2.3 Transfer of thermal energy

2.3.1 Conduction

FOCUS POINTS

★ Know how to investigate whether a material is a good or poor conductor of thermal energy.

★ Use atomic or molecular lattice vibrations and the movement of free (delocalised) electrons in metallic conductors to describe thermal conduction in solids.

★ Describe, in terms of particles, why thermal conduction is poor in gases and most liquids.

★ Understand that thermal conductors conduct thermal energy better than thermal insulators and some solids are better thermal conductors than others.

Heat from a stove is quickly transferred to all parts of a metal saucepan; metals are good conductors of heat. A poor thermal conductor, such as plastic, is often used for the handle of a saucepan to keep it cool. In this topic you will encounter experiments that demonstrate the properties of both good and bad thermal conductors.

Thermal energy can be transferred in various ways. In a solid an increase in temperature produces stronger local vibrations of the particles that are transferred to their neighbours and thermal energy is transferred progressively through the material. This is a slow process but is the main way of transferring energy in poor conductors. In good conductors, the main way of transferring thermal energy is by free electrons in the conductor; these can transfer energy from particle to particle very quickly.

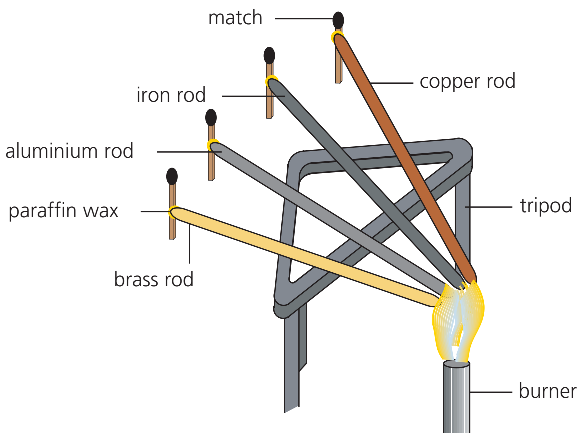
A knowledge of how heat travels is needed to keep a building or a house at a comfortable temperature in winter and in summer, if it is to be done economically and efficiently.

Conduction

The handle of a metal spoon held in a hot drink soon gets warm. Heat passes along the spoon by **conduction**.

Conduction is the flow of thermal energy (heat) through matter from places of higher temperature to places of lower temperature without movement of the matter as a whole.

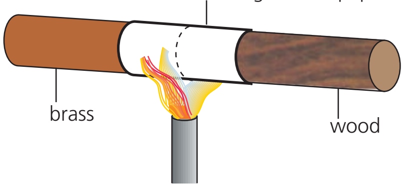
A simple demonstration of the different conducting powers of various metals is shown in Figure 2.3.1. A match is fixed to one end of each rod using a little melted wax. The other ends of the rods are heated by a burner. When the temperatures of the far ends reach the melting temperature of wax, the matches drop off. The match on copper falls first, showing it is the best **conductor**, followed by aluminium, brass and then iron.



▲ **Figure 2.3.1** Comparing conducting powers

Thermal energy is conducted faster through a rod if it has a large cross-sectional area, is short and has a large temperature difference between its ends.

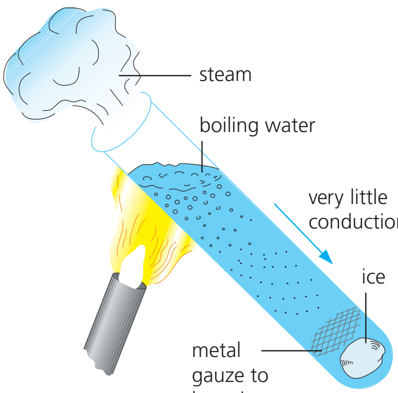
Most metals are good conductors of thermal energy; materials such as wood, glass, cork, plastics and fabrics are thermal **insulators** (poor conductors). The arrangement in Figure 2.3.2 can be used to show the difference between brass and wood. If the rod is passed through a flame several times, the paper over the wood scorches but not the paper over the brass. The brass conducts the heat away from the paper quickly, preventing the paper from reaching the temperature at which it burns. The wood conducts the thermal energy away only very slowly.



▲ **Figure 2.3.2** The paper over the brass does not burn.

Metal objects below body temperature *feel* colder than those made of bad conductors – even if all the objects are at exactly the same temperature – because they carry thermal energy away faster from the hand.

Liquids and gases also conduct thermal energy but only very slowly. Water is a very poor thermal conductor, as shown in Figure 2.3.3. The water at the top of the tube can be boiled before the ice at the bottom melts.



