surroundings inside the insulated cooler. (c) For the oil, $|Q| = 1.5 \times 2000 \times 20 = 60\,000\,J = 6.0 \times 10^4\,J$, which is less than for the water. Because the oil has a smaller specific heat capacity, the same mass cooling through the same temperature change releases less energy.

Question 7 $m = 1.2\,kg$, $\Delta T = 180 - 22 = 158\,°C$, $c = 450\,J\,kg^{-1}\,K^{-1}$.

$$Q = m\,c\,\Delta T = 1.2 \times 450 \times 158 = 85\,320\ \text{J} = 8.5 \times 10^{4}\ \text{J}$$

(to two significant figures).

Question 8 $Q = 62.7\ \text{kJ} = 62\,700\ \text{J}$, $\Delta T = 38 - 18 = 20\ °\text{C}$, $c = 4180\ \text{J kg}^{-1}\text{K}^{-1}$.

$$m = \frac{Q}{c\,\Delta T} = \frac{62\,700}{4180 \times 20} = \frac{62\,700}{83\,600} = 0.75\ \text{kg}.$$

Question 9 $m = 0.100\ \text{kg}$. Melting at $0\ °\text{C}$: $Q_1 = m\,L_f = 0.100 \times 3.34 \times 10^{5} = 33\,400\ \text{J}$. Warming the melted water from $0\ °\text{C}$ to $25\ °\text{C}$: $Q_2 = m\,c\,\Delta T = 0.100 \times 4180 \times 25 = 10\,450\ \text{J}$. Total: $Q = 33\,400 + 10\,450 = 43\,850\ \text{J} = 4.4 \times 10^{4}\ \text{J}$ (to two significant figures).

Question 10 $m_{\text{Cu}} = 0.30\ \text{kg}$, $c_{\text{Cu}} = 385\ \text{J kg}^{-1}\text{K}^{-1}$, copper starts at $80\ °\text{C}$; $m_w = 0.60\ \text{kg}$, $c_w = 4180\ \text{J kg}^{-1}\text{K}^{-1}$, water starts at $20\ °\text{C}$. Let the final temperature be T. Conservation of energy (energy lost by copper = energy gained by water) gives

$$0.30 \times 385 \times (80 - T) = 0.60 \times 4180 \times (T - 20)$$

$$115.5(80 - T) = 2508(T - 20)$$

$$9240 - 115.5\,T = 2508\,T - 50\,160$$

$$59\,400 = 2623.5\,T$$

$$T = \frac{59\,400}{2623.5} = 22.6\ °\text{C}.$$

(Check, using the unrounded T: copper loses $115.5 \times 57.36 \approx 6.6 \times 10^{3}\ \text{J}$; water gains $2508 \times 2.64 \approx 6.6 \times 10^{3}\ \text{J}$. ✓) The final temperature is much closer to the water's starting temperature than to the copper's, because the water has the much larger $m\,c$ product.

Question 11 $m = 0.050\ \text{kg}$. Two stages: condensation at $100\ °\text{C}$, then cooling of the condensed water from $100\ °\text{C}$ to $40\ °\text{C}$. Condensing: $Q_1 = m\,L_v = 0.050 \times 2.26 \times 10^{6} = 113\,000\ \text{J}$. Cooling: $Q_2 = m\,c\,\Delta T = 0.050 \times 4180 \times 60 = 12\,540\ \text{J}$. Total released: $Q = 113\,000 + 12\,540 = 125\,540\ \text{J} = 1.3 \times 10^{5}\ \text{J}$ (to two significant figures). Almost all of it comes from the condensation itself.

Question 12 $Q = 25.05\ \text{kJ} = 25\,050\ \text{J}$ melts $m = 0.0750\ \text{kg}$ of ice at $0\ °\text{C}$.

$$L_f = \frac{Q}{m} = \frac{25\,050}{0.0750} = 334\,000 = 3.34 \times 10^{5}\ \text{J kg}^{-1}.$$

Question 13 At the boiling point, the energy being supplied is used to overcome the forces of attraction between the water particles and separate them into a gas. This increases the potential-energy part of the water's thermal energy, not the particles' average kinetic energy. Since temperature is a measure of the average kinetic energy of the particles, the temperature remains constant at $100\ °\text{C}$ until all of the liquid has become vapour. Only then does further energy input raise the temperature again.

Question 14 Water has a much larger specific heat capacity than the rock and soil that make up the land (about $4180\ \text{J kg}^{-1}\text{K}^{-1}$ compared with roughly $800–900\ \text{J kg}^{-1}\text{K}^{-1}$). During the day, the energy absorbed from sunlight raises the temperature of the sea much less than it raises the temperature of the land; at night, the sea cools much less as it releases that energy. Coastal air is moderated by the nearby sea, so Melbourne's temperature swings little between day and night, while inland places such as Mildura, surrounded by land that warms and cools quickly, experience much larger daily ranges. (Rearranging $Q = m\,c\,\Delta T$ as $\Delta T = \dfrac{Q}{m\,c}$ shows this directly: for the same energy Q and similar masses, a larger c gives a smaller ΔT.)

Question 15 When steam at $100\,°C$ touches the skin, it first condenses into water at $100\,°C$, and this condensation releases the specific latent heat of vaporisation — 2.26×10^6 J per kilogram — into the skin. The condensed hot water then cools, releasing further energy. Boiling water at $100\,°C$ releases only that cooling energy; it has no change of state to contribute. So for the same mass, steam transfers far more energy to the skin than boiling water does, causing a worse burn.

Question 16 (a) Some of the energy measured by the joulemeter is transferred to the beaker and to the surrounding air rather than to the water. Her calculation treats all of the supplied energy as having warmed the water, so Q in $c = \frac{Q}{m\Delta T}$ is too large for the water alone, and the calculated c comes out higher than the accepted value. (b) For example: insulate the beaker (lagging) and put a lid on it. This reduces the energy lost to the surroundings, so a greater share of the measured energy goes into the water, bringing the calculated value closer to 4180 J kg^{-1}K^{-1}. (Other acceptable improvements include allowing for the energy absorbed by the beaker itself, or using a smaller temperature rise so that losses during the experiment are reduced.)

Question 17 For the same mass and the same temperature drop, the energy released is $Q = mc\Delta T$, which is proportional to c. Water's specific heat capacity (4180 J kg^{-1}K^{-1}) is about five times that of sand (830 J kg^{-1}K^{-1}), so each kilogram of hot water releases about five times as much energy as each kilogram of hot sand while cooling through the same interval. The water bottle therefore keeps the bed warm much longer.

Question 18 The drink with the ice ends up cooler. The $10\,g$ of water at $0\,°C$ absorbs energy only as it warms up to the final temperature. The $10\,g$ of ice at $0\,°C$ must first absorb energy to melt — $Q = mL_f = 0.010 \times 3.34 \times 10^5 = 3340$ J — and only then does the melted ice warm up to the final temperature, absorbing the same warming energy as the added water. The ice therefore takes more energy in total from the drink, and since that energy comes from the drink's own thermal energy, the drink with the ice cools more.

Theory

Every object emits electromagnetic radiation. In 2A you saw that the temperature of an object is related to the motion of its particles: the higher the temperature, the greater the average kinetic energy of its atoms and molecules. The charged particles in matter are moving as part of this motion, and moving charged particles produce electromagnetic waves. The result is that every object with a temperature above absolute zero ($0\,\mathrm{K}$) continually radiates energy in the form of electromagnetic waves. This emission is called **thermal radiation**. Like all electromagnetic waves, thermal radiation travels through a vacuum at speed c (1B) — which is how the Sun's energy reaches Earth.

Thermal radiation is spread across a range of wavelengths. A hot object does not radiate at a single wavelength. Its emitted energy is spread continuously across the electromagnetic spectrum, with a different amount of energy at each wavelength. If the intensity of the radiation (the energy emitted each second at each wavelength) is graphed against wavelength, the curve rises from zero to a single peak and then falls away again. The wavelength at which the curve reaches its peak — that is, the wavelength at which the object emits most strongly — is called the **peak wavelength**, λ_{max}. The curves used in this section are those of an idealised emitter called a **blackbody**: an object that absorbs all of the radiation falling on it and, when hot, emits as strongly as possible at every wavelength. Real objects — stars, hot metal, skin, embers — behave similarly enough that blackbody curves are a reliable guide to how they radiate.

Wien's Law. The peak wavelength of the radiation emitted by an object depends only on its temperature, and the relationship is given by **Wien's Law**:

$$\lambda_{\text{max}} T = \text{constant} = 2.9 \times 10^{-3}\,\text{m K}$$

where T is the absolute temperature in kelvin. Since the product $\lambda_{\text{max}} T$ is constant, the peak wavelength is **inversely proportional** to the absolute temperature:

$$\lambda_{\text{max}} = \frac{2.9 \times 10^{-3}}{T} \text{ and } T = \frac{2.9 \times 10^{-3}}{\lambda_{\text{max}}}.$$

A hotter object has a shorter peak wavelength; doubling the kelvin temperature halves λ_{max}. Notice that T must be in kelvin — doubling a Celsius temperature is *not* the same as doubling the absolute temperature (2A), so always convert to kelvin before substituting.

Some values calculated from Wien's Law:

Object	Temperature T	λ_{max}	Region of spectrum
Surface of the Sun	$5800\,\mathrm{K}$	$500\,\mathrm{nm}$	visible
Glowing orange steel	$1370\,\mathrm{K}$ (about $1100\,°\mathrm{C}$)	$2.1\,\mu\mathrm{m}$	infrared
Human body	$310\,\mathrm{K}$ ($37\,°\mathrm{C}$)	$9.4\,\mu\mathrm{m}$	infrared
Ice-water mixture	$273\,\mathrm{K}$ ($0\,°\mathrm{C}$)	$10.6\,\mu\mathrm{m}$	infrared

Source: International Astronomical Union, *IAU 2015 Resolution B3 on recommended nominal conversion constants for selected solar and planetary properties* (nominal solar effective temperature $5772\,\mathrm{K}$), retrieved 2026-08-18.

Only the Sun in this table peaks in the visible region. Every cooler object in the table radiates mainly in the infrared, whether it is glowing visibly or not.

Comparing the total energy emitted by objects at different temperatures. A blackbody curve changes in three linked ways as the temperature of the object increases:

1. **The curve is higher at every wavelength.** A hotter object emits more energy than a cooler one at *every* wavelength, not just near the peak.

2. **The peak is higher and shifted to shorter wavelengths.** The maximum intensity increases, and by Wien's Law the peak wavelength λ_{max} decreases.
3. **The total energy emitted increases.** The total energy radiated each second is represented by the area between the curve and the wavelength axis, summed over the whole spectrum. Because the hotter curve sits above the cooler one everywhere, it encloses a much larger area: the hotter object emits more total energy per second (for the same area of surface), and the total rises rapidly as the temperature rises.

These three features explain everyday observations:

- **The colour of a glowing object tells you its temperature.** Steel begins to glow dull red at a few hundred degrees Celsius: its λ_{max} is still in the infrared, and only the long-wavelength (red) end of the visible spectrum is emitted at all strongly. As the steel gets hotter, λ_{max} moves toward the visible region and the glow shifts from red to orange to yellow-white as more visible wavelengths are emitted strongly.
- **Objects at everyday temperatures are invisible in the dark.** At about $300\,\text{K}$ the peak wavelength is near $10\,\mu\text{m}$, deep in the infrared. Your body, your desk and the walls of your room are all radiating continually, but your eyes detect only visible light, so you cannot see the radiation. A thermal imaging camera can, because it detects infrared.
- **The colour of a star is linked to its surface temperature.** Cooler stars peak toward the red end of the visible spectrum; hotter stars peak toward the blue and violet. (Students who choose Option 2.13 take this idea further in 13A.)

Method notes. When using Wien's Law: convert any Celsius temperature to kelvin first ($T\left(\text{K}\right)=T\left({}^{\circ}\text{C}\right)+273.15$, from 2A); convert wavelengths to metres before substituting ($1\,\text{nm}=10^{-9}\,\text{m}$, $1\,\mu\text{m}=10^{-6}\,\text{m}$); and check that the answer is sensible — a hotter object must give a shorter peak wavelength.

Links to other sections. The spectrum regions used here are those of 1B. In 2D the transfer of energy by radiation is applied to climate change and global warming. Students studying Option 2.1 apply Wien's Law in 10C to the radiation re-emitted by Earth, and meet the quantitative Stefan–Boltzmann Law for the power radiated by a body.

Worked examples

Example 1 — scaffolded

The surface of the Sun has a temperature of about $5800\,\text{K}$. Calculate the peak wavelength of the electromagnetic radiation emitted by the Sun's surface, and name the region of the electromagnetic spectrum in which it lies.

Working	Comment
Wien's Law: $\lambda_{max}T=2.9\times10^{-3}\,\text{m K}$, with $T=5800\,\text{K}$.	The temperature is already in kelvin, so no conversion is needed.
$\lambda_{max}=\dfrac{2.9\times10^{-3}}{T}=\dfrac{2.9\times10^{-3}}{5800}=5.0\times10^{-7}\,\text{m}$.	Rearrange Wien's Law for λ_{max} and substitute.
$5.0\times10^{-7}\,\text{m}=500\,\text{nm}$.	$1\,\text{nm}=10^{-9}\,\text{m}$.
$500\,\text{nm}$ lies in the **visible** region.	The visible region spans about $400–700\,\text{nm}$ (1B).

