

2 THERMAL PROPERTIES



Thermal expansion of solids, liquids and gases

Why do things expand on heating?

With only two or three exceptions, all materials (solids, liquids and gases) expand as they become warmer. In the case of solids, the atoms vibrate more as the temperature goes up. So, even though they stay joined together, they move slightly further apart, and the solid expands a little in all directions.

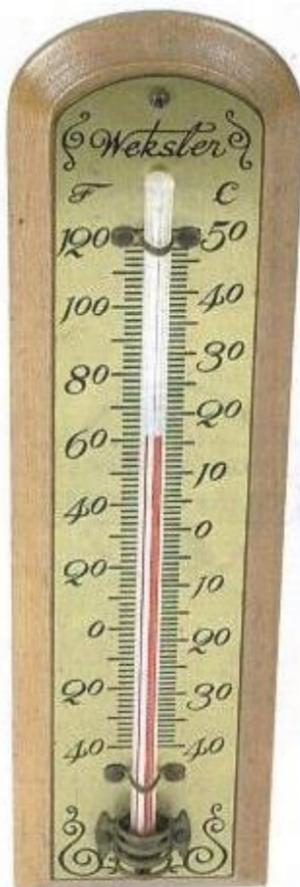
The effect is small, but not trivial. A metre rule that is heated from 0 °C to 100 °C (from the freezing point of water to its boiling point) will get 1 to 2 mm longer depending what material it is made of. Some plastics would not make good metre rules, as they would get up to 10 mm longer.

On a hot day, a 1000 km railway track can try to become more than 300 m longer. In the early days of railways, there was a gap of a few mm every 20 m, to allow the rails to expand. Modern track has no expansion gaps, though as can be seen from this picture the track has to be held extremely firmly to stop it moving. This track is on a curve and so it will try to bend sideways to the left when it gets hot.

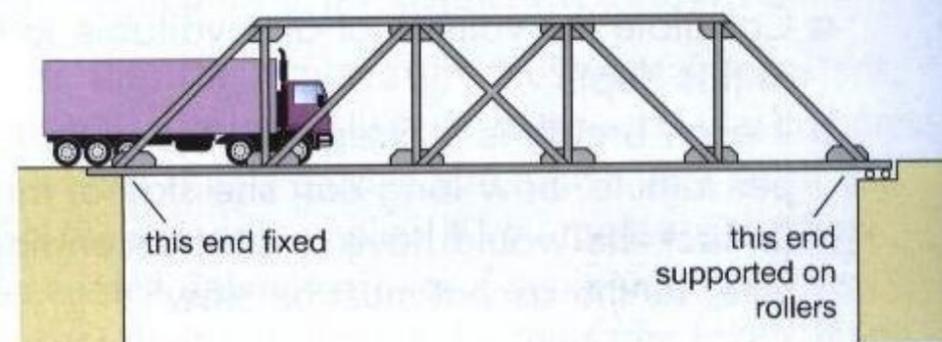


Liquids expand for the same reason. The atoms vibrate as they move around, and get slightly further apart. We talk about the increase in its volume as the temperature increases.

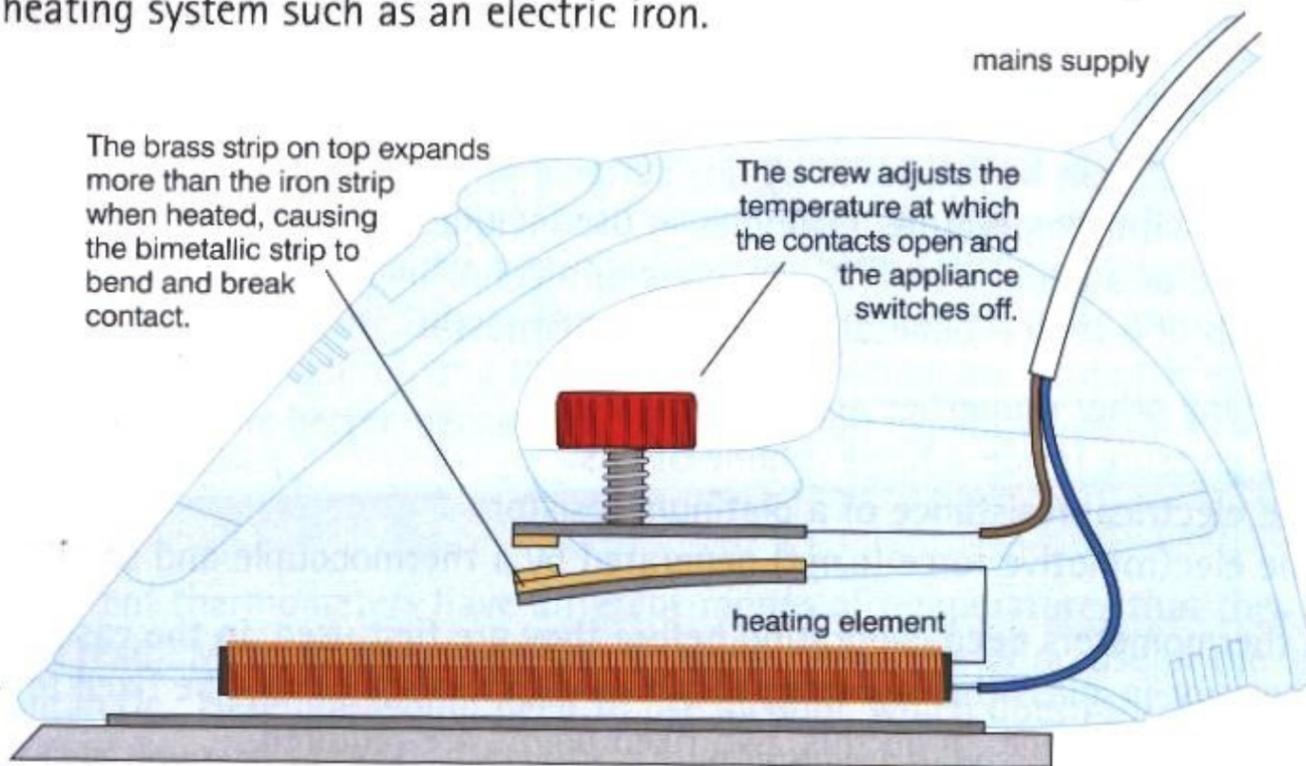
It is very difficult to prevent the thermal expansion of solids and liquids, as the material will create very large forces if it is not allowed to expand. So, for example a large bridge is always built with expansion joints to allow it to get longer on a hot day.



This thermometer has a bulb of coloured alcohol at the base, attached to a very narrow tube that is half-full of alcohol (ethanol). As the alcohol expands and contracts with change in temperature, the length of the column of alcohol goes up and down. The top of the tube is sealed off to prevent the alcohol from evaporating.



