Unit 12

Answers: Heat

Quick checks

1 b Both drops start at room temperature. The spirit's molecules hold each other less tightly, so they escape faster, and each one that escapes takes energy with it. The heat to replace it comes from your skin, so your skin cools. (Spirit actually boils at a lower temperature than water, about 78 °C, for the same reason.)

2 c Humid air already holds a lot of water vapor, so almost as many water molecules return to the cloth as leave it. Wind, a larger surface and warmth all make evaporation faster.

3 c Both turn a liquid into vapor, both take heat, and both go faster with more heat. Only evaporation happens at any temperature and only at the surface; boiling happens at one temperature, the boiling point, with bubbles all through the liquid.

4 b Every part of a heated solid moves away from every other part, as in an enlarged photograph. The hole is enlarged with the rest. Superficial expansion is an increase in area, and the area of the hole increases too.

5 c A liquid takes the shape of its container, so it has no length or area of its own to measure. It can only expand in volume.

6 b The brass grows more than the iron, and the two are joined along their length. The only way a longer strip and a shorter strip joined together can fit is to curve, with the longer one on the outside. (Cooled, it bends the other way, with the iron on the outside.)

7 b The temperature, which measures the average kinetic energy, doesn't change while ice melts. The heat goes into pulling the molecules free of each other, raising their potential energy. It comes out again when the water freezes: energy is never destroyed.

8 c In melting, the molecules only loosen and still touch and pull on each other. In boiling they are pulled right apart, and the vapor must push back the atmosphere to make room. That takes far more energy for each kilogram.

9 b Heat flows only from hotter to colder, so the final temperature must lie between the two starting temperatures. An answer outside that range always means a mistake, usually writing a fall in temperature the wrong way round.

1 a. **c** Molecules can only escape from the surface, and some are always fast enough to escape, at any temperature. Boiling is the process that happens all through a liquid at one temperature.

1 b. **c** Humid air already holds a lot of water vapor, so many molecules return to the water and evaporation slows. Warmth, wind and a larger surface all speed it up.

1 c. **b** $L = Q/m$: joules divided by kilograms. There is no temperature in it, because the temperature doesn't change while the state changes.

1 d. **c** All the heat taken in goes into freeing the molecules, raising their potential energy, so the temperature stays at the melting point until all of the solid has melted.

1 e. **b** Brass expands about one and a half times as much as iron. Joined along their length, the longer brass must lie on the outside of the curve.

1 f. **b** Superficial (areal) expansion is the increase in area. Linear is length, cubical is volume, and anomalous expansion is water's behavior between 0 °C and 4 °C.

1 g. **b** $Q = mL = 0.5 \times 2{,}260{,}000 = 1{,}130{,}000$ J. (4,520,000 J would be 2 kg; 210,000 J is warming 0.5 kg of water by 100 °C.)

1 h. **b** Energy is conserved, so the heat that leaves the hot body all goes into the cold one. Their temperatures change by different amounts, depending on their masses and specific heat capacities.

2 a. The water in the cloth evaporates. The molecules that escape are the most energetic ones, and the heat to replace their energy (the latent heat of vaporization, about 2,400,000 J for every kilogram) is taken from the forehead. So the skin, and the blood flowing under it, cool down.

2 b. Steel rails expand on hot days (linear expansion). If they were laid end to end with no gaps, they would push on each other with huge forces and bend sideways (buckle), which could derail a train. The gaps give each rail room to get longer.

2 c. Ice must first melt, and each kilogram takes in 336,000 J of latent heat from the drink while melting, without any change in its own temperature. Only then does it warm up like water. Water at 0 °C only takes in heat by warming. So the ice takes far more heat from the drink and cools it more.

2 d. In still air, the water vapor that escapes from the clothes collects around them, the air there becomes humid, and many molecules return to the cloth. Wind carries the vapor away and brings dry air, so fewer molecules return and evaporation is faster.

2 e. When steam touches the skin, it first condenses into water at 100 °C, giving out its latent heat of vaporization, 2,260 J for every gram, and only then cools like boiling water. So the same mass of steam gives the skin about ten times as much heat as boiling water.

2 f. Wires contract in cold weather. If they were hung tight, they would pull hard on the poles in winter and could snap. The sag leaves room for them to get shorter.

2 g. At the boiling point, all the heat supplied is used as latent heat: it pulls the molecules completely away from each other and pushes back the air to make room for the vapor. It raises their potential energy, not their kinetic energy, so the average kinetic energy, and so the temperature, stays the same until all the water has boiled away.

3 i.

Evaporation	Boiling
Happens only at the surface of the liquid.	Happens all through the liquid, with bubbles.
Happens at any temperature.	Happens at a fixed temperature, the boiling point.
Slow and quiet.	Fast and vigorous.
Cools the liquid.	The temperature stays constant while heat is supplied.
Depends on surface area, wind and humidity.	Doesn't depend on them.

3 ii.