Example 2 — scaffolded

The normal core temperature of the human body is $37\,°\text{C}$. Calculate the peak wavelength of the radiation emitted by the human body, and name the region of the electromagnetic spectrum in which it lies.

Working	Comment
$T=37+273.15=310.15\,\text{K}\approx310\,\text{K}$.	Wien's Law requires the absolute temperature in kelvin (2A).
$\lambda_{max}=\dfrac{2.9\times10^{-3}}{T}=\dfrac{2.9\times10^{-3}}{310}=9.4\times10^{-6}\,\text{m}$.	Rearrange Wien's Law and substitute.

Working	Comment
$9.4 \times 10^{-6}\,\text{m} = 9.4\,\mu\text{m} = 9400\,\text{nm}$.	$1\,\mu\text{m} = 10^{-6}\,\text{m}$.
$9.4\,\mu\text{m}$ lies in the **infrared** region.	Infrared wavelengths are longer than visible light (1B). This is why thermal imaging cameras can detect people in the dark.

Example 3 — unscaffolded

Measurements of the radiation from a star show that the intensity peaks at a wavelength of $400\,\text{nm}$. Calculate the surface temperature of the star, and compare it with the surface of the Sun ($5800\,\text{K}$).

The peak wavelength is $\lambda_{\max} = 400\,\text{nm} = 400 \times 10^{-9}\,\text{m} = 4.0 \times 10^{-7}\,\text{m}$. Rearranging Wien's Law for the temperature,

$$T = \frac{2.9 \times 10^{-3}}{\lambda_{\max}} = \frac{2.9 \times 10^{-3}}{4.0 \times 10^{-7}} = 7250\,\text{K} \approx 7300\,\text{K}.$$

The star's surface temperature ($7300\,\text{K}$) is higher than the Sun's ($5800\,\text{K}$), so the star is **hotter than the Sun**. This is consistent with Wien's Law: the hotter object has the shorter peak wavelength ($400\,\text{nm} < 500\,\text{nm}$).

$\therefore$ the surface temperature of the star is about $7300\,\text{K}$; it is hotter than the Sun.

Example 4 — unscaffolded

The glowing embers of a campfire are at about $900\,°\text{C}$. Calculate the peak wavelength of the radiation they emit, and compare the radiation from the embers with that from the surface of the Sun ($5800\,\text{K}$), referring to the peak wavelength and the total energy emitted.

The absolute temperature of the embers is $T = 900 + 273.15 = 1173.15\,\text{K} \approx 1173\,\text{K}$, so

$$\lambda_{\max} = \frac{2.9 \times 10^{-3}}{T} = \frac{2.9 \times 10^{-3}}{1173} = 2.5 \times 10^{-6}\,\text{m} = 2.5\,\mu\text{m},$$

which lies in the infrared region. From Example 1, the Sun's surface peaks at $500\,\text{nm} = 0.50\,\mu\text{m}$, in the visible region.

The surface of the Sun is much hotter than the embers ($5800\,\text{K}$ compared with $1173\,\text{K}$), so by Wien's Law its peak wavelength is the shorter one ($0.50\,\mu\text{m}$ against $2.5\,\mu\text{m}$). The blackbody curve for the Sun's surface also sits above the curve for the embers at every wavelength and has the greater peak intensity, so it encloses the larger area under the curve: for the same area of surface, the Sun emits far more total energy each second, across the whole spectrum, than the embers do. The embers still glow red-orange because, even though their peak is in the infrared, their curve has a tail extending into the visible region.

$\therefore$ the embers peak at $2.5\,\mu\text{m}$ (infrared); compared with the embers, the Sun peaks at a shorter wavelength and emits far more total energy.

Practice questions

Question 1 *(scaffolded)* A thermal imaging camera detects the thermal radiation emitted by the human body. The normal core temperature of the human body is $37\,°\text{C}$. (a) Convert $37\,°\text{C}$ to kelvin. (b) Write down Wien's Law, including the value and units of the constant. (c) Calculate the peak wavelength of the radiation emitted by the human body, and state the region of the electromagnetic spectrum in which it lies.

Question 2 *(scaffolded)* The filament of a traditional incandescent light globe operates at about $2700\,\text{K}$. (a) Calculate the peak wavelength of the radiation emitted by the filament. (b) State the region of the electromagnetic spectrum in which this peak lies. (c) The peak of the filament's radiation curve is not in the visible region, yet the globe emits visible light. Explain why.

Question 3 *(scaffolded)* Measurements of the radiation from a star show that the intensity peaks at a wavelength of $400\,\mathrm{nm}$. (a) Convert $400\,\mathrm{nm}$ to metres. (b) Rearrange Wien's Law to make T the subject, and calculate the surface temperature of the star. (c) The surface of the Sun is at about $5800\,\mathrm{K}$. State whether this star is hotter or cooler than the Sun, and check that your answer is consistent with Wien's Law.

Question 4 *(scaffolded)* A steel bar in a forge is heated from $600\,\mathrm{K}$ to $1200\,\mathrm{K}$. (a) Calculate the peak wavelength of the radiation emitted by the bar at $600\,\mathrm{K}$. (b) Calculate the peak wavelength of the radiation emitted by the bar at $1200\,\mathrm{K}$. (c) Describe the effect of doubling the absolute temperature on (i) the peak wavelength, and (ii) the total energy emitted across the electromagnetic spectrum.

Question 5 *(scaffolded)* In an investigation, students use a detector to measure the peak wavelength of the radiation emitted by a heated object as its temperature is increased. Their results are:

T (K)	1000	1500	2000	2500
λ_{max} (μm)	2.9	1.93	1.45	1.16

(a) For each pair of values, calculate the product $\lambda_{\text{max}} \times T$, in units of $\mathrm{m\ K}$.

(b) State the relationship between λ_{max} and T suggested by your answers.

(c) Use the relationship to predict the peak wavelength when the object is at $4000\,\mathrm{K}$.

Question 6 *(scaffolded)* The walls of a ceramic kiln radiate thermal energy with a peak wavelength of $2.3\,\mu\mathrm{m}$. (a) Rearrange Wien's Law to make T the subject. (b) Calculate the temperature of the kiln walls in kelvin. (c) Convert your answer to degrees Celsius.

Question 7 The surface of the Sun has a temperature of about $5800\,\mathrm{K}$. Calculate the peak wavelength of the electromagnetic radiation emitted by the Sun's surface, and state the region of the spectrum in which it lies.

Question 8 A glowing red heating element on an electric stove has a temperature of $1000\,°\mathrm{C}$. Calculate the peak wavelength of the radiation it emits.

Question 9 On a cold winter night, a thermal imaging camera being used in a home energy audit records radiation peaking at a wavelength of $10.5\,\mu\mathrm{m}$ from the external wall of a house. Calculate the temperature of the wall in kelvin and in degrees Celsius.

Question 10 The thermal radiation from a star peaks at a wavelength of $700\,\mathrm{nm}$. Calculate the surface temperature of the star.

Question 11 An object is heated from $300\,\mathrm{K}$ to $900\,\mathrm{K}$. (a) Calculate the peak wavelength of the radiation it emits at $300\,\mathrm{K}$. (b) Calculate the peak wavelength of the radiation it emits at $900\,\mathrm{K}$. (c) State the factor by which the peak wavelength changes as the object is heated.

Question 12 The filament of a halogen light globe operates at $3000\,\mathrm{K}$. Calculate its peak wavelength, and compare it with the peak wavelength of the $2700\,\mathrm{K}$ filament in Question 2 ($\lambda_{\text{max}} \approx 1070\,\mathrm{nm}$). State which filament has the shorter peak wavelength, and explain why.

Question 13 A steelworker notices that a piece of steel glows dull red when it is only just hot enough to glow, but orange-yellow when it is much hotter. Use Wien's Law to explain why the colour of the glowing steel changes with temperature.

Question 14 Two people standing in a completely dark room cannot see each other with their eyes, yet a thermal imaging camera detects them immediately. Explain why, referring to the temperature of the human body and the region of the spectrum in which it radiates.

Question 15 A student claims: "A cool object, such as an ice cube, does not emit electromagnetic radiation, because it does not glow." Evaluate this claim using the ideas of this section.

Question 16 The blackbody curves of two objects, A and B, are drawn on the same axes. Curve A peaks at a shorter wavelength than curve B, and the peak intensity of curve A is higher. (a) Identify the hotter object, justifying your answer. (b) Compare the total energy emitted each second by the two objects, for the same area of surface.

Question 17 A bluish-white star has a surface temperature of about $10\,000\,\mathrm{K}$. (a) Calculate the peak wavelength of the radiation it emits, and name the region of the spectrum in which it lies. (b) The peak lies outside the visible region, yet the star appears bluish-white to our eyes. Explain why.

Question 18 A traditional incandescent light globe becomes very hot to be near, and most of the energy supplied to it ends up heating the room rather than lighting it. Use the idea of thermal radiation curves to explain why, referring to the filament temperature (about $2700\,\mathrm{K}$) and the visible region of the spectrum (about $400–700\,\mathrm{nm}$).

Answers

Question 1 (a) $310\,\mathrm{K}$; (b) $\lambda_{max}T = 2.9 \times 10^{-3}\,\mathrm{m\ K}$; (c) $9.4 \times 10^{-6}\,\mathrm{m}$ ($9.4\,\mu\mathrm{m}$), infrared. **Question 2** (a) $1.1 \times 10^{-6}\,\mathrm{m}$ ($\approx 1070\,\mathrm{nm}$); (b) infrared; (c) the curve has a tail extending into the visible region, so some visible light is emitted even though the peak is in the infrared. **Question 3** (a) $4.0 \times 10^{-7}\,\mathrm{m}$; (b) $T = \dfrac{2.9 \times 10^{-3}}{\lambda_{max}}$, $T \approx 7300\,\mathrm{K}$; (c) hotter than the Sun; consistent, because the hotter object peaks at the shorter wavelength ($400\,\mathrm{nm} < 500\,\mathrm{nm}$). **Question 4** (a) $4.8 \times 10^{-6}\,\mathrm{m}$ ($4.8\,\mu\mathrm{m}$); (b) $2.4 \times 10^{-6}\,\mathrm{m}$ ($2.4\,\mu\mathrm{m}$); (c)(i) the peak wavelength halves; (ii) the total energy emitted increases — the curve is higher at every wavelength and encloses a larger area. **Question 5** (a) $\approx 2.9 \times 10^{-3}\,\mathrm{m\ K}$ in each row; (b) λ_{max} is inversely proportional to T ($\lambda_{max}T = \mathrm{constant}$) — Wien's Law; (c) $\approx 7.3 \times 10^{-7}\,\mathrm{m}$ ($730\,\mathrm{nm}$). **Question 6** (a) $T = \dfrac{2.9 \times 10^{-3}}{\lambda_{max}}$; (b) $\approx 1260\,\mathrm{K}$; (c) $\approx 990\,°\mathrm{C}$. **Question 7** $5.0 \times 10^{-7}\,\mathrm{m}$ ($500\,\mathrm{nm}$), visible region. **Question 8** $T = 1273\,\mathrm{K}$; $\lambda_{max} = 2.3 \times 10^{-6}\,\mathrm{m}$ ($2.3\,\mu\mathrm{m}$). **Question 9** $276\,\mathrm{K}$; $3\,°\mathrm{C}$. **Question 10** $\approx 4100\,\mathrm{K}$. **Question 11** (a) $9.7 \times 10^{-6}\,\mathrm{m}$ ($9.7\,\mu\mathrm{m}$); (b) $3.2 \times 10^{-6}\,\mathrm{m}$ ($3.2\,\mu\mathrm{m}$); (c) the peak wavelength decreases by a factor of 3. **Question 12** $9.7 \times 10^{-7}\,\mathrm{m}$ ($970\,\mathrm{nm}$); the $3000\,\mathrm{K}$ halogen filament has the shorter peak wavelength, because the hotter object peaks at the shorter wavelength. **Question 13** As the temperature rises, λ_{max} decreases (Wien's Law), so the visible glow strengthens and shifts from red toward orange-yellow; see solutions for the full model answer. **Question 14** The body radiates mainly in the infrared ($\lambda_{max} \approx 9.4\,\mu\mathrm{m}$), which eyes cannot detect but a thermal imaging camera can; see solutions for the full model answer. **Question 15** The claim is incorrect: every object above $0\,\mathrm{K}$ emits thermal radiation; a cool object radiates in the infrared without glowing visibly; see solutions for the full model answer. **Question 16** (a) object A; (b) A emits more total energy each second. **Question 17** (a) $2.9 \times 10^{-7}\,\mathrm{m}$ ($290\,\mathrm{nm}$), ultraviolet; (b) the curve extends into the visible region, where the short-wavelength (blue and violet) end is emitted most strongly. **Question 18** At $2700\,\mathrm{K}$ the filament peaks at about $1.1\,\mu\mathrm{m}$ (infrared), so most of the radiated energy is infrared that heats the room, and only a small visible tail provides light; see solutions for the full model answer.

Fully-worked solutions

Question 1 (a) $T = 37 + 273.15 = 310.15\,\mathrm{K} \approx 310\,\mathrm{K}$. (b) Wien's Law is $\lambda_{max}T = \mathrm{constant} = 2.9 \times 10^{-3}\,\mathrm{m\ K}$, where λ_{max} is the peak wavelength in metres and T is the absolute temperature in kelvin. (c) $\lambda_{max} = \dfrac{2.9 \times 10^{-3}}{T} = \dfrac{2.9 \times 10^{-3}}{310} = 9.4 \times 10^{-6}\,\mathrm{m} = 9.4\,\mu\mathrm{m}$. This lies in the **infrared** region of the electromagnetic spectrum.