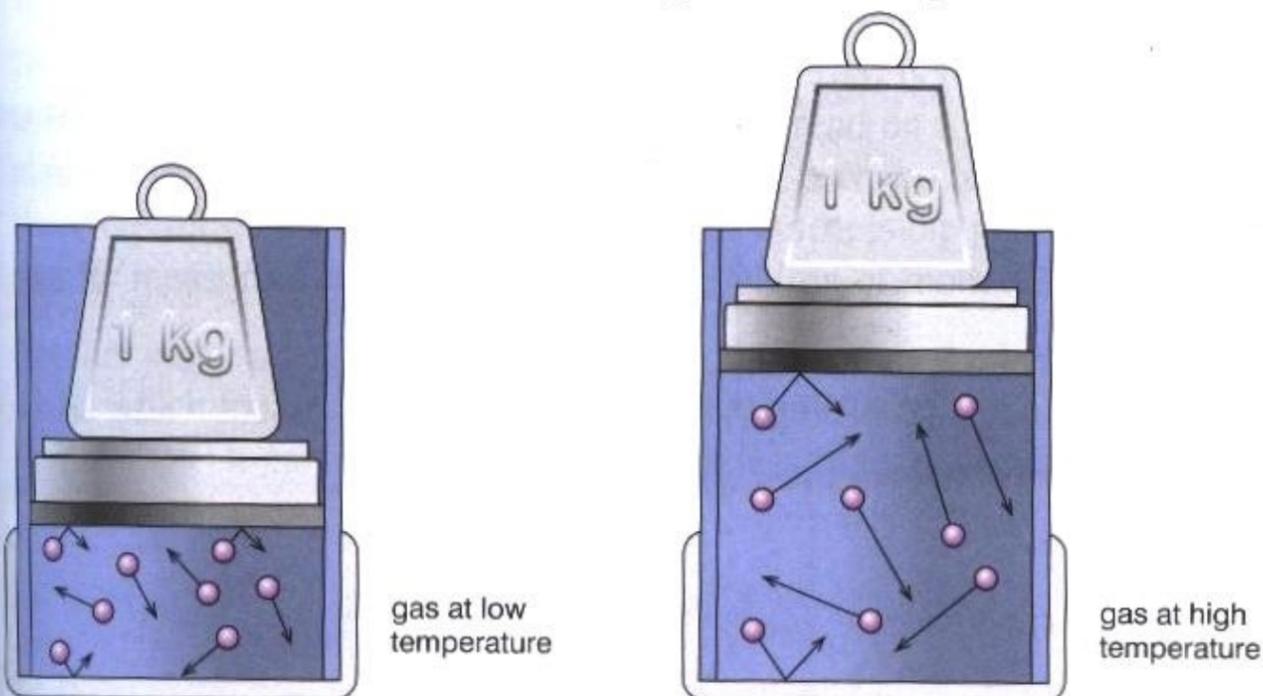
However the effect can also be useful. Metals expand at different rates as their temperatures rise. So if strips of two metals are bound closely together, and are warmed, they bend as one metal expands more than the other. Bimetallic strips like this can be used to control the temperature in a heating system such as an electric iron.



Like other liquids, water contracts as its temperature falls, and its density increases. Unlike other liquids, when its temperature falls below $4\text{ }^{\circ}\text{C}$, water begins to expand again, and becomes less dense. This is called the anomalous expansion of water. The density falls even further as it freezes, because the water molecules form an open crystal structure in the solid state. So ice is less dense than water, while almost all other materials are more dense in the solid state than as a liquid.

Gases behave completely differently. Firstly, we don't have to allow the gas to expand if it gets hotter; if we put it in a sealed container then we can just allow the pressure to increase instead. Secondly, if we do allow a gas to expand, then it will increase in volume much more than solids or liquids do as it gets hotter. Between $0\text{ }^{\circ}\text{C}$ and $100\text{ }^{\circ}\text{C}$ it will expand by a third, so 300 cm^3 of gas will become 400 cm^3 .

In the diagram below the piston compresses the gas with a constant force so that the pressure of the gas is constant. We know from the molecular model that the piston is supported by the collisions of the molecules with the underside of the piston. If the temperature of the gas increases, the pressure starts to increase because the molecules travel faster, and they hit the piston harder. Hence the piston starts to move up. The piston stops moving up when the pressure has dropped to the original value.



The result is that we have heated the gas and allowed its volume to increase at constant pressure. Note that initially the pressure was made up of many molecules hitting the piston slowly. After the gas has heated up and expanded, the same pressure is made of fewer collisions with the piston, but these collisions are from molecules moving faster.

Measurement of temperature

Temperature can be measured by any suitable physical property that changes with temperature. Examples in use include:

- volume of a liquid – mercury-in-glass or alcohol-in-glass thermometer
- length of a solid – bimetallic strip in a thermostat.

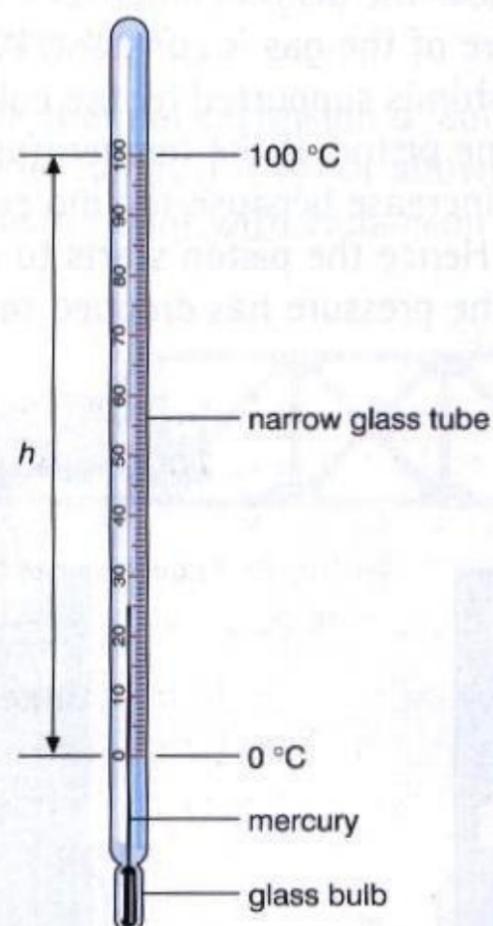
But many other properties are used:

- the pressure inside a fixed volume of gas
- the electrical resistance of a platinum resistor
- the electromotive force (e.m.f) generated by a thermocouple and so on.

All thermometers need calibrating before they are first used. In the case of a mercury-in-glass thermometer, this means that a scale must be fixed to it in the right place. To do this, two fixed points are required.

In science, the Celsius and Kelvin scales are used, though other scales are met elsewhere. The two fixed points used by the Celsius scale, as originally defined, are the melting point of ice, defined as $0\text{ }^{\circ}\text{C}$, and the boiling point of water at standard atmospheric pressure, defined as $100\text{ }^{\circ}\text{C}$. (At lower pressures it boils at a lower temperature.)