▲ **Figure 2.3.3** Water is a poor conductor of thermal energy.

Conduction and the particle model

Two processes occur in metals. Metals have a large number of 'free' (delocalised) electrons (Topic 4.2.2) which move about within the metal. When one part of a metal is heated, the electrons there move faster (their kinetic energy increases) and move further. As a result, they are able to interact with particles in cooler parts, so passing on their energy and raising the temperature of these parts. This process occurs quickly.

The second process is much slower. The atoms or molecules at the hot part make colder neighbouring particles vibrate more vigorously. These atomic or molecular lattice vibrations are less important in metals, but are the only way conduction can occur in non-metals since these do not have free electrons; hence non-metals are poor conductors of heat and are good insulators.

There are many solids which have fewer free electrons available to transfer thermal energy than metals do and so are less good thermal conductors than metals but better thermal conductors than insulators. For example, the semiconductors used in electronic circuits can have a range of thermal conductivities between those of metals and insulators.

Liquids and gases are generally less dense than solids and their particles are further apart. They do not have a regularly ordered particle structure, so it is difficult to set up lattice vibrations, and they do not usually have free electrons. They are therefore less good thermal conductors than solids.

Test yourself

1 Explain what is meant by thermal conduction.
2 Why is thermal conduction poor in gases and most liquids?

2.3.2 Convection

FOCUS POINTS

★ Know that thermal energy transfer in liquids and gases usually occurs by convection.
★ Use density changes to explain convection in liquids and gases.
★ Describe some experiments to show convection.

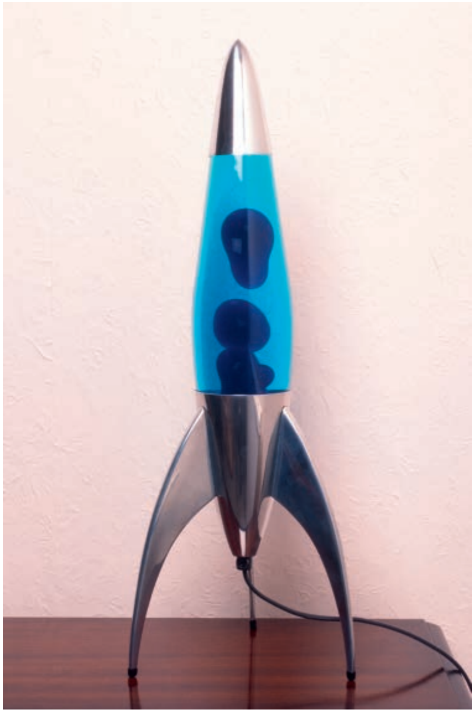
You may have a convector heater in your home which helps to keep you warm in winter. In convection, heat is transferred by the motion of matter and it is an important method for transferring thermal energy in liquids and gases. When the temperature of a fluid increases, thermal expansion reduces its density and the warmer, less dense parts of the fluid tend to rise, while cooler, denser parts will sink. The combination sets up fluid flows known as convection currents that transfer thermal energy from places of high temperature to those of lower temperature by motion of the fluid itself. In the case of a convector heater, convection currents are set up in the air in the room.

Convection in liquids

Convection is the usual method by which thermal energy (heat) travels through fluids such as liquids and gases. It can be shown in water by dropping a few crystals of potassium permanganate down a tube to the bottom of a beaker or flask of water. When the tube is removed and the beaker heated just below the crystals by a *small* flame (Figure 2.3.4a), purple streaks of water rise upwards and fan outwards.

▲ **Figure 2.3.4a** Convection currents shown by potassium permanganate in water.

Streams of warm, moving fluids are called **convection currents.** They arise when a fluid is heated because it expands, becomes less dense and is forced upwards by surrounding cooler, denser fluid which moves under it. We say 'hot water (or hot air) rises'. Warm fluid behaves like a cork released under water: being less dense it bobs up. Lava lamps (Figure 2.3.4b) use this principle.



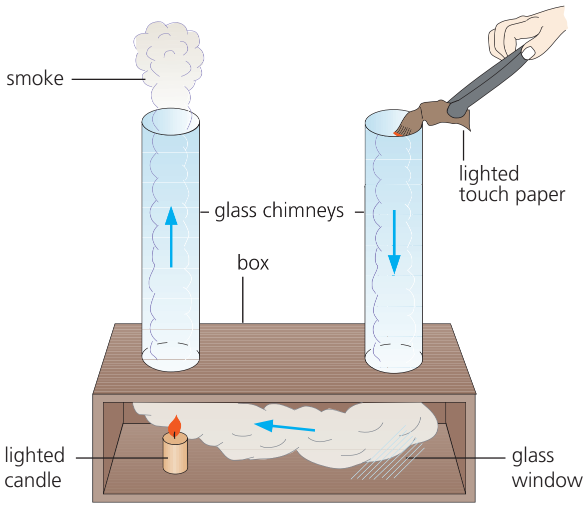
▲ **Figure 2.3.4b** Lava lamps make use of convection.