Linear expansion	Superficial expansion	Cubical expansion
Increase in length on heating.	Increase in area on heating.	Increase in volume on heating.
Matters for long, thin things.	Matters for flat things.	Matters for blocks, liquids and gases.
Rails, wires, rods.	Metal sheets, roofs, tiles.	A metal ball, mercury in a thermometer, air in a tyre.
Shown by a rod turning a pointer.	Shown by a coin and a hole.	Shown by the ball and ring.

3 iii.

Latent heat of fusion	Latent heat of vaporization
Heat needed to change a solid into a liquid at its melting point.	Heat needed to change a liquid into a vapor at its boiling point.
Given out when the liquid freezes.	Given out when the vapor condenses.
The molecules are only loosened; they still touch.	The molecules are pulled completely apart, and the vapor pushes back the air.
For ice, 336,000 J/kg.	For water, 2,260,000 J/kg, about 6.7 times larger.

3 iv.

Specific heat capacity	Specific latent heat
Heat needed to raise the temperature of 1 kg of a substance by 1 °C.	Heat needed to change the state of 1 kg of a substance at constant temperature.
The temperature changes.	The temperature doesn't change.
Increases the kinetic energy of the molecules.	Increases the potential energy of the molecules.
$Q = ms(T_2 - T_1)$; unit J/(kg °C).	$Q = mL$; unit J/kg.
Water: 4,200 J/(kg °C).	Water: 336,000 J/kg (fusion), 2,260,000 J/kg (vaporization).

4 a. **Evaporation** is the change of a liquid into its vapor from its surface, at any temperature below its boiling point.
The molecules of a liquid move with a range of speeds, and the temperature depends on their average kinetic energy. Only the fastest molecules at the surface have enough energy to break free of the attraction of their neighbors and escape into the air. When the most energetic molecules leave, the average kinetic energy of the molecules left behind falls, so the temperature of the liquid falls. Heat then flows into the liquid from its surroundings, so they cool too. This is the cooling effect of evaporation, seen in sweating and in the clay *matka*.

4 b.
- **Temperature:** the hotter the liquid, the more molecules are fast enough to escape. Clothes dry faster in the sun.
- **Surface area:** molecules escape only from the surface, so a larger surface evaporates faster. Tea cools faster in a saucer; grains are spread thin to dry.
- **Humidity:** in humid air many vapor molecules return to the liquid, so evaporation is slow. Clothes dry slowly in the monsoon.
- **Wind:** moving air carries the vapor away. Clothes dry faster on a windy day; fanning cools a wet face.
- **Nature of the liquid:** liquids with weaker forces between their molecules (spirit, petrol) evaporate faster than water.
- **Air pressure:** lower air pressure lets molecules escape more easily, so evaporation is faster at high altitude.

4 c. The molecules of a solid vibrate about fixed places, held by the forces between them. When the solid is heated, they gain energy and vibrate with bigger swings. The force between two molecules pushes back much more strongly when they are squeezed together than it pulls when they move apart, so with bigger swings each molecule moves much farther outward than inward, and its average distance from its neighbors increases. Every distance between neighboring molecules grows a little, so the solid grows in length, area and volume: it expands. On cooling, the swings get smaller and the solid contracts.

4 d. Any four of:

- **Railway tracks** would buckle in the heat: gaps or expansion joints are left between rails.
- **Bridges** grow and shrink: they rest on rollers at one end and have expansion joints in the road.
- **Overhead wires** would snap in winter: they are hung with a sag.
- **Thick glass** cracks when hot liquid is poured in: cooking glass is made of borosilicate glass, which expands little.
- **Bottles and petrol tanks** filled to the brim overflow or burst in the heat: a space is left at the top.
- **Bimetallic strips** use expansion to switch circuits in thermostats, fire alarms and circuit breakers.
- **Iron tyres** are fitted on cart wheels while hot, and grip tightly as they cool.

4 e. **Latent heat** is the heat absorbed or given out by a substance during a change of state, without any change in its temperature.
The temperature of a substance depends on the average kinetic energy of its molecules. In ice, the molecules are held in fixed places by their attraction for each other. At 0 °C, the heat supplied doesn't make them vibrate any faster; it is used to pull them free of their fixed places against those forces, which increases their potential energy. Since their kinetic energy doesn't change, the temperature stays at 0 °C until all the ice has melted. Only then does the heat raise the molecules' kinetic energy again, and the temperature rises.

4 f. In melting, the molecules are only loosened from their fixed places; in the liquid they are still close together and still attract each other. In boiling, each molecule must be pulled completely away from all its neighbors, so much more work is done against the forces between them. The vapor also takes up about 1,600 times the volume of the water, and pushing back the atmosphere to make that room takes more energy still. So the latent heat of vaporization (2,260,000 J/kg) is about 6.7 times the latent heat of fusion (336,000 J/kg).

4 g. **Heat equation (principle of calorimetry):** when a hot body and a cold body are in contact in an insulated system, the heat lost by the hot body is equal to the heat gained by the cold body, until both are at the same temperature.
For a change of temperature, $Q = ms(T_2 - T_1)$, where m is the mass, s the specific heat capacity and $T_2 - T_1$ the change in temperature.
For a change of state at constant temperature, $Q = mL$, where L is the specific latent heat.