To calibrate the mercury-in-glass thermometer at these two fixed points, the thermometer is immersed first in a beaker containing melting ice, and the $0\text{ }^{\circ}\text{C}$ point is marked. It is then immersed in the steam from a boiling kettle and the $100\text{ }^{\circ}\text{C}$ point is marked. Finally the distance between the marks (distance h in the diagram) is divided into 100 equal distances, each corresponding to one degree. The scale can be extended beyond $100\text{ }^{\circ}\text{C}$ to measure higher temperatures, and below $0\text{ }^{\circ}\text{C}$ to measure negative temperatures.



SENSITIVITY, RANGE AND LINEARITY

To measure temperature, we need a thermometer using a property that varies in a regular way over a suitable range of temperatures.

Sensitivity

A thermometer is **sensitive** if it gives a large response to a small change in temperature. This gives you a better chance to detect a small temperature change. To make a liquid-in-glass thermometer sensitive, you need a large bulb (so that the actual increase in volume is large) and a very narrow glass tube (so that the change in volume causes a large movement of the liquid up or down the tube). The use of a liquid that expands more than mercury is also helpful, and this is one way in which an alcohol-in-glass thermometer is better, because alcohol (ethanol) expands five times as much as mercury.

Range

Different thermometers have different ranges of temperatures that they can read. Mercury freezes at $-38\text{ }^{\circ}\text{C}$, and so would be of no use in the Antarctic. Here one would need to use alcohol, which doesn't freeze until it gets down to $-114\text{ }^{\circ}\text{C}$. Likewise, a thermometer filled with alcohol would be no use for measuring temperatures in an oven, as it would break when the temperature reaches $78\text{ }^{\circ}\text{C}$, and the liquid boils.

Linearity

When a thermometer is calibrated (see page 64), it is common to mark the ice point ($0\text{ }^{\circ}\text{C}$) and the steam point ($100\text{ }^{\circ}\text{C}$) and to divide the region in between into 100 equal parts. This assumes that the property doing the measuring changes by the same amount for every unit of temperature change. Such a property means that the thermometer has **linearity**. The expansion of the liquid in a liquid-in-glass thermometer does expand fairly linearly, so we can rely on the values we get from such thermometers.

Accuracy

An **accurate** thermometer is one that gives correct values of temperature. Students sometimes get confused between the terms **sensitive** and **accurate**. However, a sensitive thermometer is not necessarily an accurate one. A sensitive thermometer is one that can detect small changes in temperature, but if the scale has been incorrectly marked, or if the property doing the measuring varies in a noticeably non-linear manner, then the readings from this sensitive thermometer will not be accurate. Try to avoid using the word *accurate* in places where you mean *sensitive*.

THE THERMOCOUPLE

The thermocouple is an electrical thermometer that is the most common type used in industry. It is electrical, and so can be read on a remote dial; it can measure temperatures of over $1000\text{ }^{\circ}\text{C}$; and it is cheap to make. It is ideal therefore for measuring the temperature of inaccessible parts of a jet engine, and for measuring the temperature of a cauldron of molten steel.

Another major advantage of the thermocouple is that it can be made very small, which means that it will respond very quickly to a change in temperature; it can be made to respond in less than 1 second.

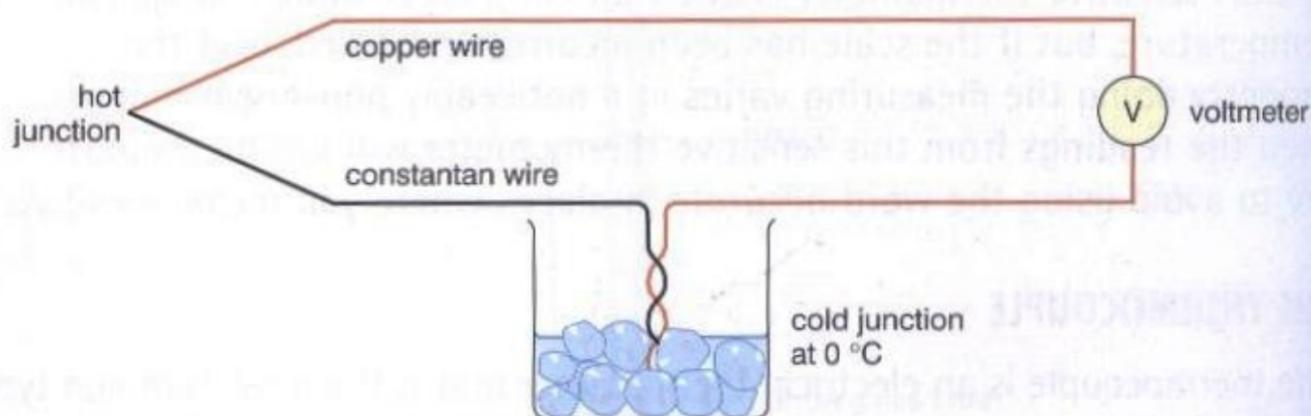
This oil refinery will use hundreds of thermocouples measuring the temperature at critical points, and sending the information to display panels and computers in the central control rooms.



The thermocouple is based on the fact that any two metals in contact generate a tiny voltage (actually a tiny e.m.f.). In order to measure this voltage with a voltmeter, the two metals need to form a circuit, which as in the diagram below, means that there must be two junctions. If the junctions are at the same temperature, there will be no voltage because the two voltages will cancel out, but if the junctions are at different temperatures, the difference between the two voltages can be measured with a voltmeter. One junction is placed at the point where the temperature is to be measured. The other junction is kept at room temperature, or for accurate work it is placed in a beaker of melting ice to take it to $0\text{ }^{\circ}\text{C}$.