Question 2 (a) $\lambda_{max} = \dfrac{2.9 \times 10^{-3}}{T} = \dfrac{2.9 \times 10^{-3}}{2700} = 1.1 \times 10^{-6}\,\mathrm{m} \approx 1070\,\mathrm{nm}$. (b) $1070\,\mathrm{nm}$ is longer than visible wavelengths ($400\text{–}700\,\mathrm{nm}$), so the peak lies in the **infrared** region. (c) A blackbody curve does not stop at the peak: it falls away on either side but still has a value at every wavelength. The $2700\,\mathrm{K}$ filament's curve has a tail extending into the visible region, so the filament emits visible light at all visible wavelengths — the globe glows yellow-white — even though most of the radiated energy is infrared.

Question 3 (a) $400\,\mathrm{nm} = 400 \times 10^{-9}\,\mathrm{m} = 4.0 \times 10^{-7}\,\mathrm{m}$. (b) Rearranging Wien's Law, $T = \dfrac{2.9 \times 10^{-3}}{\lambda_{max}} = \dfrac{2.9 \times 10^{-3}}{4.0 \times 10^{-7}} = 7250\,\mathrm{K} \approx 7300\,\mathrm{K}$. (c) The star ($7300\,\mathrm{K}$) is **hotter** than the Sun ($5800\,\mathrm{K}$). Check: Wien's Law says the hotter object peaks at the shorter wavelength. The Sun peaks at $500\,\mathrm{nm}$ (Example 1) and this star at $400\,\mathrm{nm}$, which is indeed shorter, so the answer is consistent.

Question 4 (a) $\lambda_{max} = \dfrac{2.9 \times 10^{-3}}{600} = 4.8 \times 10^{-6}\,\mathrm{m} = 4.8\,\mu\mathrm{m}$. (b) $\lambda_{max} = \dfrac{2.9 \times 10^{-3}}{1200} = 2.4 \times 10^{-6}\,\mathrm{m} = 2.4\,\mu\mathrm{m}$. (c)(i) Doubling the absolute temperature halves the peak wavelength ($4.8\,\mu\mathrm{m} \rightarrow 2.4\,\mu\mathrm{m}$), because λ_{max} is inversely proportional to T. (ii) The total energy emitted across the electromagnetic spectrum increases: the $1200\,\mathrm{K}$ curve lies above the $600\,\mathrm{K}$ curve at every wavelength, has the higher peak, and encloses the larger area under the curve.

Question 5 (a) Converting each peak wavelength to metres first: $1000 \times 2.9 \times 10^{-6} = 2.9 \times 10^{-3}\,\mathrm{m\ K}$; $1500 \times 1.93 \times 10^{-6} = 2.9 \times 10^{-3}\,\mathrm{m\ K}$; $2000 \times 1.45 \times 10^{-6} = 2.9 \times 10^{-3}\,\mathrm{m\ K}$; $2500 \times 1.16 \times 10^{-6} = 2.9 \times 10^{-3}\,\mathrm{m\ K}$. (b) The product $\lambda_{\max} T$ is constant, so $\lambda_{\max}$ is **inversely proportional** to T: this is Wien's Law, $\lambda_{\max} T = 2.9 \times 10^{-3}\,\mathrm{m\ K}$. (c) $\lambda_{\max} = \frac{2.9 \times 10^{-3}}{4000} = 7.3 \times 10^{-7}\,\mathrm{m} \approx 730\,\mathrm{nm}$.

Question 6 (a) $T = \frac{2.9 \times 10^{-3}}{\lambda_{\max}}$. (b) $\lambda_{\max} = 2.3\,\mu\mathrm{m} = 2.3 \times 10^{-6}\,\mathrm{m}$, so $T = \frac{2.9 \times 10^{-3}}{2.3 \times 10^{-6}} = 1261\,\mathrm{K} \approx 1260\,\mathrm{K}$. (c) $T = 1261 - 273.15 = 987.85\,°\mathrm{C} \approx 990\,°\mathrm{C}$.

Question 7 $\lambda_{\max} = \frac{2.9 \times 10^{-3}}{T} = \frac{2.9 \times 10^{-3}}{5800} = 5.0 \times 10^{-7}\,\mathrm{m} = 500\,\mathrm{nm}$. This lies in the **visible** region (about 400–$700\,\mathrm{nm}$), which is why our eyes are sensitive to sunlight.

Question 8 $T = 1000 + 273.15 = 1273.15\,\mathrm{K} \approx 1273\,\mathrm{K}$. $\lambda_{\max} = \frac{2.9 \times 10^{-3}}{1273} = 2.3 \times 10^{-6}\,\mathrm{m} = 2.3\,\mu\mathrm{m}$ (infrared).

Question 9 $T = \frac{2.9 \times 10^{-3}}{\lambda_{\max}} = \frac{2.9 \times 10^{-3}}{10.5 \times 10^{-6}} = 276\,\mathrm{K}$. In degrees Celsius: $276 - 273.15 = 2.85\,°\mathrm{C} \approx 3\,°\mathrm{C}$. The wall is at about $3\,°\mathrm{C}$.

Question 10 $\lambda_{\max} = 700\,\mathrm{nm} = 7.0 \times 10^{-7}\,\mathrm{m}$. $T = \frac{2.9 \times 10^{-3}}{7.0 \times 10^{-7}} = 4143\,\mathrm{K} \approx 4100\,\mathrm{K}$.

Question 11 (a) $\lambda_{\max} = \frac{2.9 \times 10^{-3}}{300} = 9.7 \times 10^{-6}\,\mathrm{m} = 9.7\,\mu\mathrm{m}$. (b) $\lambda_{\max} = \frac{2.9 \times 10^{-3}}{900} = 3.2 \times 10^{-6}\,\mathrm{m} = 3.2\,\mu\mathrm{m}$. (c) The absolute temperature triples ($300\,\mathrm{K} \rightarrow 900\,\mathrm{K}$), so the peak wavelength decreases by a factor of 3 ($9.7\,\mu\mathrm{m} \rightarrow 3.2\,\mu\mathrm{m}$).

Question 12 $\lambda_{\max} = \frac{2.9 \times 10^{-3}}{3000} = 9.7 \times 10^{-7}\,\mathrm{m} = 970\,\mathrm{nm}$. This is shorter than the $1070\,\mathrm{nm}$ peak of the $2700\,\mathrm{K}$ filament. The $3000\,\mathrm{K}$ halogen filament has the shorter peak wavelength because, by Wien's Law, the hotter object always peaks at the shorter wavelength.

Question 13 Model answer (3 marks): By Wien's Law, $\lambda_{\max} T = \text{constant}$, so the peak wavelength decreases as the temperature of the steel increases (1 mark). When the steel is only just hot enough to glow, its $\lambda_{\max}$ is in the infrared and only the tail of its curve reaches the visible region — strongest at the long-wavelength (red) end — so it glows dull red (1 mark). When the steel is much hotter, $\lambda_{\max}$ moves closer to the visible region, the visible part of the curve becomes stronger across more colours, and the glow shifts toward orange-yellow (1 mark).

Question 14 Model answer (3 marks): The human body is at about $310\,\mathrm{K}$, so by Wien's Law its peak wavelength is about $9.4\,\mu\mathrm{m}$, in the infrared region (1 mark). Human eyes detect only visible light, and a body at this temperature emits almost no visible radiation, so the people cannot see each other in the dark (1 mark). A thermal imaging camera detects infrared radiation, which the body emits strongly, so it can detect the people immediately (1 mark).

Question 15 Model answer (3 marks): The claim is incorrect (1 mark). Every object with a temperature above absolute zero emits thermal radiation; an ice cube at about $273\,\mathrm{K}$ radiates with a peak wavelength of about $11\,\mu\mathrm{m}$, in the infrared (1 mark). Glowing visibly is not the same as radiating: an object only glows when its temperature is high enough for its radiation curve to extend strongly into the visible region, so a cool object radiates without glowing (1 mark).

Question 16 (a) Object **A** is hotter. By Wien's Law, $\lambda_{\max} T = \text{constant}$, so the object with the shorter peak wavelength has the higher absolute temperature; curve A peaks at the shorter wavelength. (b) For the same area of surface, **A emits more total energy each second**. The total energy radiated is represented by the area under the curve; curve A lies above curve B at every wavelength and has the higher peak, so it encloses the larger area.

Question 17 (a) $\lambda_{\max} = \dfrac{2.9 \times 10^{-3}}{10\,000} = 2.9 \times 10^{-7}\,\text{m} = 290\,\text{nm}$. This lies in the **ultraviolet** region. (b) The peak being in the ultraviolet does not mean the star emits only ultraviolet. Its blackbody curve still extends into the visible region, and within the visible wavelengths it emits the short-wavelength (blue and violet) end most strongly, because the visible region sits on the falling short-wavelength side of the peak. Our eyes receive mostly blue and violet light from the star, so it appears bluish-white.

Question 18 Model answer (4 marks): The filament operates at about $2700\,\text{K}$, so by Wien's Law its peak wavelength is about $1.1\,\mu\text{m}$ ($1070\,\text{nm}$), which lies in the infrared region (1 mark). The visible region spans only about 400–$700\,\text{nm}$, well short of the peak (1 mark). Most of the area under the filament's radiation curve — and therefore most of the energy it radiates each second — lies in the infrared, not the visible region (1 mark). Infrared radiation absorbed by the surroundings is felt as heat, so most of the energy supplied to the globe heats the room, and only the small visible tail of the curve provides light (1 mark).

Theory

Scope. This subtopic applies the energy ideas of Chapter 2, as set out in the *VCE Physics Study Design*, Unit 1, Area of Study 1: *"apply concepts of energy transfer, energy transformation, temperature change and change of state to climate change and global warming."* The detailed mechanism by which individual greenhouse gases absorb and re-emit infrared radiation, and the evidence that human activity is changing the atmosphere's composition, belong to Option 2.1 (Section 10C). Here the atmosphere is treated as a layer that slows the outward transfer of energy, and the focus is the energy accounting.

> **A note about the terms.** The study design uses *climate change* and *global warming* without defining them. In this subtopic they are used in the sense given by the Intergovernmental Panel on Climate Change (IPCC): *global warming* means the long-term rise in Earth's average surface temperature, and *climate change* means long-term shifts in climate patterns, including temperature, rainfall and wind, that persist for decades or longer. Other definitions exist and are not interchangeable with these.

Earth's energy budget. The Sun is the main source of energy for Earth's climate system — the atmosphere, the ocean, the land, the ice, and the living things on Earth. The Sun transfers energy to Earth by **radiation**: electromagnetic waves, mainly ultraviolet, visible and infrared (Section 1B), travel through the vacuum of space. When this radiation reaches Earth, some is reflected back to space by clouds and by bright surfaces such as ice and snow, and the rest is absorbed. When radiation is absorbed by the land, the ocean or the atmosphere, the energy is **transformed** into thermal energy, and the temperature of the absorbing material rises (Section 2A).

At the same time, Earth itself radiates energy back to space. Because Earth is much cooler than the Sun, the radiation it emits has a much longer peak wavelength and carries far less energy per square metre (Section 2C): Earth emits almost entirely infrared radiation.

If the energy Earth absorbs from the Sun equals the energy Earth radiates back to space, the average temperature of the climate system stays roughly steady. If more energy is absorbed than is emitted, the climate system gains thermal energy and warms; if less is absorbed than is emitted, it cools. Everything in this subtopic follows from keeping track of that energy: where it goes, what form it takes, and what it does to temperatures and to the state of water.

The natural greenhouse effect. Most of the infrared radiation emitted by Earth's surface would escape directly to space, but some is absorbed by certain gases in the atmosphere — water vapour, carbon dioxide and methane are the most important. These **greenhouse gases** re-emit the energy in all directions, including back toward the surface. The effect is to slow the net transfer of energy from the surface to space, rather like a blanket slows the transfer of thermal energy from your body. Because of this natural greenhouse effect, Earth's average surface temperature is warm enough for liquid water; with no greenhouse effect at all it would be well below freezing. (Section 10C studies how each gas absorbs and re-emits infrared radiation, and the evidence that human activity is strengthening this effect. In this subtopic we use only the energy consequence: the atmosphere slows the outward transfer of energy.)

Global warming means that the outward transfer has been slowed a little further, so that for an extended period the climate system absorbs more energy than it emits. The extra energy does not disappear: it is stored in the climate system, and it appears as **temperature change** ($Q = m c \Delta T$, Section 2B) and as **change of state** ($Q = m L$, Section 2B).

Where the extra energy goes: temperature change. Measurements show that more than about 90% of the extra energy accumulating in the climate system is absorbed by the ocean.

Source: Intergovernmental Panel on Climate Change, Sixth Assessment Report, retrieved 2026-08-18.

Two facts about water explain this. First, water has a large **specific heat capacity**, $c = 4.18 \times 10^3\ \mathrm{J\ kg^{-1}\ K^{-1}}$: it takes a great deal of energy to raise the temperature of water by even one degree. Second, the ocean covers most of Earth's surface and is very deep, so its total mass is enormous. A large m and a large c together mean that the ocean can absorb huge amounts of energy for a modest temperature rise.

The land, by contrast, has a much smaller effective heat capacity: the ground is shallow in the layer that stores heat, and rock and soil have smaller specific heat capacities than water. For the same energy input, the land surface warms several times more than the ocean surface. This is why observations of warming are larger over land than over the ocean. Australia's mean temperature, for example, has risen by more than $1.5\,°\mathrm{C}$ since national records began in 1910.