Convection is the flow of thermal energy through a fluid from places of higher temperature to places of lower temperature by movement of the fluid itself.

Convection in air

Black marks often appear on the wall or ceiling above a lamp or a radiator. They are caused by dust being carried upwards in air convection currents produced by the hot lamp or radiator.

A laboratory demonstration of convection currents in air can be given using the apparatus of Figure 2.3.5. The direction of the convection current created by the candle is made visible by the smoke from the touch paper (made by soaking brown paper in strong potassium nitrate solution and drying it).



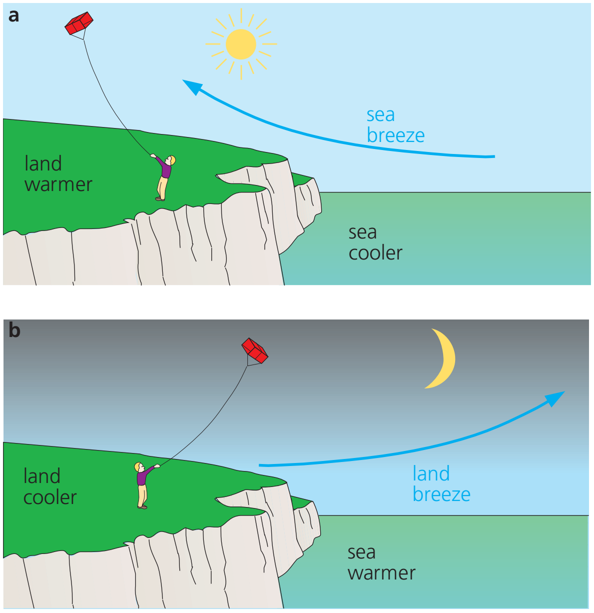
▲ **Figure 2.3.5** Demonstrating convection in air.

Natural convection currents

Coastal breezes

During the day the temperature of the land increases more quickly than that of the sea (because the specific heat capacity of the land is much smaller; see Topic 2.2.2). The hot air above the land rises and is replaced by colder air from the sea. A breeze from the sea results (Figure 2.3.6a).

At night the opposite happens. The sea has more thermal energy to transfer and cools more slowly. The air above the sea is warmer than that over the land and a breeze blows from the land (Figure 2.3.6b).



▲ **Figure 2.3.6** Coastal breezes are due to convection: **a** day; **b** night.

Gliding

Gliders, including hang-gliders (Figure 2.3.7), are carried along on hot air currents, called thermals.

▲ **Figure 2.3.7** Once airborne, a hang-glider pilot can stay aloft for several hours by flying from one thermal to another.

Test yourself

3 Explain the advantage of placing an electric immersion heater in a tank of water
 a near the top
 b near the bottom.
4 Why does hot air rise?

2.3.3 Radiation

FOCUS POINTS

- ★ Understand that thermal radiation is infrared radiation that does not require a transmission medium and that this radiation is emitted by all objects.
- ★ Describe the effects of surface colour and texture on the emission, absorption and reflection of thermal radiation.

- ★ Understand the factors which affect the amount of radiation emitted by an object.
- ★ Understand that a balance between rate of energy received and energy transferred must be achieved for an object to maintain a constant temperature.
- ★ Know that factors controlling the balance between incoming radiation and radiation emitted from the Earth's surface affect the temperature of the Earth.
- ★ Describe experiments to distinguish between good and bad absorbers and emitters of infrared radiation.
- ★ Know that surface temperature and surface area of an object affect the rate of emission of radiation.

On a sunny day it is pleasant to feel the warmth of the radiation reaching you from the Sun. Radiation is the third way of transferring thermal energy from one place to another without the need of a transmission medium. On reaching Earth, the Sun's rays are partly reflected, absorbed or transmitted by objects. Shiny white surfaces are good reflectors of radiation but dull black surfaces are good absorbers. The efficiency of emission and absorption of radiation depends on the nature of the surface of the material.

The rate of radiation emission depends on the temperature of the object. The temperature of the Earth is controlled by the balance between radiation absorbed and emitted.

Radiation is a third way in which thermal energy can travel but, whereas conduction and convection both need matter to be present, radiation can occur in a vacuum; particles of matter are not involved. Radiation is the way thermal energy reaches us from the Sun.