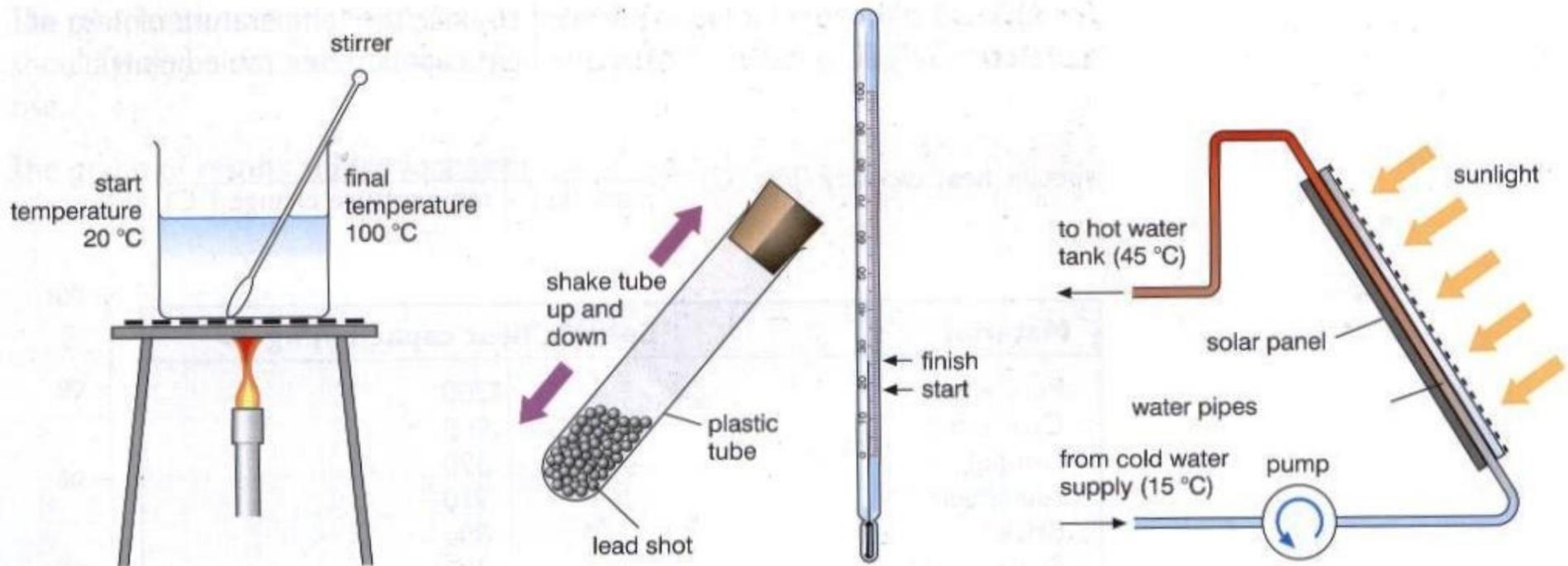
There are tables of data available showing what voltage equals what temperature.

In practice, many different metals are used, but two metals often chosen are copper and an alloy called constantan. The junctions are made by twisting the wires tightly together.



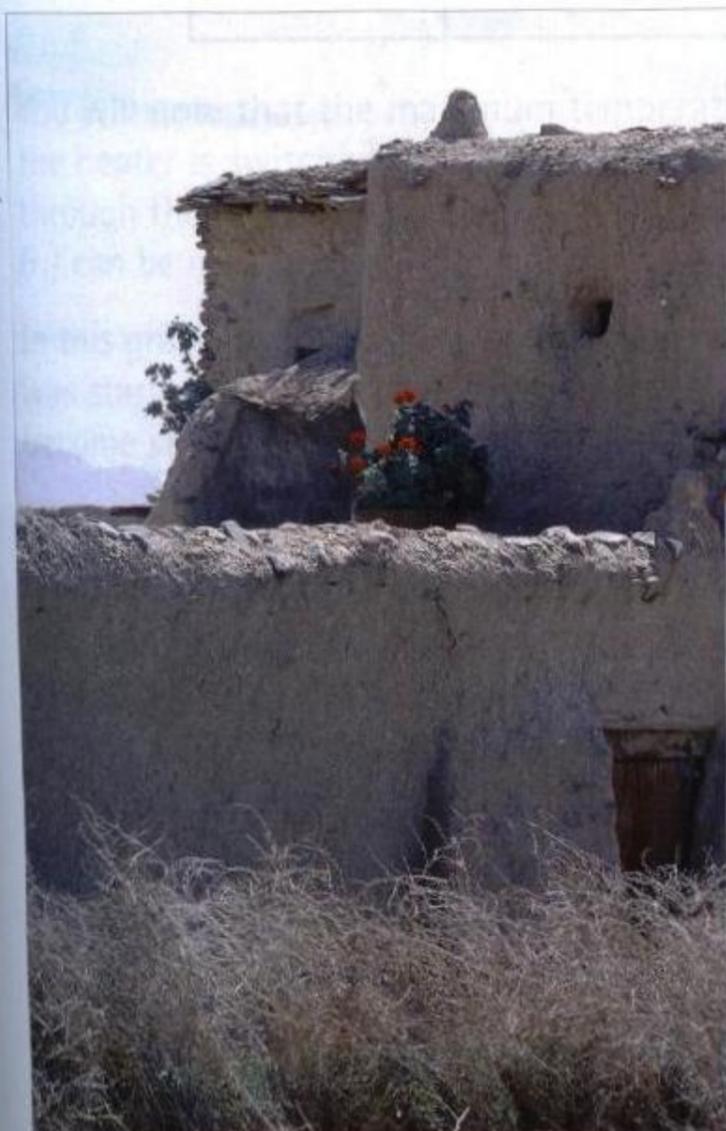
Thermal capacity

You make things hotter by transferring energy to them. When you heat up soup on a cooker ring, heat flows from the hot ring to the cold saucepan and then to the soup. You can also make things hot by rubbing or shaking them (see diagrams right). For example, rubbing your hands together helps to warm them up on a cold day. The kinetic energy of the movement is transferred to internal energy in your hands. A rise in temperature of an object shows that its internal energy has increased.



You need more energy to heat up a large amount of material than a small amount. All materials are made up of tiny particles. The larger the mass of the material, the more particles there are to share the added heat energy, so the smaller the temperature rise. Some materials are harder to heat up than others.

A large object, made of a material that takes a large amount of energy to heat up, will be able to store a great quantity of internal energy. We say that this object has a high thermal capacity. The thermal capacity of an object can be very important. It is the low thermal capacity of the thermocouple that means it can respond very quickly to changes in temperature. On the other hand it is the high thermal capacity of the world's oceans that allows countries near the sea to avoid suffering from extremes of temperature, as the oceans can release large amounts of heat if the land is cooler than the sea, and absorb it if the land is hotter.



This traditional mud house has very thick walls and is ideally suited for hot countries. The high thermal capacity of the walls causes the house to warm up slowly during the day and to cool down slowly at night.