Source: Bureau of Meteorology and CSIRO, State of the Climate 2024, retrieved 2026-08-18.

Globally, 2024 was the warmest year in the 175-year observational record, with a global mean near-surface temperature of $1.55 \pm 0.13\,°\mathrm{C}$ above the 1850–1900 average.

Source: World Meteorological Organization, State of the Global Climate 2024, retrieved 2026-08-18.

Once energy is absorbed at the surface it is redistributed by the three transfers of Section 2A: by **conduction** from the warm ground or sea surface into the air in contact with it, by **convection** as warm air rises and cooler air moves in (and as ocean currents move warm water around the globe), and by evaporation, which carries energy away from the surface as latent heat.

Change of state: melting ice. Extra energy in the climate system also drives changes of state, and a change of state occurs at constant temperature. The melting of land ice — the ice sheets of Antarctica and Greenland, and mountain glaciers — requires the specific latent heat of fusion of ice, $L = 3.34 \times 10^5\,\mathrm{J\,kg^{-1}}$. That is a very large amount of energy to absorb with no temperature change at all: the energy goes into breaking down the ordered structure of the solid rather than into raising the kinetic energy of the particles.

Melting *land* ice matters for sea level because the meltwater runs into the ocean and adds new water to it. Warming seawater also expands slightly, adding to the rise. Between 1901 and 2018 the global mean sea level rose by about $0.20\,\mathrm{m}$.

Source: Intergovernmental Panel on Climate Change, Sixth Assessment Report, retrieved 2026-08-18.

Melting ice that already floats as sea ice, by contrast, does not by itself significantly raise sea level: the ice is already in the ocean, and the meltwater occupies about the same volume as the seawater the floating ice displaced.

Change of state: evaporation and storms. A warmer ocean and warmer land surfaces evaporate more water. By the kinetic model of Section 2A, evaporation cools the surface: the fastest molecules escape, and each kilogram of water that evaporates carries away roughly $2.3 \times 10^6\,\mathrm{J}$ of latent heat (the specific latent heat of vaporisation of water is $2.26 \times 10^6\,\mathrm{J\,kg^{-1}}$ at $100\,°\mathrm{C}$). That energy is not lost — it is released back into the atmosphere when the vapour condenses into cloud. More evaporation means more water vapour carrying more latent heat, and more energy released in storms and rainfall systems. This is one reason a warming climate is expected to produce more intense rainfall events.

A feedback: ice and reflectivity. Bright surfaces such as ice and snow reflect a large fraction of the incoming radiation; dark surfaces such as open ocean absorb much more of it. When sea ice melts, darker ocean surface is exposed, more radiation is absorbed, more thermal energy is stored, and more ice melts. An effect that amplifies the change that started it is called a **feedback** — this one is an ice–reflectivity feedback. Feedbacks are one reason a small change to the energy budget can grow.

Observations in Australia. The energy ideas above are not hypothetical; they are visible in Australian observations. Australia's mean temperature has risen by more than $1.5\,°\mathrm{C}$ since 1910, with warming in every state and territory. The ocean around Australia is warming too, and periods of unusually high sea surface temperature — **marine heatwaves** — have contributed to mass coral bleaching on the Great Barrier Reef, in which corals expel the algae they depend on when the water is too warm. Recorded mass bleaching events include the summers of 1998, 2002, 2016, 2017, 2020, 2022, 2024 and 2025.

Source: Australian Institute of Marine Science, Long-Term Monitoring Program, retrieved 2026-08-19.

Key ideas

- Energy reaches Earth from the Sun by radiation and is transformed into thermal energy when absorbed; Earth radiates infrared energy back to space. A steady average temperature requires the two to balance.

- The natural greenhouse effect slows the outward transfer of energy; a strengthened greenhouse effect means energy in exceeds energy out, and the climate system stores the difference.
- Stored energy causes temperature change ($Q = m c \Delta T$) and change of state ($Q = m L$).
- The ocean stores most of the extra energy because water has a large specific heat capacity and the ocean's mass is enormous; the land warms more quickly.
- Melting land ice absorbs latent heat at constant temperature and adds water to the ocean; more evaporation carries more latent heat into storms.
- The greenhouse-gas mechanism and the evidence for human influence are studied in Section 10C (Option 2.1).

Worked examples

Example 1 — scaffolded

In summer the surface water of Port Phillip Bay can warm from $14.0\,°C$ to $22.0\,°C$. Take a sample of bay water of mass $1.0 \times 10^4\,kg$. (a) Calculate the energy absorbed by this water as it warms through that range. (b) The same energy is transferred to $1.0 \times 10^4\,kg$ of dry sand on the nearby Mornington Peninsula. Calculate the temperature rise of the sand. (c) Use your answers to explain why coastal Victoria has milder temperature swings than inland Victoria. Use $c = 4.18 \times 10^3\,J\,kg^{-1}K^{-1}$ for water and $c = 8.0 \times 10^2\,J\,kg^{-1}K^{-1}$ for dry sand.

Working	Comment
(a) $\Delta T = 22.0 - 14.0 = 8.0\,°C$.	First find the temperature change.
$Q = m c \Delta T = 1.0 \times 10^4 \times 4.18 \times 10^3 \times 8.0 = 3.3 \times 10^8\,J$.	Use $Q = m c \Delta T$ for a temperature change.
(b) Same Q, same mass, smaller c: $\Delta T = \frac{Q}{m c} = \frac{3.344 \times 10^8}{1.0 \times 10^4 \times 8.0 \times 10^2} = 42\,°C$.	Rearrange $Q = m c \Delta T$; keep an extra figure in Q until the end.
(c) The same energy input raises the sand's temperature about five times as much as the water's.	Water's larger specific heat capacity makes it warm and cool more slowly.

The ocean absorbs and releases large amounts of energy with only small temperature changes, so coastal regions are kept mild; inland, the land surface heats and cools quickly, giving hotter days and colder nights.

Example 2 — scaffolded

In spring, a patch of seasonal snow of mass $2500\,kg$ melts near Mount Hotham in the Victorian Alps. The snow is already at $0\,°C$. (a) Calculate the energy the snow absorbs as it melts. (b) Show that this is about 80 times the energy needed to warm the resulting meltwater by $1.0\,°C$. Use $L = 3.34 \times 10^5\,J\,kg^{-1}$ for ice and $c = 4.18 \times 10^3\,J\,kg^{-1}K^{-1}$ for water.

Working	Comment
(a) Melting is a change of state at constant temperature, so use $Q = m L$.	The energy goes into melting, not into raising the temperature.
$Q = 2500 \times 3.34 \times 10^5 = 8.35 \times 10^8\,J$.	Specific latent heat of fusion of ice.
(b) Warming the meltwater by $1.0\,°C$: $Q = m c \Delta T = 2500 \times 4.18 \times 10^3 \times 1.0 = 1.0 \times 10^7\,J$.	Use $Q = m c \Delta T$ for the liquid water.
Ratio: $\frac{8.35 \times 10^8}{1.045 \times 10^7} = 79.9 \approx 80$.	Melting absorbs a great deal more energy than a $1\,°C$ warming.

This is why melting ice is such a large energy store: a warming climate supplies latent heat to ice at constant temperature, and none of that energy shows up on a thermometer while the melting continues.

Example 3 — unscaffolded

The mass of Earth's atmosphere is about $5.2\times10^{18}\,\mathrm{kg}$ and the mass of the ocean is about $1.4\times10^{21}\,\mathrm{kg}$ (Source: Trenberth and Smith, The Mass of the Atmosphere: A Constraint on Global Analyses, Journal of Climate, 18, 864–875, 2005; U.S. Geological Survey, Water Science School: How Much Water is There on Earth?, retrieved 2026-08-24). Take $c=1.0\times10^{3}\,\mathrm{J\,kg^{-1}\,K^{-1}}$ for air and $c=4.18\times10^{3}\,\mathrm{J\,kg^{-1}\,K^{-1}}$ for seawater. In 2024 the global mean near-surface temperature was $1.55\,°\mathrm{C}$ above the 1850–1900 average (Source: World Meteorological Organization, State of the Global Climate 2024, retrieved 2026-08-18). (a) Calculate the energy needed to warm the entire atmosphere by $1.55\,°\mathrm{C}$. (b) Calculate the energy needed to warm the entire ocean by the same amount, and compare the two. (c) Hence explain why the ocean, not the atmosphere, stores most of the extra energy in the climate system.

(a) Warming the atmosphere is a temperature change, so $Q=mc\,\Delta T$:

$$Q_{\mathrm{atm}}=5.2\times10^{18}\times1.0\times10^{3}\times1.55=8.1\times10^{21}\,\mathrm{J}.$$

(b) For the ocean:

$$Q_{\mathrm{ocean}}=1.4\times10^{21}\times4.18\times10^{3}\times1.55=9.1\times10^{24}\,\mathrm{J}.$$

Comparing,

$$\frac{Q_{\mathrm{ocean}}}{Q_{\mathrm{atm}}}=\frac{9.1\times10^{24}}{8.1\times10^{21}}\approx1100.$$

Warming the whole ocean by $1.55\,°\mathrm{C}$ takes about 1100 times as much energy as warming the whole atmosphere by the same amount.

(c) Because the ocean's mass is enormous and water's specific heat capacity is large, the ocean can absorb far more energy than the atmosphere for the same temperature rise. This matches observation: more than about 90% of the extra energy accumulating in the climate system is stored in the ocean, yet the deep ocean's average temperature has risen far less than $1.55\,°\mathrm{C}$. The ocean acts as a huge energy buffer, slowing the warming of the air above it.

Example 4 — unscaffolded

Between 1901 and 2018 the global mean sea level rose by about $0.20\,\mathrm{m}$ (Source: Intergovernmental Panel on Climate Change, Sixth Assessment Report, retrieved 2026-08-18). In a simple model, suppose half of this rise, $0.10\,\mathrm{m}$, came from the melting of land ice, and take the ocean's surface area as $3.6\times10^{14}\,\mathrm{m^2}$ and the density of the meltwater as $1.0\times10^{3}\,\mathrm{kg\,m^{-3}}$. (a) Calculate the volume of meltwater added to the ocean. (b) Calculate the mass of ice that must have melted to provide it. (c) Calculate the energy needed to melt that much ice at $0\,°\mathrm{C}$, using $L=3.34\times10^{5}\,\mathrm{J\,kg^{-1}}$. (d) Glacier ice is usually below $0\,°\mathrm{C}$ before it melts. Taking $c=2.1\times10^{3}\,\mathrm{J\,kg^{-1}\,K^{-1}}$ for ice, show that warming ice from $-10\,°\mathrm{C}$ to $0\,°\mathrm{C}$ adds about 6% to the energy found in (c).

(a) The meltwater spreads over the ocean surface:

$$V=A\times h=3.6\times10^{14}\times0.10=3.6\times10^{13}\,\mathrm{m^3}.$$

(b) Using $m=\rho V$:

$$m=1.0\times10^{3}\times3.6\times10^{13}=3.6\times10^{16}\,\mathrm{kg}.$$

(c) Melting is a change of state, so $Q=mL$:

$$Q=3.6\times10^{16}\times3.34\times10^{5}=1.2\times10^{22}\,\mathrm{J}.$$

(d) First warming the ice through $10\,°\mathrm{C}$:

$$Q=mc\,\Delta T=3.6\times10^{16}\times2.1\times10^{3}\times10=7.6\times10^{20}\,\mathrm{J}.$$

As a fraction of the melting energy,

$$\frac{7.6 \times 10^{20}}{1.2 \times 10^{22}} \approx 0.06,$$

that is, about 6%. So the true energy cost of producing the meltwater is a little larger than the latent-heat calculation alone. (In reality, some of the sea-level rise also comes from the expansion of warming seawater, so the ice-melt share assumed here is only a model.)

Practice questions

Useful values: specific heat capacity of water $c = 4.18 \times 10^3\ \text{J kg}^{-1}\text{K}^{-1}$; specific heat capacity of ice $c = 2.1 \times 10^3\ \text{J kg}^{-1}\text{K}^{-1}$; specific latent heat of fusion of ice $L = 3.34 \times 10^5\ \text{J kg}^{-1}$; specific latent heat of vaporisation of water $L = 2.26 \times 10^6\ \text{J kg}^{-1}$; 1 litre of water has a mass of about $1\ \text{kg}$; 1 year $= 3.16 \times 10^7\ \text{s}$.

Question 1 In 2024 the global mean near-surface temperature was $1.55\ °\text{C}$ above the 1850–1900 average (Source: World Meteorological Organization, State of the Global Climate 2024, retrieved 2026-08-18). Suppose the 1850–1900 average was $13.6\ °\text{C}$. (a) Calculate the 2024 global mean temperature in degrees Celsius. (b) Convert the 1850–1900 average and the 2024 mean to kelvin. (c) State the temperature rise of $1.55\ °\text{C}$ as a rise in kelvin, and explain why the two numbers are the same.

Question 2 A mass of $5.0 \times 10^5\ \text{kg}$ of surface seawater off the east coast of Tasmania warms by $0.80\ °\text{C}$ during a marine heatwave. (a) Write the relationship between energy transferred, mass, specific heat capacity and temperature change. (b) Calculate the energy absorbed by the seawater. (c) Name the energy transformation that occurred when the seawater absorbed radiation from the Sun.