4 h. The graph rises steeply from −20 °C to 0 °C (the **ice warms**), stays flat at 0 °C (the **ice melts**: ice and water together, latent heat of fusion), rises from 0 °C to 100 °C (the **water warms**, less steeply than the ice because water's specific heat capacity is about twice ice's), stays flat at 100 °C for a long time (the **water boils**: water and steam together, latent heat of vaporization), then rises again from 100 °C (the **steam warms**). The boiling stretch is about 6.7 times as long as the melting stretch, because the latent heat of vaporization is about 6.7 times the latent heat of fusion. The HeatingCurve widget in 12.3 draws it to scale.

4 i. A bimetallic strip of two metals that expand by different amounts (such as brass and iron) is placed in the iron's heater circuit, with its tip touching a contact. While the iron is cool, the strip is straight, the contact is closed and current flows through the heater. When the iron reaches the set temperature, the metal that expands more makes the strip bend away from the contact, the circuit is broken and the heater switches off. As the iron cools, the strip straightens, touches the contact again and the heater switches on. Turning the knob moves the contact closer or farther, which sets the temperature at which this happens.

5 a.
$$Q = mL = 0.5 \times 336{,}000 = 168{,}000$$
168,000 J.

5 b.
$$Q = mL = 2 \times 2{,}260{,}000 = 4{,}520{,}000$$
4.52×10^6 J.

5 c. Warm the ice: $Q_1 = 0.5 \times 2{,}100 \times 5 = 5{,}250$
Melt it: $Q_2 = 0.5 \times 336{,}000 = 168{,}000$
$Q = 5{,}250 + 168{,}000 =$ **173,250 J.**

5 d. Warm: $Q_1 = 0.1 \times 4{,}200 \times 80 = 33{,}600$
Boil: $Q_2 = 0.1 \times 2{,}260{,}000 = 226{,}000$
$Q = 33{,}600 + 226{,}000 =$ **259,600 J.**

5 e. Warm the ice: $1 \times 2{,}100 \times 10 = 21{,}000$
Melt it: $1 \times 336{,}000 = 336{,}000$
Warm the water: $1 \times 4{,}200 \times 100 = 420{,}000$
Boil it: $1 \times 2{,}260{,}000 = 2{,}260{,}000$
Total = **3,037,000 J** (about 3.04×10^6 J). Boiling takes $2{,}260{,}000 \div 3{,}037{,}000 =$ **about 74%** of it.

5 f. $Q = mL = 1 \times 336{,}000 = 336{,}000$
$t = \frac{Q}{P} = \frac{336{,}000}{500} = 672$
672 s, about 11.2 minutes.

5 g. Heat lost: $0.2 \times 4{,}200 \times (25 - T) = 840(25 - T)$
Heat gained: $0.04 \times 336{,}000 + 0.04 \times 4{,}200 \times T = 13{,}440 + 168T$
$21{,}000 - 840T = 13{,}440 + 168T$
$7{,}560 = 1{,}008T$, so $T = 7.5$ °.
7.5 °C. (Check: the water could give 21,000 J by cooling to 0 °C, more than the 13,440 J the ice needs to melt, so all the ice does melt.)

5 h. Heat gained by the water: $0.5 \times 4{,}200 \times 60 = 126{,}000$
Heat lost by m kg of steam: $m \times 2{,}260{,}000 + m \times 4{,}200 \times 20 = 2{,}344{,}000\,m$
$2{,}344{,}000\,m = 126{,}000$, so $m = 0.0538$.
About 54 g of steam.

5 i. Heat lost by the water and the calorimeter:
$(0.3 \times 4{,}200 + 0.2 \times 385)(30 - T) = (1{,}260 + 77)(30 - T) = 1{,}337(30 - T)$
Heat gained by the ice: $0.05 \times 336{,}000 + 0.05 \times 4{,}200 \times T = 16{,}800 + 210T$
$40{,}110 - 1{,}337T = 16{,}800 + 210T$
$23{,}310 = 1{,}547T$, so $T = 15.1$ °.
About 15.1 °C.

5 j. $Q = Pt = 1{,}500 \times 600 = 900{,}000$

$$L = \frac{Q}{m} = \frac{900{,}000}{0.39} = 2{,}307{,}692$$

About 2.31×10^6 J/kg. It is larger because not all the kettle's 900,000 J went into boiling water: some heat escaped to the air and warmed the kettle itself. Dividing all of it by the mass boiled away gives too large a value.

5 k. Heat lost by the juice = heat gained by the cold water:
$0.25 \times 4{,}200 \times (30 - T) = 0.05 \times 4{,}200 \times T$
$7.5 - 0.25T = 0.05T$, so $T = 25$ °.
25 °C, against 11.7 °C with ice. The ice takes 16,800 J from the juice just to melt, without warming at all, before its water starts to warm like the cold water. That latent heat does most of the cooling.