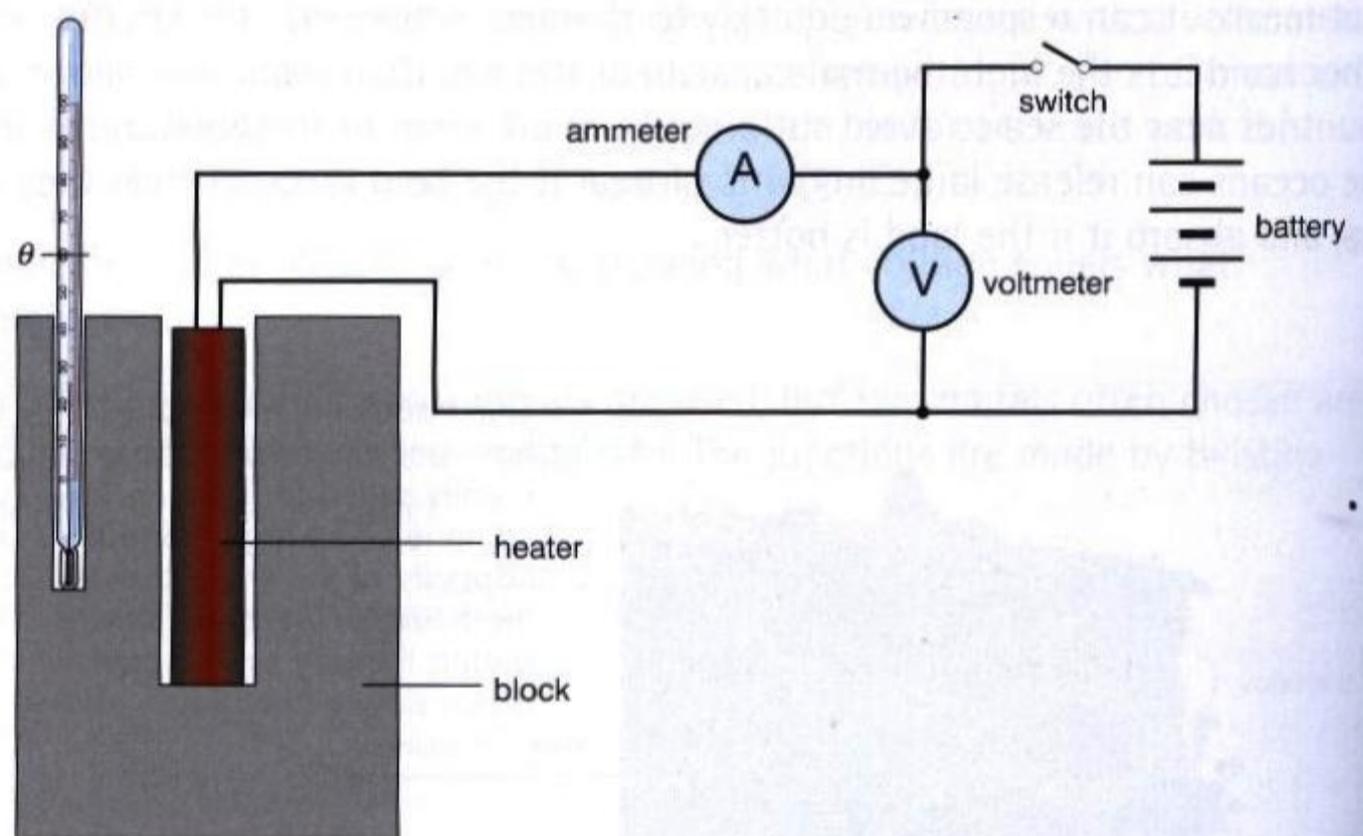
The amount of energy (in joules) needed to raise the temperature of 1 kg of a material by 1 °C is called the specific heat capacity (see table below).

$$\text{specific heat capacity (J/kg } ^\circ\text{C)} = \frac{\text{energy used (J)}}{\text{mass (kg)} \times \text{temperature change (} ^\circ\text{C)}}$$

Material	Specific heat capacity/J/kg °C
Pure water	4200
Coal ash	900
Copper	390
Aluminium	910
Brick	800
Pyrex glass	780
Stainless steel	510
Concrete	3350
Magnetite (Fe ₃ O ₄)	940

Specific heat capacities of different materials.

To measure the specific heat capacity of a solid material, drill two holes into a block of the material, one for a thermometer, and one for an electrical heater.

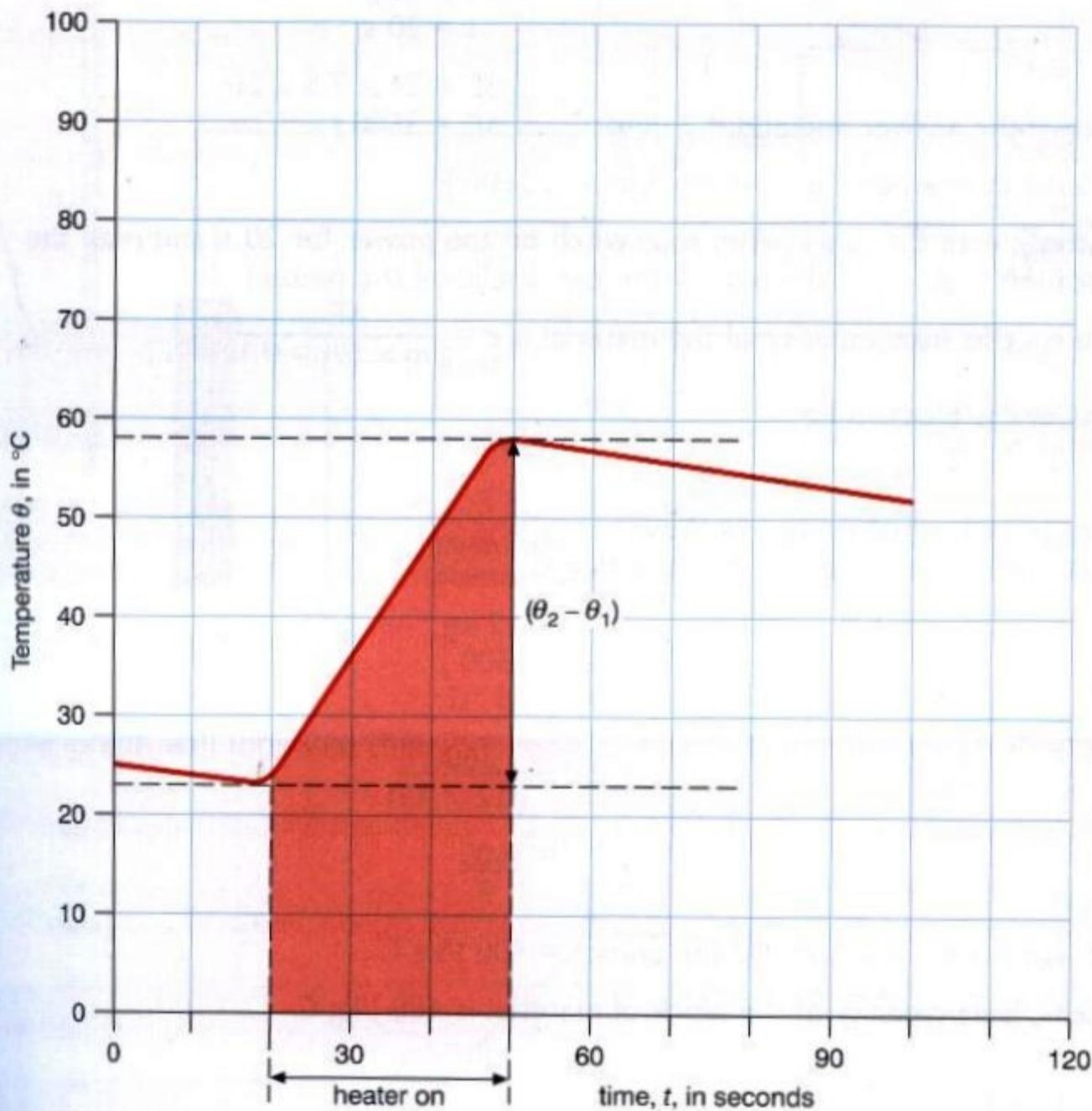


The electrical heater is connected to a low-voltage power supply or a battery. Two meters are required: an ammeter to measure the electrical current in the heater, and a voltmeter to measure the potential difference across the heater. As an alternative a joulemeter can be fitted in place of the ammeter.