Question 3 On a sunny day, $8.4 \times 10^5\ \text{J}$ of energy is transferred to a $20\ \text{kg}$ sample of water and to a separate $20\ \text{kg}$ sample of granite in the Victorian Alps. Take $c = 7.9 \times 10^2\ \text{J kg}^{-1}\text{K}^{-1}$ for granite. (a) Show that the temperature rise of the water is about $10\ °\text{C}$. (b) Calculate the temperature rise of the granite. (c) Use your answers to explain why inland towns such as Mildura have much hotter days and colder nights than coastal towns such as Mallacoota.

Question 4 At the Mount Buller ski resort, a snow-making machine produces a layer of snow. Overnight in spring, $1200\ \text{kg}$ of snow at $0\ °\text{C}$ melts. (a) Name the change of state and the specific latent heat involved. (b) Calculate the energy absorbed by the snow as it melts. (c) Explain why the temperature of the snow and meltwater stays at $0\ °\text{C}$ until all the snow has melted.

Question 5 A block of ice of mass $5.0\ \text{kg}$ is taken from a freezer at $-8.0\ °\text{C}$. (a) Calculate the energy needed to warm the ice to $0\ °\text{C}$. (b) Calculate the further energy needed to melt the ice at $0\ °\text{C}$. (c) Hence state the total energy needed to turn the freezer block into water at $0\ °\text{C}$.

Question 6 A student models the warming of land and ocean using two identical containers, one holding $0.50\ \text{kg}$ of water and the other $0.50\ \text{kg}$ of dry sand, placed under a lamp. Both start at $20.0\ °\text{C}$. After 10 minutes the water is at $21.5\ °\text{C}$ and the sand is at $26.0\ °\text{C}$. (a) Identify the independent variable, the dependent variable and one controlled variable in this investigation. (b) Calculate the energy absorbed by the water and by the sand. Take $c = 8.0 \times 10^2\ \text{J kg}^{-1}\text{K}^{-1}$ for dry sand. (c) Name the main energy transfer from the lamp to the containers. (d) Explain, using your results, why the sand's temperature rose more than the water's.

Question 7 An outdoor swimming pool in Melbourne holds $25\,000$ litres of water. During a week of sunny weather its temperature rises by $6.0\ °\text{C}$. Calculate the energy the pool water has absorbed.

Question 8 During a marine heatwave off south-eastern Australia, the ocean absorbs about $8.0 \times 10^{18}\ \text{J}$ of extra energy, mixed through about $2.0 \times 10^{15}\ \text{kg}$ of surface water. Calculate the resulting temperature rise of that water.

Question 9 On a hot summer day in northern Victoria, about $1.2 \times 10^7\ \text{kg}$ of water evaporates from irrigated fields and waterways in part of the Murray–Darling Basin. Calculate the energy carried away from the surface by this evaporation.

Question 10 An iceberg of mass $2.4 \times 10^{8}\,\mathrm{kg}$ calves from an Antarctic ice shelf and drifts into warmer water, where it melts completely. The meltwater then warms by $8.0\,°\mathrm{C}$. (a) Calculate the energy absorbed as the iceberg melts at $0\,°\mathrm{C}$. (b) Calculate the further energy absorbed as the meltwater warms by $8.0\,°\mathrm{C}$. (c) Compare the two energies and state what this tells you about latent heat.

Question 11 In a simple energy-budget model, Earth radiates about $240\,\mathrm{W}$ of energy to space per square metre of surface. Suppose a change in the atmosphere reduces this outgoing transfer by 0.40%. (a) Show that the resulting energy imbalance is about $1\,\mathrm{W\,m^{-2}}$. (b) Taking Earth's surface area as $5.1 \times 10^{14}\,\mathrm{m}^2$, calculate the extra power retained by the whole climate system. (c) Calculate the extra energy retained in one year. (d) State what happens to the average temperature of the climate system while this imbalance continues, and why.

Question 12 Between 1901 and 2018 the global mean sea level rose by about $0.20\,\mathrm{m}$ (Source: Intergovernmental Panel on Climate Change, Sixth Assessment Report, retrieved 2026-08-18). In a simple model, suppose all of this rise came from the melting of land ice. Take the ocean's surface area as $3.6 \times 10^{14}\,\mathrm{m}^2$ and the density of the meltwater as $1.0 \times 10^{3}\,\mathrm{kg\,m^{-3}}$. (a) Calculate the volume of meltwater added to the ocean. (b) Calculate the mass of ice that melted. (c) Calculate the energy needed to melt that much ice at $0\,°\mathrm{C}$. (d) Give one reason why this model overstates the share of the rise due to melting ice.

Question 13 Mallacoota, on the far east coast of Victoria, has much smaller swings between summer and winter temperatures than Mildura, in north-western Victoria, even though the two towns are at similar latitudes. Explain this difference, referring to specific heat capacity and to energy transfers between the ocean and the air.

Question 14 A student claims: "When ice melts, it absorbs energy, so its temperature must rise." (a) Identify the error in this claim and explain what happens to the energy absorbed during melting. (b) Distinguish between the effect of melting *land* ice and melting *sea ice* on sea level, with a reason for each.

Question 15 Earth's average temperature is roughly steady when the energy absorbed from the Sun equals the energy radiated back to space. (a) Describe the main energy transfers and transformations in this budget: from the Sun to Earth's surface, and from the surface back toward space. (b) Explain, in terms of the energy budget, why the surface and the ocean warm if a change in the atmosphere makes it harder for outgoing infrared radiation to reach space. You do not need to name the gases involved or their mechanism (studied in Section 10C).

Question 16 Explain why a warmer ocean can drive more intense storms and heavier rainfall, referring to evaporation, latent heat and condensation.

Question 17 Sea ice is bright and reflects much of the radiation that reaches it; open ocean water is dark and absorbs most of the radiation that reaches it. Explain how the melting of sea ice can amplify warming. In your answer, identify this kind of process by name.

Question 18 The table below shows, approximately, how the extra energy accumulating in the climate system is shared between its parts.

Store	Approximate share of extra energy
Ocean	91%
Land	5%
Melting ice	3%
Atmosphere	1%

Source: Intergovernmental Panel on Climate Change, Sixth Assessment Report, retrieved 2026-08-18.

(a) Explain why the ocean's share is so large, referring to the ocean's mass and the specific heat capacity of water.
(b) Discuss two consequences for the climate of the ocean storing most of the extra energy. In your answer, refer to at least one Australian observation.

Answers

Question 1 (a) $15.2\,°\text{C}$; (b) $286.8\,\text{K}$ and $288.3\,\text{K}$; (c) $1.55\,\text{K}$ — a change of $1\,°\text{C}$ equals a change of $1\,\text{K}$. **Question 2** (a) $Q = m\,c\,\Delta T$; (b) $1.7\times10^{9}\,\text{J}$; (c) radiation (electromagnetic) energy is transformed into thermal energy. **Question 3** (a) $10\,°\text{C}$; (b) $53\,°\text{C}$; (c) see solution. **Question 4** (a) melting (fusion); specific latent heat of fusion; (b) $4.0\times10^{8}\,\text{J}$; (c) see solution. **Question 5** (a) $8.4\times10^{4}\,\text{J}$; (b) $1.7\times10^{6}\,\text{J}$; (c) $1.8\times10^{6}\,\text{J}$. **Question 6** (a) independent: the material (water or sand); dependent: the temperature rise; controlled: mass, lamp distance, time, starting temperature (any one); (b) water $3.1\times10^{3}\,\text{J}$, sand $2.4\times10^{3}\,\text{J}$; (c) radiation; (d) see solution. **Question 7** $6.3\times10^{8}\,\text{J}$. **Question 8** $0.96\,°\text{C}$. **Question 9** $2.7\times10^{13}\,\text{J}$. **Question 10** (a) $8.0\times10^{13}\,\text{J}$; (b) $8.0\times10^{12}\,\text{J}$; (c) melting absorbed ten times more energy than an $8\,°\text{C}$ warming. **Question 11** (a) $0.96\,\text{W m}^{-2}$; (b) $4.9\times10^{14}\,\text{W}$; (c) $1.5\times10^{22}\,\text{J}$; (d) it rises. **Question 12** (a) $7.2\times10^{13}\,\text{m}^{3}$; (b) $7.2\times10^{16}\,\text{kg}$; (c) $2.4\times10^{22}\,\text{J}$; (d) see solution. **Question 13** see solution. **Question 14** see solution. **Question 15** see solution. **Question 16** see solution. **Question 17** see solution. **Question 18** see solution.

Fully-worked solutions

Question 1 The 1850–1900 average is taken as $13.6\,°\text{C}$, and 2024 was $1.55\,°\text{C}$ warmer. (a) $T = 13.6 + 1.55 = 15.15 \approx 15.2\,°\text{C}$. (b) To convert Celsius to kelvin, add 273.15: $13.6 + 273.15 = 286.75\,\text{K} \approx 286.8\,\text{K}$ and $15.15 + 273.15 = 288.30\,\text{K} \approx 288.3\,\text{K}$. (c) The rise is $1.55\,\text{K}$. The Celsius and kelvin scales have steps of the same size — they differ only in where zero is placed — so a temperature *change* has the same numerical value on both scales.

Question 2 $m = 5.0\times10^{5}\,\text{kg}$, $\Delta T = 0.80\,°\text{C}$. (a) $Q = m\,c\,\Delta T$. (b) $Q = 5.0\times10^{5}\times4.18\times10^{3}\times0.80 = 1.7\times10^{9}\,\text{J}$. (c) Radiation energy from the Sun was absorbed by the seawater and transformed into thermal energy of the water.

Question 3 $Q = 8.4\times10^{5}\,\text{J}$, $m = 20\,\text{kg}$. (a) For the water, $\Delta T = \dfrac{Q}{m\,c} = \dfrac{8.4\times10^{5}}{20\times4.18\times10^{3}} = 10\,°\text{C}$, as required. (b) For the granite, $\Delta T = \dfrac{Q}{m\,c} = \dfrac{8.4\times10^{5}}{20\times7.9\times10^{2}} = 53\,°\text{C}$. (c) The same energy input raises the granite's temperature about five times as much as the water's, because rock has a much smaller specific heat capacity than water. Inland, the thin layer of dry ground stores little energy per degree, so it heats quickly during the day and cools quickly at night, giving Mildura hot days and cold nights. Coastal Mallacoota is moderated by the nearby ocean, which absorbs and releases large amounts of energy with only small temperature changes, keeping days cooler and nights warmer.

Question 4 $m = 1200\,\text{kg}$ of snow at $0\,°\text{C}$. (a) The change of state is melting (fusion), and the relevant quantity is the specific latent heat of fusion, $L = 3.34\times10^{5}\,\text{J kg}^{-1}$. (b) $Q = m\,L = 1200\times3.34\times10^{5} = 4.0\times10^{8}\,\text{J}$. (c) During a change of state the temperature is constant. The energy absorbed does not increase the kinetic energy of the particles — which is what temperature measures — but goes into breaking down the ordered structure of the solid, increasing the particles' potential energy. The temperature stays at $0\,°\text{C}$ until all the snow has melted.

Question 5 $m = 5.0\,\text{kg}$, from $-8.0\,°\text{C}$. (a) Warming the ice: $Q = m\,c\,\Delta T = 5.0\times2.1\times10^{3}\times8.0 = 8.4\times10^{4}\,\text{J}$. (b) Melting the ice at $0\,°\text{C}$: $Q = m\,L = 5.0\times3.34\times10^{5} = 1.7\times10^{6}\,\text{J}$. (c) Total: $8.4\times10^{4} + 1.67\times10^{6} = 1.75\times10^{6} \approx 1.8\times10^{6}\,\text{J}$. Notice that melting the ice takes twenty times more energy than warming it through $8\,°\text{C}$.

Question 6 (a) The independent variable is the material (water or sand). The dependent variable is the temperature rise. Controlled variables include the mass of each sample ($0.50\,\text{kg}$), the lamp height, the exposure time (10 minutes) and the starting temperature ($20.0\,°\text{C}$); any one of these is acceptable. (b) Water: $Q = m\,c\,\Delta T = 0.50\times4.18\times10^{3}\times1.5 = 3.1\times10^{3}\,\text{J}$. Sand: $Q = m\,c\,\Delta T = 0.50\times8.0\times10^{2}\times6.0 = 2.4\times10^{3}\,\text{J}$. (c) Energy travels from the lamp to the containers by radiation. (d) The two samples absorbed similar amounts of energy, but the sand's temperature rose four times as much because sand has a much smaller specific heat capacity than water: less energy is needed per degree of temperature rise. (The small difference in the two calculated energies is expected in a real experiment, where some energy is lost to the surroundings at different rates.)

Question 7 25 000 litres of water has a mass of about 25 000 kg.

$$Q = mc\Delta T = 25\,000 \times 4.18 \times 10^3 \times 6.0 = 6.3 \times 10^8\ \text{J}.$$

Question 8 $\Delta T = \dfrac{Q}{mc} = \dfrac{8.0 \times 10^{18}}{2.0 \times 10^{15} \times 4.18 \times 10^3} = \dfrac{8.0 \times 10^{18}}{8.36 \times 10^{18}} = 0.96\ {}^\circ\text{C}$. A rise of almost $1\ {}^\circ\text{C}$ across a large mass of water is a large amount of stored energy — which is why marine heatwaves can stress marine life such as corals.

Question 9 Evaporation is a change of state, so $Q = mL$ with the specific latent heat of vaporisation:

$$Q = 1.2 \times 10^7 \times 2.26 \times 10^6 = 2.7 \times 10^{13}\ \text{J}.$$

This energy is carried away from the surface (cooling it) and is released into the atmosphere when the vapour condenses.