The heater should have a start and stop switch, and you need an accurate thermometer to measure the temperature of the block. To make the experiment more accurate the surface of the block can be covered with thermal insulation such as expanded polystyrene to prevent heat loss.

The temperature of the block should be read, perhaps every 10 s. The heater should then be switched on for long enough to get a reasonable temperature rise.

The graph of results should look something like this:



You will note that the maximum temperature is reached many seconds after the heater is switched off. This is because it takes time for the heat to spread through the block. From the graph the maximum temperature change $(\theta_2 - \theta_1)$ can be measured.

In this graph, the block was still cooling down slowly when the experiment was started. It would have been better to wait for the temperature to become steady before starting.

Some of the physics here is covered in more detail in the section on electricity (see pages 112–141).

You can use the results of the experiment to calculate the specific heat capacity as shown on the next page.

The increase in internal energy E of the block is $\Delta E = V \times I \times t$

ΔE = change in internal energy in joules

V = potential difference in volts

I = electrical current in amps

t = time in seconds

Substituting in the values:

$$V = 24 \text{ V}$$

$$I = 7.5 \text{ A}$$

$$t = 20 \text{ s}$$

$$\Delta E = 24 \times 7.5 \times 20$$

$$\Delta E = 3600 \text{ J}$$

Write down the answer and add the units:

The increase in internal energy of the block is 3600 J

(Alternatively, with the joulemeter, you switch on the power for 20 s, and read the number of joules given to the block from the display of the meter.)

Now, the specific heat capacity of the material is $c = \frac{\Delta E}{m \times (\theta_2 - \theta_1)}$

m = mass of the block in kg

$\theta_2 - \theta_1$ = temperature change in $^{\circ}\text{C}$

ΔE = change in internal energy, as above

c = specific heat capacity of the block in $\text{J/kg}^{\circ}\text{C}$

Substituting in the values:

$$m = 0.2 \text{ kg}$$

$$\Delta E = 3600 \text{ J}$$

$$\theta_2 - \theta_1 = 45 \text{ }^{\circ}\text{C}$$

$$c = \frac{3600}{(0.2 \times 45)}$$

$$= \frac{3600}{9}$$

Write down the answer and add the units: = 400 $\text{J/kg}^{\circ}\text{C}$

The specific heat capacity of the block of material is 400 $\text{J/kg}^{\circ}\text{C}$

WORKED EXAMPLE

An electric kettle has a power of 2 kW (2000 J/s). How long will it take to boil 1 l of water starting at 20 $^{\circ}\text{C}$?

The specific heat capacity of water = 4200 $\text{J/kg}^{\circ}\text{C}$.

Write down the equation:

$$c = \frac{\Delta E}{m \times (\theta_2 - \theta_1)}$$

Rearrange the equation:

$$\Delta E = c \times m \times (\theta_2 - \theta_1)$$

Now 1 l of water is 1 kg of water.

The water has to go from 20 $^{\circ}\text{C}$ to 100 $^{\circ}\text{C}$, a rise of 80 $^{\circ}\text{C}$.

Substitute the values:

$$\Delta E = 4200 \times 1 \times 80$$

Work out the answer and write down the units:

$$\Delta E = 336\,000 \text{ J}$$

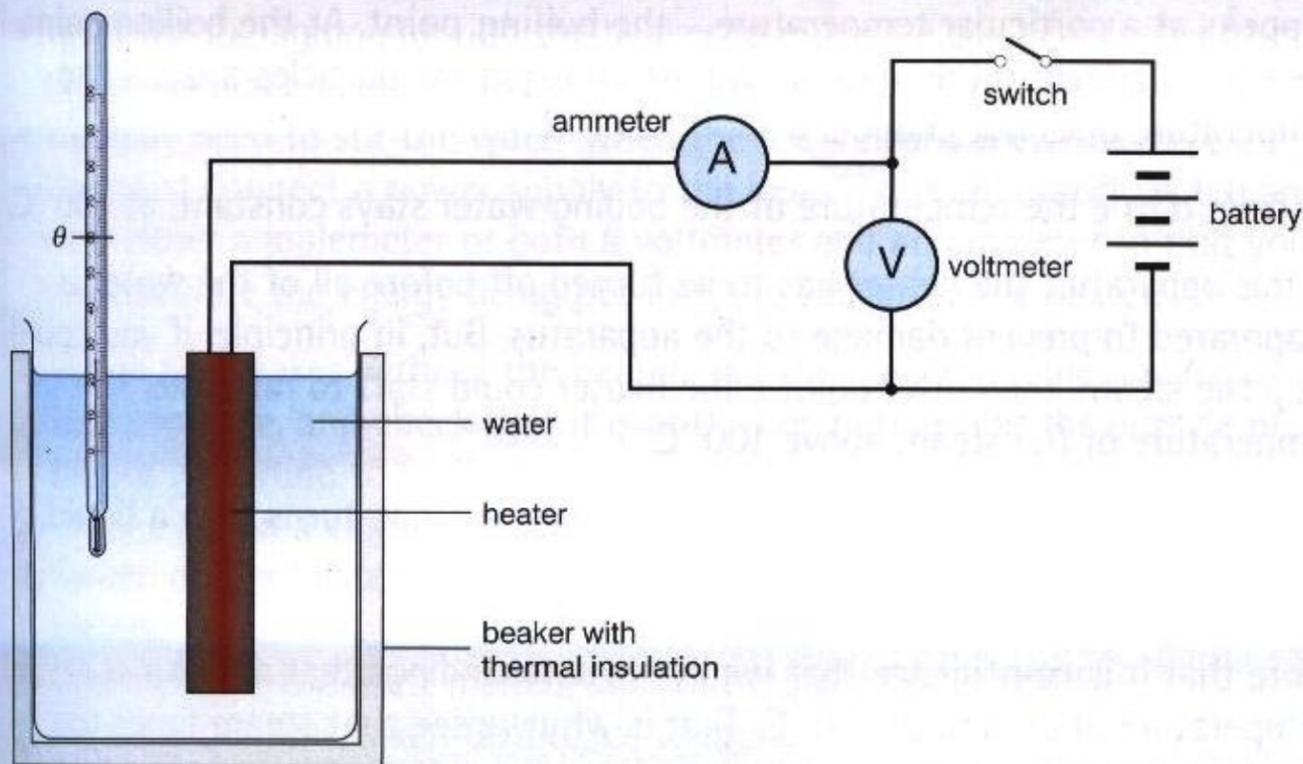
The water requires 336 000 J of heat to boil. The kettle can put 2000 J into the water each second. Therefore it will take $336\,000/2000$ seconds to boil = 168 s. Just under three minutes.

What about cooling down?

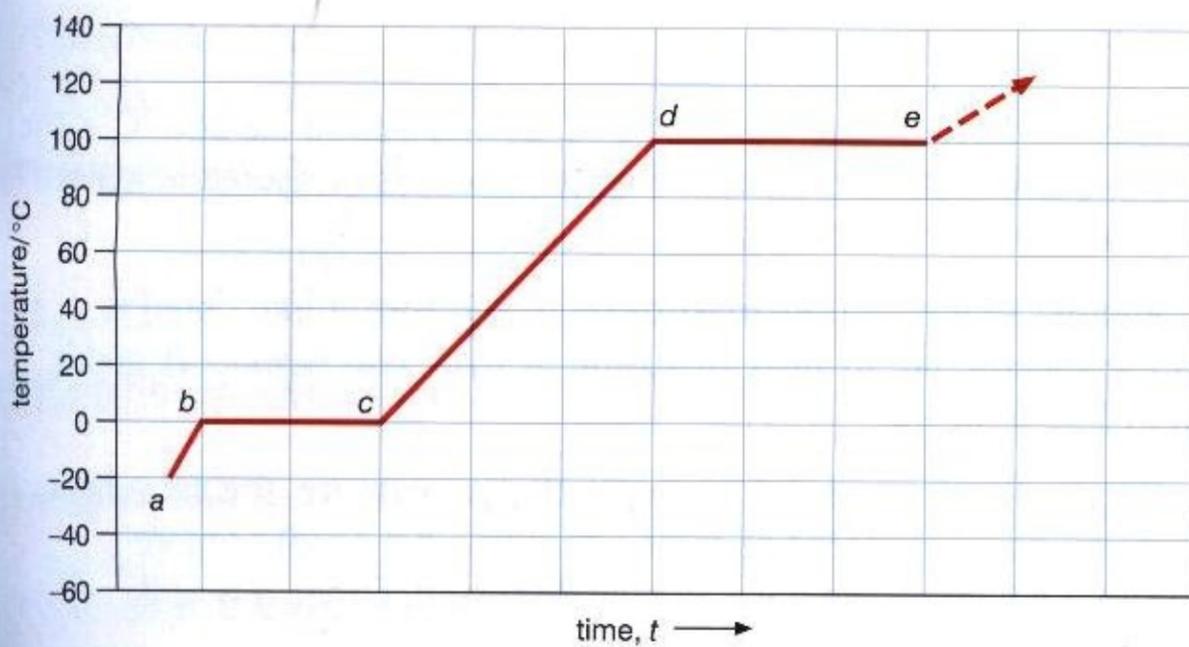
When the energy is being transferred away from an object, that is it is cooling down, the formula is used in exactly the same way. This time, instead of calculating the energy transferred to the object, the answer refers to the energy transferred away from it.

Melting and boiling

If you take a beaker that contains pieces of extremely cold ice and warm it up with an electrical heater, you can measure the temperature of the ice (and then water) every few seconds, and plot a graph of the temperature of the ice and water as the contents of the beaker warm up.



The graph will look like this:



From point a to point b the ice is warming up, but it is not starting to melt. (This is similar to the behaviour of ice-cream after you take it out of the freezer, as it slowly takes heat out of the air and warms up without melting to begin with.)

Along line a - b , the heater is increasing the internal energy of the ice, and this is shown by the increase in temperature.

From point b to point c , the beaker contains a mixture of ice and water. The temperature stays constant, at 0 °C, and the heater melts the ice.

This makes a very important point. The energy from the heater has gone into the beaker, and so the internal energy of the contents of the beaker has gone up, but the temperature has not gone up. The energy has been used to melt the ice, and it is stored in the water. (In fact you have to put in almost as much energy to melt the ice as you will do, in the next step, to raise the water from freezing point to boiling point.) The same latent energy must



be removed again to turn the water back into ice. (The word 'latent' means 'hidden'.) This is why it takes a freezer so long to freeze water.

From point *c* to point *d*, the input of heat energy into the water raises its temperature from 0 °C to 100 °C, and at point *d* the water boils.

In boiling, every particle in the liquid has enough energy to break away. This happens at a particular temperature – the **boiling point**. At the boiling point, the energy added to the material will be breaking the particles apart – the temperature does not change.

So from *d* to *e* the temperature of the boiling water stays constant, at 100 °C.

In this apparatus, the heater has to be turned off before all of the water is evaporated to prevent damage to the apparatus. But, in principle, if you could keep the steam, then after point *e* the heater could start to raise the temperature of the steam above 100 °C.

Condensation, the reverse of boiling, is where the gas turns into a liquid, and solidification is the reverse of melting.

Note that it is coincidence that we live in surroundings that are at a temperature of around 20–30 °C. That is why we see that steam tends to condense to water, and ice tends to melt to water. If we lived on a really hot planet like Mercury, then all water would tend to turn to steam. And on a cold planet, it would all tend to turn to ice.

LATENT HEAT

The extra energy stored by the water at 0 °C, as opposed to ice at 0 °C, is the **latent heat of fusion** (symbol *L*) of the water, and it is measured in joules. ('Fusion' is another word for solidifying.)

The heat required to melt a **unit mass** of solid, and turn it into liquid is known as the **specific latent heat of fusion** of that solid (symbol *l*), and is measured in J/kg or in J/g.

When you heat a liquid or a solid, and raise its temperature, the extra heat energy that you put in is stored as more vibration (in a solid) or more movement (in a liquid), as we have already discussed. Either way, it is definitely stored as a form of kinetic energy.

But while the solid is melting, the extra heat energy is used to weaken the bonds between the molecules and move the atoms slightly further apart against the attraction of the bonds. This energy is stored as potential energy, as in a stretched spring. So the internal energy of a liquid, or a gas, consists of some energy that is kinetic and some that is potential.

We use the term '**latent heat of vaporisation**' to describe the energy that is needed to change the state from liquid to gas at the boiling point of the liquid.

The latent heat of vaporisation is the additional potential energy carried by the gas, stored in the broken bonds between the molecules.

This extra energy is carried by the steam, and is what makes steam so dangerous.

The heat required to turn a **unit mass** of liquid into gas is known as the **specific latent heat of vaporisation** (symbol *l*), and is measured in J/kg or in J/g.