Question 10 $m = 2.4 \times 10^8\ \text{kg}$. (a) Melting: $Q = mL = 2.4 \times 10^8 \times 3.34 \times 10^5 = 8.0 \times 10^{13}$ J. (b) Warming the meltwater by $8.0\ {}^\circ\text{C}$: $Q = mc\Delta T = 2.4 \times 10^8 \times 4.18 \times 10^3 \times 8.0 = 8.0 \times 10^{12}$ J. (c) Melting the iceberg absorbed ten times as much energy as warming all of the meltwater by $8\ {}^\circ\text{C}$. Changes of state involve far larger energy transfers than the temperature changes that accompany them, because latent heats are large.

Question 11 Outgoing transfer $240\ \text{W m}^{-2}$; reduced by 0.40%. (a) Imbalance $= 240 \times 0.0040 = 0.96\ \text{W m}^{-2}$, which is about $1\ \text{W m}^{-2}$. (b) Extra power $= 0.96 \times 5.1 \times 10^{14} = 4.9 \times 10^{14}\ \text{W}$. (c) Energy in one year $= Pt = 4.9 \times 10^{14} \times 3.16 \times 10^7 = 1.5 \times 10^{22}$ J. (d) While energy in exceeds energy out, the climate system stores the difference, so its average temperature rises. Most of this stored energy goes into the ocean. The warming continues until the outgoing transfer grows large enough to balance the incoming transfer again.

Question 12 Rise $0.20\ \text{m}$, all assumed to come from melting land ice. (a) $V = A \times h = 3.6 \times 10^{14} \times 0.20 = 7.2 \times 10^{13}\ \text{m}^3$. (b) $m = \rho V = 1.0 \times 10^3 \times 7.2 \times 10^{13} = 7.2 \times 10^{16}\ \text{kg}$. (c) $Q = mL = 7.2 \times 10^{16} \times 3.34 \times 10^5 = 2.4 \times 10^{22}$ J. (d) Part of the observed sea-level rise comes from the thermal expansion of warming seawater rather than from added meltwater, so assuming all of the rise is meltwater overstates the amount of ice that melted. (The energy in (c) is therefore an overestimate too.)

Question 13 Water has a large specific heat capacity, so the ocean warms slowly in summer and cools slowly in winter, absorbing and releasing large amounts of energy with only small temperature changes. Coastal Mallacoota is moderated by the nearby ocean: energy transfers from the ocean to the air (by conduction, convection and evaporation) keep winter nights milder, and the ocean's slow warming keeps summer days cooler. Inland Mildura sits over dry land with a much smaller effective heat capacity: the ground heats quickly on sunny days and cools quickly on clear nights, so both summer days and winter nights are more extreme.

Question 14 (a) The error is assuming that absorbed energy must raise the temperature. During melting the temperature stays constant at $0\ {}^\circ\text{C}$: the energy absorbed goes into breaking down the ordered structure of the solid — increasing the potential energy of the particles — rather than increasing their kinetic energy, which is what temperature measures. (b) Melting land ice adds new water to the ocean, because meltwater that was stored on land runs into the sea, so sea level rises. Melting sea ice does not significantly raise sea level, because the ice is already floating in the ocean; when it melts, the meltwater occupies about the same volume as the seawater the floating ice displaced.

Question 15 (a) Energy is transferred from the Sun to Earth by radiation, which needs no medium. Some incoming radiation is reflected; the radiation that is absorbed by the land, the ocean and the atmosphere is transformed into thermal energy, raising temperatures. Energy is redistributed within the climate system by conduction (from the surface to the air in contact with it), by convection (rising warm air and ocean currents) and by evaporation. Energy finally leaves the climate system by radiation, as infrared radiation emitted to space. (b) If the atmosphere makes it harder for outgoing infrared radiation to reach space, the rate at which energy leaves is reduced, so energy out is less than energy in. The climate system therefore stores the difference each year. Stored energy increases the thermal energy of the ocean, land and air ($Q = mc\Delta T$), raising temperatures, and drives changes of state such as the melting of ice ($Q = mL$). The warming continues until the warmer surface and atmosphere radiate enough energy to space for the outgoing transfer to balance the incoming transfer again — at a higher average temperature than before.

Question 16 A warmer ocean evaporates more water, because more molecules at the surface have enough kinetic energy to escape. Each kilogram of water vapour carries away about 2.3×10^6 J of latent heat. When the vapour rises and condenses into cloud, that energy is released into the atmosphere. More evaporation therefore means more latent heat is delivered to the atmosphere, giving storms and rainfall systems more energy to draw on — which is why a warming climate is expected to bring more intense storms and heavier rainfall events.

Question 17 Bright sea ice reflects much of the incoming radiation, while dark open water absorbs most of it. When sea ice melts, darker ocean surface is exposed, so more radiation is absorbed and transformed into thermal energy. The warmer ocean then melts more ice, exposing still more dark water. The change therefore amplifies itself. A process like this, in which the result of a change feeds back to make the change larger, is called a feedback — this one is an ice–reflectivity feedback.

Question 18 (a) The ocean covers most of Earth's surface and is very deep, so its mass is enormous, and water has a large specific heat capacity. Since $Q = mc\Delta T$, a large m and a large c mean the ocean can absorb far more energy than the atmosphere or the land for the same temperature rise — so it takes the largest share of the extra energy. (b) First, the ocean acts as a buffer: because it absorbs most of the extra energy, the warming of the air and the land so far is smaller than it would otherwise have been — but the stored energy remains in the climate system for a long time, since water cools slowly. Second, the stored energy has observable consequences: warming seawater expands, adding to sea-level rise, and the extra energy stored near the surface drives marine heatwaves. In Australia, marine heatwaves have contributed to mass coral bleaching on the Great Barrier Reef; recorded mass bleaching events include the summers of 1998, 2002, 2016, 2017, 2020, 2022, 2024 and 2025 (Source: Australian Institute of Marine Science, Long-Term Monitoring Program, retrieved 2026-08-19).

Topic 1 Test A — Light and heat (multiple choice)

Time allowed: 25 minutes · 20 marks · One scientific calculator permitted · The formula sheet (back of the Practice Examinations booklet) may be used.

Choose the response that is correct or that best answers the question. A correct answer scores 1 mark; an incorrect answer scores 0. Marks are not deducted for incorrect answers. No marks are given if more than one answer is completed for any question. Unless otherwise indicated, the diagrams in this test are not drawn to scale. Where required, take the gravitational field strength to be $g = 9.8\,\mathrm{N\ kg^{-1}}$.

Question 1

One end of a rope is shaken up and down, sending a wave along it. Which of the following does the wave transfer along the rope?

A. The particles of the rope, but not energy

B. Energy, but not the particles of the rope

C. Both the particles of the rope and energy

D. Neither energy nor particles — nothing at all moves along the rope

Question 2

A radio station broadcasts at a frequency of $6.0 \times 10^5\,\mathrm{Hz}$. Taking the speed of radio waves to be $3.0 \times 10^8\,\mathrm{m\ s^{-1}}$, which of the following is closest to the wavelength of the broadcast?

A. $500\,\mathrm{m}$

B. $0.0020\,\mathrm{m}$

C. $5.0\,\mathrm{m}$

D. $1.8 \times 10^{14}\,\mathrm{m}$

Question 3

Which of the following lists electromagnetic waves in order of increasing frequency?

A. Gamma rays, X-rays, ultraviolet, visible light

B. Visible light, infrared, microwaves, radio waves

C. Radio waves, infrared, visible light, ultraviolet

D. Radio waves, visible light, infrared, ultraviolet

Question 4

Unlike sound waves, electromagnetic waves

A. require a material medium in order to travel.

B. are longitudinal waves.

C. cannot carry energy from one place to another.

D. can travel through a vacuum.

Question 5

The refractive index of ice is 1.31. Taking the speed of light in a vacuum to be $3.0 \times 10^{8}\,\mathrm{m\,s^{-1}}$, which of the following is closest to the speed of light in ice?

A. $3.93 \times 10^{8}\,\mathrm{m\,s^{-1}}$

B. $2.29 \times 10^{8}\,\mathrm{m\,s^{-1}}$

C. $3.00 \times 10^{8}\,\mathrm{m\,s^{-1}}$

D. $1.75 \times 10^{8}\,\mathrm{m\,s^{-1}}$

Question 6

Light of wavelength 600 nm in air has a frequency of $5.0 \times 10^{14}\,\mathrm{Hz}$. It enters a glass block of refractive index 1.50. Which of the following is closest to the frequency of the light inside the glass?

A. $5.0 \times 10^{14}\,\mathrm{Hz}$

B. $3.3 \times 10^{14}\,\mathrm{Hz}$

C. $7.5 \times 10^{14}\,\mathrm{Hz}$

D. $2.5 \times 10^{14}\,\mathrm{Hz}$

Question 7

A ray of light travelling in air meets the flat surface of a glycerol block (refractive index 1.47) at an angle of incidence of 40°. Which of the following is closest to the angle of refraction inside the glycerol?

A. 40.0°

B. 70.9°

C. 29.4°

D. 25.9°

Question 8

Light travels through water (refractive index 1.33) with a wavelength of 450 nm. Which of the following is closest to the wavelength of this light in air?

A. 338 nm

B. 450 nm

C. 599 nm

D. 300 nm

Question 9

For total internal reflection to occur when light meets a boundary between two transparent media,

A. the light must be travelling from the medium of lower refractive index into the medium of higher refractive index, and the angle of incidence must be greater than the critical angle.

B. the light must be travelling from the medium of higher refractive index into the medium of lower refractive index, and the angle of incidence must be greater than the critical angle.

C. the light must be travelling from the medium of higher refractive index into the medium of lower refractive index, and the angle of incidence must be less than the critical angle.

D. the light must be travelling in a vacuum before it reaches the boundary, whatever the angle of incidence.

Question 10

Light travelling inside acrylic (refractive index 1.49) meets a boundary with water (refractive index 1.33). Which of the following is closest to the critical angle for this boundary?

A. 63.2°

B. 26.8°

C. 48.8°

D. 41.8°

Question 11

A pulse of light travels along a straight optical fibre of length $30\,\text{km}$. The refractive index of the fibre's core is 1.50. Taking the speed of light in a vacuum to be $3.0 \times 10^8\,\text{m s}^{-1}$, which of the following is closest to the time taken for the pulse to travel the length of the fibre?

A. $100\,\mu\text{s}$

B. $225\,\mu\text{s}$

C. $1.5\,\text{ms}$

D. $150\,\mu\text{s}$

Question 12

In a particular glass, violet light travels more slowly than red light. Compared with red light travelling through the same glass, the violet light has

A. a lower frequency.

B. a longer wavelength.

C. a shorter wavelength.

D. a higher frequency.

Question 13

An observer sees a primary rainbow in which the red band appears higher in the sky than the violet band. This is because, after the sunlight interacts with the raindrops, the red light

A. is refracted through a larger angle than the violet light.

B. reaches the observer at an angle of about 42° to the direction of the incoming sunlight, a larger angle than for violet light.

C. has a shorter wavelength than the violet light.

D. undergoes total internal reflection inside the drops, while the violet light does not.

Question 14

A certain liquid boils at $90\,\mathrm{K}$. Which of the following is closest to this temperature in degrees Celsius?

A. $-90\,°\mathrm{C}$

B. $363\,°\mathrm{C}$

C. $-183\,°\mathrm{C}$

D. $90\,°\mathrm{C}$

Question 15

On a cold day, the layer of air touching the inside of a brick wall transfers energy to the wall, warming it slightly. The energy transfer from this layer of air to the wall occurs mainly by

A. conduction.

B. convection.

C. radiation.

D. evaporation.

Question 16

When a liquid evaporates, the remaining liquid cools. The best explanation is that the molecules that escape from the liquid

A. absorb thermal radiation from the surroundings as they leave.

B. have below-average kinetic energy, leaving faster molecules behind.

C. carry away the specific latent heat of fusion of the liquid.

D. have above-average kinetic energy, so the average kinetic energy of the molecules left behind decreases.

Question 17

The specific heat capacity of ethanol is $2440\,\mathrm{J\,kg^{-1}\,K^{-1}}$. A $0.50\,\mathrm{kg}$ sample of ethanol is heated from $20\,°\mathrm{C}$ to $60\,°\mathrm{C}$. Which of the following is closest to the energy absorbed by the ethanol?

A. $48.8\,\mathrm{kJ}$

B. $12.2\,\mathrm{kJ}$

C. $83.6\,\mathrm{kJ}$

D. $97.6\,\mathrm{kJ}$

Question 18

The specific latent heat of fusion of ice is 3.34×10^5 J kg^{-1}. Which of the following is closest to the energy required to melt 0.25 kg of ice at 0 °C?

A. 334 kJ

B. 8.35 kJ

C. 83.5 kJ

D. 1.3×10^3 kJ

Question 19

The glowing element of a toaster reaches a temperature of about 800 °C. Using Wien's Law, $\lambda_{max} T = 2.9 \times 10^{-3}$ m K, which of the following is closest to the peak wavelength of the radiation emitted by the element?