AN EXPERIMENT TO MEASURE THE SPECIFIC LATENT HEAT OF FUSION OF ICE

To use the apparatus in the illustration (right), you must take a number of practical precautions both for safety and to make the experiment more accurate.

- You must fix the beaker of water so that the water cannot be spilled.
- You must fix lagging around the beaker to minimise the heat losses from the beaker. (See pages 77–81.)
- You may need to stir the water when the ice is nearly melted.
- You must connect a power supply to the heater with an on/off switch and with either a joulemeter or both a voltmeter and an ammeter so that you can calculate the energy being put into the beaker by the heater.



Using a heater to measure the latent heat of fusion for ice.

1. Weigh the beaker without the heater, and then assemble the apparatus.
2. Take some ice, and check that it is at $0\text{ }^{\circ}\text{C}$ by noting that the outside of the ice is starting to melt.
3. Dry the ice on a cloth or tissues and put a suitable amount into the beaker.
4. Switch on the heater, and start a stopwatch. Note the readings on the meters.
5. When the ice is almost melted, start stirring the water gently.
6. Measure the time taken for the ice to melt.
7. Weigh the beaker plus the water.

WORKED EXAMPLE

$$\text{Mass of beaker} = 100\text{ g}$$

$$\text{Mass of beaker} + \text{water} = 237\text{ g}$$

$$\begin{aligned} \text{Mass of water} &= 237 - 100 \\ &= 137\text{ g} \\ &= 0.137\text{ kg} \end{aligned}$$

The initial mass of ice was the same.

$$\begin{aligned} \text{Time for ice to melt} &= 5\text{ min } 20\text{ s} \\ &= 320\text{ s} \end{aligned}$$

$$\text{Energy } E \text{ put into the ice} = V \times I \times t$$

E = change in internal energy in joules

V = potential difference in volts

I = electrical current in amps

t = time in seconds

$$\text{Substitute the values: } V = 24\text{ V}$$

$$I = 6\text{ A}$$

$$t = 320\text{ s}$$

$$E = 24 \times 6 \times 320$$

$$\begin{aligned} \text{Work out the answer and write down the unit:} \\ &= 46\,080\text{ J} \end{aligned}$$

$$\text{Specific latent heat of fusion } l = \frac{E}{m}$$

E = change in internal energy in joules

m = mass in kg

Substitute the values:

$$l = \frac{46\,080}{0.137}$$

$$\begin{aligned} \text{Work out the answer and write down the unit:} \\ &= 336\,350\text{ J kg} \\ &= 336\text{ kJ/kg} \end{aligned}$$

This idealised experiment gives approximately the value that is generally accepted. If you try the same experiment you are likely to get a different reading, as it is all too easy to get a large error due to heat loss from the beaker and other factors that are hard to eliminate.

An alternative method is set as one of the questions at the end of this chapter (see page 76).

TO MEASURE THE SPECIFIC LATENT HEAT OF VAPORISATION OF WATER

1. Use the same apparatus as in the experiment on the previous page. Put sufficient water in the beaker and weigh the beaker plus water.
2. Put the heater into the beaker, and switch on. Check the readings on the meters.
3. When the water boils, start the stopwatch and let the water boil for a few minutes.
4. Let the beaker cool to a safe temperature and weigh it again.

WORKED EXAMPLE

Mass of beaker + water before the experiment = 237 g

Mass of beaker + water after the experiment = 218 g

Mass of water boiled off = (237 – 218)
= 19 g
= 0.019 kg

Water boiled for 5 minutes = 300 s

Energy E put into the boiling water $= V \times I \times t$

Substitute the values: $E = 24 \times 6 \times 300$

Work out the answer and write down the unit: $E = 43\,200 \text{ J}$

Specific latent heat of evaporation: $I = \frac{E}{m}$

Substitute the values: $I = \frac{43200}{0.019}$

Work out the answer and write down the unit: $I = 2\,273\,684 \text{ J/kg}$
 $I = 2273 \text{ kJ/kg}$

A* EXTRA

- The properties of water are very strange. Not only does it require a great deal of heat to change its temperature, it is also unique in that it expands as it freezes. This makes ice less dense than liquid water, so ice floats (as the *Titanic* found out). This has been vital to evolution – life can survive at the bottom of ponds, where the water stays liquid, even when the surface has frozen.

Water is strange

Water has a surprisingly high specific heat capacity. This means that a lot of energy has to be transferred to change the temperature of water significantly. This is important in several ways.

- Water makes an excellent coolant for machines such as car engines. It can remove a lot of energy from the machine without boiling.
- The temperature of the seas and oceans remains fairly steady, as huge energy transfers are needed to significantly change the temperature of that much water. This helps keep the planet at a fairly even temperature, which is good for living things.

Note: A lot of confusion is caused by the different uses of the word 'steam'. In science, the word should be used to mean the invisible vapour that water turns into when it boils. This vapour is at 100 °C and is extremely dangerous to the human skin due to the energy that it contains. As soon as steam cools a little, it turns into the white clouds that we see when the kettle boils. These white clouds are made of small droplets of water, and are much safer than true steam. (It is true that in casual conversation we all call these clouds 'steam', but they are not steam in the scientific meaning.)



In this photograph, you can see that the steam coming out of the chimney is almost invisible. As the steam travels up, its temperature drops and it turns into clouds of water droplets.

The words 'evaporation' and 'boiling' also cause confusion. When a liquid evaporates it loses molecules from its surface. This will occur to an open container of water at any temperature; the water left in a cup will eventually evaporate. The molecules of water in the cup will have a range of energies. And even at room temperature the molecules with the highest energies will leave the surface.

A liquid boils when its temperature reaches boiling point. At this temperature the molecules have enough energy to leave the liquid in large quantities even inside the liquid. These molecules collect to form large bubbles of vapour and cause the liquid to move violently.

Many solids evaporate slowly, which is why you can smell dry food, coffee beans, for example. Some people even claim to be able to smell a sheet of zinc metal, even though the evaporation rate is incredibly low.

Note that the boiling point depends strongly on air pressure. People who live in high mountains have difficulty cooking food or making hot drinks, as the water may boil at $80\text{ }^{\circ}\text{C}$ or lower, depending on the altitude. Astronauts wear spacesuits to prevent their blood from boiling at $37\text{ }^{\circ}\text{C}$.

REVIEW QUESTIONS

- Q1** Explain the following observations:
- A steel ruler is often marked 'Use at $20\text{ }^{\circ}\text{C}$ '.
 - If you pour boiling water into a drinking glass, the glass may crack.
 - If you pour a very cold drink into a drinking glass, the outside of the glass will become wet.
 - If you leave frozen food in a freezer for several weeks without covering it, the outside surface of the food will suffer from what is called 'freezer burn' and will look dry and unpleasant.