A. 3.6×10^{-6} m

B. 2.7×10^{-6} m

C. 1.1×10^{-5} m

D. 2.7×10^{-3} m

Question 20

The blackbody radiation curve of star X peaks at a wavelength of 600 nm. Star Y has twice the surface temperature of star X. Compared with star X, the radiation emitted by star Y peaks

A. at 1200 nm, and star Y emits more energy at every wavelength.

B. at 600 nm, and star Y emits more energy at every wavelength.

C. at 300 nm, and star Y emits less energy at every wavelength.

D. at 300 nm, and star Y emits more energy at every wavelength.

End of Topic 1 Test A

Topic 1 Test A — solutions

Question	Answer	Question	Answer
1	B	11	D
2	A	12	C
3	C	13	B
4	D	14	C
5	B	15	A
6	A	16	D
7	D	17	A
8	C	18	C
9	B	19	B
10	A	20	D

Question 1 — B. A wave is a travelling disturbance that transfers energy from the source outwards; the particles of the medium oscillate about fixed positions and are not carried along with the wave. **A** and **C** wrongly claim that the particles themselves travel; **D** denies that anything is transferred at all.

Question 2 — A. $v = f\lambda$, so $\lambda = \frac{v}{f} = \frac{3.0 \times 10^8}{6.0 \times 10^5} = 500\,\mathrm{m}$. **B** calculates f / v (the reciprocal); **C** is out by a factor of 100 in the frequency; **D** multiplies f and v instead of dividing.

Question 3 — C. The electromagnetic spectrum in order of increasing frequency is: radio, microwave, infrared, visible light, ultraviolet, X-rays, gamma rays. **A** and **B** run in order of decreasing frequency; **D** swaps the positions of infrared and visible light.

Question 4 — D. Electromagnetic waves do not need a medium and can travel through a vacuum; sound waves need a material medium. **A** describes sound waves; **B** is wrong — electromagnetic waves are transverse; **C** is false, since all waves carry energy.

Question 5 — B. $n = \frac{c}{v}$, so $v = \frac{c}{n} = \frac{3.0 \times 10^8}{1.31} = 2.29 \times 10^8\,\mathrm{m\ s^{-1}}$. **A** multiplies c by n; **C** assumes the speed is unchanged in the medium; **D** divides c by n^2.

Question 6 — A. The frequency of light is set by the source and does not change when the light enters a new medium; only the speed and the wavelength change. **B** divides the frequency by n; **C** multiplies it by n; **D** halves it, as though the frequency changed along with the wavelength.

Question 7 — D. Snell's Law: $n_1 \sin\theta_1 = n_2 \sin\theta_2$, so $\sin\theta_2 = \frac{\sin 40^\circ}{1.47} = \frac{0.643}{1.47} = 0.437$, giving $\theta_2 = 25.9^\circ$. **A** assumes no refraction occurs; **B** multiplies by n instead of dividing ($1.47 \sin 40^\circ$); **C** uses $n = 1.31$ (ice) instead of 1.47.

Question 8 — C. The wavelength in a medium is $\lambda_{\text{medium}} = \frac{\lambda_{\text{air}}}{n}$, so in reverse $\lambda_{\text{air}} = n\lambda_{\text{medium}} = 1.33 \times 450 = 599\,\mathrm{nm}$. **A** divides by n again; **B** assumes the wavelength is unchanged; **D** divides by 1.5 rather than multiplying by 1.33.

Question 9 — B. Total internal reflection needs both conditions: the light travels from the medium of higher refractive index into the medium of lower refractive index, and the angle of incidence exceeds the critical angle. **A** reverses the direction of travel; **C** describes an angle below the critical angle, where the light refracts out; **D** is not a condition of the effect.

Question 10 — A. $\sin\theta_c = \frac{n_2}{n_1} = \frac{1.33}{1.49} = 0.893$, so $\theta_c = 63.2^\circ$. **B** gives the complementary angle ($90^\circ - 63.2^\circ$); **C** is the critical angle for a water–air boundary; **D** is the critical angle for a glass–air boundary computed with refractive index 1.50 ($\sin^{-1}(1/1.50) = 41.8^\circ$); neither medium in the question has this refractive index.

Question 11 — D. The speed in the core is $v = \frac{c}{n} = \frac{3.0\times10^8}{1.50} = 2.00\times10^8\,\mathrm{m\,s^{-1}}$, so $t = \frac{d}{v} = \frac{30\,000}{2.00\times10^8} = 1.50\times10^{-4}\,\mathrm{s} = 150\,\mu\mathrm{s}$. **A** uses c rather than the reduced speed in the core; **B** divides the speed by n^2; **C** is out by a factor of 10.

Question 12 — C. The frequency of the light is unchanged in the glass. Since $v = f\lambda$, a lower speed at the same frequency means a shorter wavelength. **A** and **D** wrongly change the frequency; **B** reverses the relationship.

Question 13 — B. Red light emerges from the raindrops at about 42° to the direction of the incoming sunlight and violet light at about 40°; the larger angle places the red band higher in the sky. **A** is false — violet light is refracted more than red; **C** is false — red light has the longer wavelength; **D** is false — both colours undergo one total internal reflection inside each drop.

Question 14 — C. $T(^\circ\mathrm{C}) = T(\mathrm{K}) - 273.15 = 90 - 273.15 = -183\,^\circ\mathrm{C}$. **A** changes the sign of the number only; **B** adds 273 instead of subtracting it; **D** leaves the number unchanged.

Question 15 — A. Energy transfer between two substances in direct contact — air molecules colliding with the surface of the wall — is conduction. **B** is the bulk movement of a fluid; **C** needs no contact at all; **D** involves a change of state.

Question 16 — D. Evaporation removes the fastest-moving molecules, which have above-average kinetic energy. The average kinetic energy of the molecules left behind is therefore lower, and since temperature is a measure of this average, the liquid cools. **A** invents radiation absorbed during escape; **B** reverses which molecules escape; **C** names the wrong latent heat — fusion applies to melting, not vaporisation.

Question 17 — A. $Q = mc\Delta T = 0.50\times2440\times40 = 48\,800\,\mathrm{J} = 48.8\,\mathrm{kJ}$. **B** uses $\Delta T = 10\,\mathrm{K}$; **C** uses water's specific heat capacity ($4180\,\mathrm{J\,kg^{-1}K^{-1}}$); **D** uses $\Delta T = 80\,\mathrm{K}$, having added the two temperatures together.

Question 18 — C. $Q = mL = 0.25\times3.34\times10^5 = 8.35\times10^4\,\mathrm{J} = 83.5\,\mathrm{kJ}$. **A** is the energy needed for $1.0\,\mathrm{kg}$; **B** is out by a factor of 10; **D** divides L by m instead of multiplying.

Question 19 — B. First convert to kelvin: $T = 800 + 273.15 = 1073.15\,\mathrm{K} \approx 1073\,\mathrm{K}$. Then $\lambda_{max} = \frac{2.9\times10^{-3}}{1073} = 2.7\times10^{-6}\,\mathrm{m}$. **A** forgets to convert to kelvin and uses 800; **C** uses $273\,\mathrm{K}$ instead of the element's temperature; **D** keeps the correct mantissa but slips the power of ten from 10^{-6} to 10^{-3} (a micrometre/millimetre prefix slip).

Question 20 — D. By Wien's Law, λ_{max} is inversely proportional to T, so doubling the temperature halves the peak wavelength: $300\,\mathrm{nm}$. A hotter blackbody also emits more energy at every wavelength. **A** doubles the peak wavelength instead of halving it; **B** leaves the peak unchanged; **C** has the correct wavelength but wrongly claims less energy at every wavelength.

Topic 1 Test B — Light and heat (written responses)

Time allowed: 50 minutes · 40 marks · One scientific calculator permitted · The formula sheet (back of the Practice Examinations booklet) may be used. In questions where more than one mark is available, appropriate working must be shown.

Answer all questions in the spaces provided. Where a final answer has a required unit, give your answer in that unit. Unless otherwise indicated, the diagrams in this test are not drawn to scale. Take the gravitational field strength to be $g = 9.8\ \text{N kg}^{-1}$.

Question 1 (5 marks)

An office hot-water dispenser heats $0.80\ \text{kg}$ of water from $18\ °\text{C}$ to $96\ °\text{C}$. The specific heat capacity of water is $4180\ \text{J kg}^{-1}\text{K}^{-1}$.

a. Show that the energy absorbed by the water is about $2.6\times10^{5}\ \text{J}$. 1 mark

b. The heating element supplies energy at a rate of $2400\ \text{J s}^{-1}$. Assuming that all of this energy goes into the water, calculate the time taken to heat the water. Give your answer in s. 2 marks

c. In practice, the time measured is longer than your answer to part **b.** Explain why. 1 mark

d. The dispenser is then used to heat $1.6\ \text{kg}$ of water from the same starting temperature, with the same heating element. Explain, using $Q = mc\,\Delta T$, why the temperature rise of the water per second is smaller in the early part of the heating than it was for the $0.80\ \text{kg}$ sample. 1 mark

Question 2 (5 marks)

In a laboratory, $0.050\ \text{kg}$ of ice at $0\ °\text{C}$ melts completely, and the resulting water is then warmed to $20\ °\text{C}$. The specific latent heat of fusion of ice is $3.34\times10^{5}\ \text{J kg}^{-1}$, and the specific heat capacity of water is $4180\ \text{J kg}^{-1}\text{K}^{-1}$.

a. Show that the energy required to melt the ice is $1.67\times10^{4}\ \text{J}$. 1 mark

b. Calculate the energy required to warm the melted ice from $0\ °\text{C}$ to $20\ °\text{C}$. Give your answer in J. 2 marks

c. State the total energy supplied during the whole process. Give your answer in J. 1 mark

d. While the ice is melting, its temperature remains at $0\ °\text{C}$ even though energy is still being supplied. Explain, in terms of the particles of the ice, where this energy is going. 1 mark

Question 3 (6 marks)

A ray of red laser light travelling in air meets the flat surface of a crown glass block (refractive index 1.52) at an angle of incidence of $35°$. The wavelength of the light in air is $650\ \text{nm}$. Take the speed of light in a vacuum to be $3.0\times10^{8}\ \text{m s}^{-1}$.

a. Show that the angle of refraction inside the glass is about $22°$. 1 mark

b. Calculate the speed of this light inside the glass. Give your answer in m s^{-1}. 2 marks

c. Calculate the wavelength of this light inside the glass. Give your answer in nm. 2 marks

d. The ray reaches the opposite, parallel face of the block and emerges back into air. State the angle that the emerging ray makes with the normal to that face, and explain your reasoning. 1 mark

Question 4 (5 marks)

Inside an ice sculpture (refractive index 1.31), a ray of light meets the flat boundary between the ice and the air.

a. Show that the critical angle for the ice–air boundary is $49.8°$. 1 mark

b. The ray meets the boundary at an angle of incidence of 35°. Calculate the angle of refraction in the air. Give your answer in degrees. 2 marks

c. A second ray inside the ice meets the same boundary at an angle of incidence of 55°. State what happens to this ray at the boundary, and justify your answer. 1 mark

d. (Circle your answer.) If the ice were replaced by a transparent material with a higher refractive index, the critical angle at the boundary with air would be: *greater* / *smaller* / *the same*. Justify your answer. No calculations are required. 1 mark

Question 5 (5 marks)

In a furnace, a block of aluminium is heated until it begins to melt at $660\,°\text{C}$. Wien's Law is $\lambda_{max} T = 2.9 \times 10^{-3}\,\text{m K}$.

a. Convert the melting temperature of the aluminium to kelvin. 1 mark

b. Calculate the peak wavelength of the thermal radiation emitted by the aluminium at this temperature. Give your answer in m. 2 marks

c. The peak you calculated in part **b.** is not in the visible part of the electromagnetic spectrum. Explain why a worker standing near the furnace still feels warmth on their skin. 1 mark

d. The furnace is then raised to $1200\,°\text{C}$. Calculate the new peak wavelength of the radiation emitted. Give your answer in m. 1 mark

Question 6 (5 marks)

Measurements show that more than about 90% of the extra energy accumulating in the climate system is absorbed by the ocean.

Source: Intergovernmental Panel on Climate Change, Sixth Assessment Report, retrieved 2026-08-18.

In a simplified model, a layer of seawater of mass $4.0 \times 10^{12}\,\text{kg}$ absorbs $8.0 \times 10^{16}\,\text{J}$ of extra energy. The specific heat capacity of seawater is $4180\,\text{J kg}^{-1}\text{K}^{-1}$.

a. Show that the temperature rise of this layer of seawater is about $4.8\,\text{K}$. 1 mark

b. Rock has a specific heat capacity of about $840\,\text{J kg}^{-1}\text{K}^{-1}$. Calculate the temperature rise if the same energy were absorbed by the same mass of rock, and use your answers to explain why land surfaces warm more than the ocean surface for the same energy input. Give your answer in K. 2 marks

c. State one effect that the extra energy stored in the ocean can have on weather systems or on marine ecosystems such as the Great Barrier Reef. 1 mark

d. Explain, in terms of an energy budget, why Earth's mean surface temperature rises when the radiation escaping to space is reduced while the incoming radiation from the Sun is unchanged. 1 mark

Question 7 (3 marks)

A $0.50\,\text{kg}$ aluminium block (specific heat capacity $900\,\text{J kg}^{-1}\text{K}^{-1}$) at $90\,°\text{C}$ is placed in contact with a $0.50\,\text{kg}$ iron block (specific heat capacity $450\,\text{J kg}^{-1}\text{K}^{-1}$) at $20\,°\text{C}$. The two blocks are well insulated from their surroundings.

a. State the direction of the energy transfer between the blocks, and the condition for the transfer to stop. 1 mark

b. Without calculating the final temperature, predict whether the final common temperature of the blocks is $55\,°\text{C}$, above $55\,°\text{C}$ or below $55\,°\text{C}$. Justify your prediction using the specific heat capacities. 2 marks

Question 8 (6 marks)

A student investigates how the travel time of a light pulse depends on the length of an optical fibre. She sends identical pulses into fibres of the same core material but different lengths, and measures the travel time of each pulse. Her results are:

Length L (km)	5.0	10.0	15.0	20.0	25.0
Travel time t (μs)	24.0	49.5	74.0	97.5	122.5

She plots t on the vertical axis against L on the horizontal axis and draws a straight line of best fit. Two points on her line are $(4.0\,\text{km}, 19.6\,\mu\text{s})$ and $(24.0\,\text{km}, 117.6\,\mu\text{s})$. Take the speed of light in a vacuum to be $3.0 \times 10^{8}\,\text{m s}^{-1}$.

a. Identify the independent variable and the dependent variable in this investigation. 1 mark

b. Using the two points on the line of best fit, calculate the gradient of the line. Give your answer in $\mu\text{s km}^{-1}$. 2 marks

c. The gradient of the line equals $1/v$, where v is the speed of the pulse in the fibre's core. (i) Show that v is about $2.0 \times 10^{8}\,\text{m s}^{-1}$. (ii) Determine the refractive index of the core. 2 marks

d. Suggest one reason why her measured times scatter about the line of best fit rather than lying exactly on it. 1 mark

End of Topic 1 Test B

Topic 1 Test B — solutions

Question 1 $m = 0.80\,\text{kg}$; $\Delta T = 96 - 18 = 78\,\text{K}$ (a change of $78\,°\text{C}$ is the same size as a change of $78\,\text{K}$); $c = 4180\,\text{J kg}^{-1}\text{K}^{-1}$.

(a) $Q = m\,c\,\Delta T = 0.80 \times 4180 \times 78 = 260\,832\,\text{J} \approx 2.6 \times 10^5\,\text{J}$, as required. **(1 mark: correct substitution and result.)**

(b) With $P = 2400\,\text{J s}^{-1}$ and all the energy going into the water,

$$t = \frac{Q}{P} = \frac{2.608 \times 10^5}{2400} = 109\,\text{s}\,(\text{about } 1.1 \times 10^2\,\text{s to two significant figures}).$$

(1 mark $t = Q/P$; **1 mark** correct value, $109–110\,\text{s}$.)

(c) Not all of the energy supplied by the element goes into the water: some is transferred to the surroundings and to the body of the dispenser itself, so the water gains energy more slowly than $2400\,\text{J}$ each second. **(1 mark: energy is lost/transferred to the surroundings or the dispenser, so less than the full power heats the water.)**

(d) From $Q = m\,c\,\Delta T$, the temperature rise for a given energy input is $\Delta T = Q/(m\,c)$. With the same element, the energy supplied each second is the same, but the mass has doubled, so the rise in temperature each second is smaller (halved). **(1 mark: same energy per second shared by a larger mass gives a smaller temperature rise per second, via $\Delta T = Q/(m\,c)$.)**

Question 2 $m = 0.050\,\text{kg}$; $L = 3.34 \times 10^5\,\text{J kg}^{-1}$; $c = 4180\,\text{J kg}^{-1}\text{K}^{-1}$.

(a) $Q = m\,L = 0.050 \times 3.34 \times 10^5 = 1.67 \times 10^4\,\text{J}$, as required. **(1 mark: correct substitution and result.)**

(b) $Q = m\,c\,\Delta T = 0.050 \times 4180 \times 20 = 4180\,\text{J}$. (**1 mark** $Q = m\,c\,\Delta T$ with $\Delta T = 20\,\text{K}$; **1 mark** correct value $4180\,\text{J}$.)

(c) Total $= 1.67 \times 10^4 + 4180 = 20\,880\,\text{J} \approx 2.1 \times 10^4\,\text{J}$. **(1 mark: correct total, $20\,900\,\text{J}$ or $2.1 \times 10^4\,\text{J}$.)**

(d) During melting, the energy supplied breaks down the ordered structure of the solid (overcoming the forces holding the molecules in fixed positions) rather than increasing the kinetic energy of the molecules. Since the average kinetic energy does not change, the temperature stays at $0\,°\text{C}$. **(1 mark: energy breaks down the solid structure / separates the particles rather than raising their kinetic energy, so the temperature is unchanged.)**

Question 3 $n_1 = 1.00$ (air), $n_2 = 1.52$, $\theta_1 = 35^\circ$, $\lambda_{\text{air}} = 650\,\text{nm}$.

(a) By Snell's Law, $n_1 \sin\theta_1 = n_2 \sin\theta_2$, so

$$\sin\theta_2 = \frac{1.00 \times \sin 35^\circ}{1.52} = \frac{0.574}{1.52} = 0.377\,,$$

giving $\theta_2 = 22.2^\circ \approx 22^\circ$, as required. **(1 mark: correct use of Snell's Law giving about 22°.)**

(b) $v = \dfrac{c}{n} = \dfrac{3.0 \times 10^8}{1.52} = 1.97 \times 10^8\,\text{m s}^{-1}$. (**1 mark** $v = c/n$; **1 mark** correct value $1.97 \times 10^8\,\text{m s}^{-1}$.)

(c) The wavelength in the medium is $\lambda_{\text{glass}} = \dfrac{\lambda_{\text{air}}}{n} = \dfrac{650}{1.52} = 428\,\text{nm}$. (**1 mark** $\lambda_{\text{glass}} = \lambda_{\text{air}}/n$; **1 mark** correct value $428\,\text{nm}$.)

(d) The emerging ray makes an angle of 35° with the normal — the same as the original angle of incidence. At the second face Snell's Law applies in reverse ($1.52 \sin 22.2^\circ = 1.00 \sin\theta$, giving $\theta = 35^\circ$), so the path of the ray is reversible and the emerging ray is parallel to the incident ray. **(1 mark: emerges at 35°, justified by reversibility / Snell's Law applied back into air.)**

Question 4 $n_{\text{ice}} = 1.31$, $n_{\text{air}} = 1.00$.

(a) $\sin\theta_c = \frac{n_2}{n_1} = \frac{1.00}{1.31} = 0.763$, so $\theta_c = 49.8^\circ$, as required. **(1 mark: correct substitution and result.)**

(b) By Snell's Law, $1.31\sin 35^\circ = 1.00\sin\theta_2$, so

$$\sin\theta_2 = 1.31 \times 0.574 = 0.751,$$

giving $\theta_2 = 48.7^\circ$. **(1 mark** Snell's Law with light going from ice to air; **1 mark** correct value 48.7°.)

(c) The angle of incidence (55°) is greater than the critical angle (49.8°), so the ray undergoes total internal reflection: it reflects back into the ice and no light emerges into the air. **(1 mark: total internal reflection, justified by $55^\circ > 49.8^\circ$.)**

(d) **Smaller.** The critical angle obeys $\sin\theta_c = n_2/n_1 = 1.00/n_1$. A higher refractive index n_1 gives a smaller value of $\sin\theta_c$, and therefore a smaller critical angle. **(1 mark: circles *smaller* AND justifies via $\sin\theta_c = 1/n$ decreasing as n increases. The circled option alone scores 0.)**

Question 5 $T = 660\,°\text{C}$; Wien's Law constant $= 2.9 \times 10^{-3}\,\text{m K}$.

(a) $T = 660 + 273.15 = 933.15\,\text{K} \approx 933\,\text{K}$. **(1 mark: correct conversion, $933\,\text{K}$.)**

(b) $\lambda_{max} = \frac{2.9 \times 10^{-3}}{933} = 3.1 \times 10^{-6}\,\text{m}$. **(1 mark** $\lambda_{max} = 2.9 \times 10^{-3}/T$ with T in kelvin; **1 mark** correct value $3.1 \times 10^{-6}\,\text{m}$.)

(c) At this temperature the aluminium emits mostly infrared radiation. Infrared radiation is absorbed by the skin, where it raises the skin's thermal energy and is sensed as warmth — visible light is not needed for this. **(1 mark: the radiation is mainly infrared, which is absorbed by the skin / transfers energy to it.)**

(d) $T = 1200 + 273.15 = 1473.15\,\text{K} \approx 1473\,\text{K}$, so $\lambda_{max} = \frac{2.9 \times 10^{-3}}{1473} = 2.0 \times 10^{-6}\,\text{m}$. **(1 mark: correct value $2.0 \times 10^{-6}\,\text{m}$.)**

Question 6 $m = 4.0 \times 10^{12}\,\text{kg}$; $Q = 8.0 \times 10^{16}\,\text{J}$; $c_{\text{seawater}} = 4180\,\text{J kg}^{-1}\,\text{K}^{-1}$.

(a) $\Delta T = \frac{Q}{mc} = \frac{8.0 \times 10^{16}}{4.0 \times 10^{12} \times 4180} = \frac{8.0 \times 10^{16}}{1.67 \times 10^{16}} = 4.8\,\text{K}$, as required. **(1 mark: correct substitution and result.)**

(b) For the rock,

$$\Delta T = \frac{Q}{mc} = \frac{8.0 \times 10^{16}}{4.0 \times 10^{12} \times 840} = \frac{8.0 \times 10^{16}}{3.36 \times 10^{15}} = 23.8\,\text{K} \approx 24\,\text{K}.$$

The rock warms about five times more than the seawater for the same energy and the same mass, because rock has a much smaller specific heat capacity than water: $\Delta T = Q/(mc)$ is larger when c is smaller. This is why land surfaces warm more than the ocean surface for the same energy input. **(1 mark** correct value, $23.8\,\text{K}$ or $24\,\text{K}$; **1 mark** links the larger rise to the smaller specific heat capacity of rock.)

(c) Any one of: more evaporation from the warmer ocean, carrying more latent heat into storms and producing more intense rainfall events; marine heatwaves that stress or bleach coral on reefs such as the Great Barrier Reef; expansion of the warmed seawater, contributing to sea-level rise. **(1 mark: any one valid effect of the stored ocean energy on weather or marine ecosystems.)**

(d) If the incoming radiation is unchanged but less radiation escapes to space, the climate system absorbs more energy than it emits. The extra energy is stored in the system, so the mean temperature rises until the outgoing radiation again balances the incoming radiation. **(1 mark: energy in exceeds energy out, so the stored energy — and hence the mean temperature — rises until a new balance is reached.)**

Question 7 $m = 0.50\,\text{kg}$ each; $c_{\text{Al}} = 900\,\text{J kg}^{-1}\text{K}^{-1}$ at $90\,°\text{C}$; $c_{\text{Fe}} = 450\,\text{J kg}^{-1}\text{K}^{-1}$ at $20\,°\text{C}$.

(a) Energy is transferred from the hotter aluminium block ($90\,°\text{C}$) to the cooler iron block ($20\,°\text{C}$). The transfer stops when the two blocks reach the same temperature (thermal equilibrium). **(1 mark: correct direction and the same-temperature/equilibrium condition.)**

(b) **Above** $55\,°\text{C}$**.** Aluminium's specific heat capacity ($900\,\text{J kg}^{-1}\text{K}^{-1}$) is twice iron's ($450\,\text{J kg}^{-1}\text{K}^{-1}$), so each kilogram of aluminium releases twice as much energy for each kelvin it cools as each kilogram of iron absorbs for each kelvin it warms. The same energy transfer therefore produces a smaller temperature change in the aluminium than in the iron: the aluminium cools by less than the iron warms, so the final temperature sits closer to $90\,°\text{C}$ than to $20\,°\text{C}$ — that is, above the midpoint of $55\,°\text{C}$. (A full calculation gives $66.7\,°\text{C}$.) **(1 mark** predicts above $55\,°\text{C}$; **1 mark** justifies via the larger specific heat capacity of aluminium giving it a smaller temperature change for the same energy transfer.)

Question 8 Line of best fit through the points $(4.0\,\text{km}, 19.6\,\mu\text{s})$ and $(24.0\,\text{km}, 117.6\,\mu\text{s})$.

(a) The **independent variable** is the length of the fibre L (deliberately varied by the student); the **dependent variable** is the travel time t (measured for each length). **(1 mark: both variables correctly identified.)**

(b) Using the two points on the line of best fit:

$$\text{gradient} = \frac{\Delta t}{\Delta L} = \frac{117.6 - 19.6}{24.0 - 4.0} = \frac{98.0}{20.0} = 4.90\,\mu\text{s km}^{-1}.$$

(1 mark two well-separated on-line points used (not raw data points); **1 mark** correct gradient $4.90\,\mu\text{s km}^{-1}$, equivalent to $4.90 \times 10^{-9}\,\text{s m}^{-1}$.)

(c)

(i) $\text{gradient} = 1/v$, so

$$v = \frac{1}{\text{gradient}} = \frac{1.0\,\text{km}}{4.90\,\mu\text{s}} = \frac{1000}{4.90 \times 10^{-6}} = 2.04 \times 10^8\,\text{m s}^{-1} \approx 2.0 \times 10^8\,\text{m s}^{-1},$$

as required. (ii) The refractive index of the core is

$$n = \frac{c}{v} = \frac{3.0 \times 10^8}{2.04 \times 10^8} = 1.47.$$

(1 mark shows $v \approx 2.0 \times 10^8\,\text{m s}^{-1}$ from the gradient; **1 mark** correct refractive index 1.47, using the carried-through value of v.)

(d) Any one of: uncertainty in measuring the travel times (limited resolution of the timing instrument); uncertainty in the lengths of the fibres; the pulses spread out as they travel, making the exact arrival time hard to judge. **(1 mark: any one valid source of the scatter, stated as measurement uncertainty or pulse spreading.)**