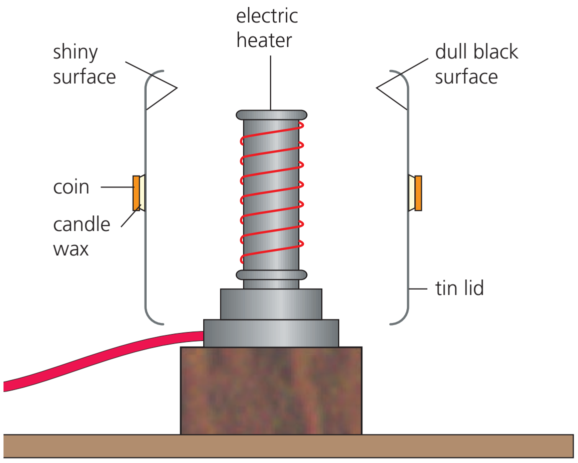
Radiation has all the properties of electromagnetic waves (Topic 3.3), and travels with the speed of light. Thermal radiation is **infrared radiation** and all objects emit this radiation. When it falls on an object, it is partly reflected, partly transmitted and partly absorbed: the absorbed radiation raises the temperature of the object.

Buildings in hot countries are often painted white (Figure 2.3.8). This is because white surfaces are good reflectors of radiation and so help to keep the houses cool.

▲ **Figure 2.3.8** White painted buildings.

Good and bad absorbers

Some surfaces absorb radiation better than others, as may be shown using the apparatus in Figure 2.3.9. The inside surface of one lid is shiny and of the other dull black. The coins are stuck on the outside of each lid with candle wax. If the heater is midway between the lids, they each receive the same amount of radiation. After a few minutes the wax on the black lid melts and the coin falls off. The shiny lid stays cool and the wax unmelted.



▲ **Figure 2.3.9** Comparing absorbers of radiation

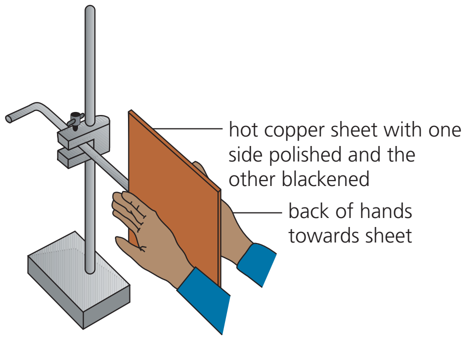
Dull black surfaces are *better* **absorbers** of radiation than *white shiny surfaces*, which are instead good *reflectors* of radiation. Reflectors on electric fires are made of polished metal because of its good reflecting properties.

Good and bad emitters

Some surfaces also emit radiation better than others when they are hot. If you hold the backs of your hands on either side of a hot copper sheet that has one side polished and the other side blackened (Figure 2.3.10), it will be found that your hands feel warmer near the dull black surface. The dull black surface is a *better* **emitter** *of radiation* than the shiny one.

The cooling fins on the heat exchangers at the back of a refrigerator are painted black so are good emitters of radiation and they transfer thermal energy more quickly. By contrast, saucepans that are polished are poor emitters and keep their heat longer.

In general, surfaces that are good absorbers of radiation are good emitters when hot.



▲ **Figure 2.3.10** Comparing emitters of radiation

Temperature and rate of emission of radiation

Radiation is emitted by all bodies above absolute zero and consists mostly of infrared radiation, but light and ultraviolet are also present if the body is very hot (e.g. the Sun). For an object to maintain a constant temperature, energy must transfer away from the object at the same rate that the object receives energy. If the average energy radiated is less than that absorbed, the temperature of the object will rise. If the average energy radiated is more than that absorbed, the temperature of the object will fall.

The greenhouse effect

The warmth from the Sun is not cut off by a sheet of glass but the warmth from a red-hot fire can be blocked by glass. The radiation from very hot bodies like the Sun is mostly light and short-wavelength infrared. The radiation from less hot objects, such as a fire, is largely long-wavelength infrared which, unlike light and short-wavelength infrared, cannot pass through glass.

Light and short-wavelength infrared from the Sun penetrate the glass of a greenhouse and are absorbed by the soil, plants, etc., raising their temperature. These in turn emit infrared but, because of their relatively low temperature, this has a long wavelength and is not transmitted by the glass. The greenhouse thus acts as a ‘heat-trap’ and its temperature rises.

Carbon dioxide and other gases such as methane in the Earth’s atmosphere act in a similar way to the glass of a greenhouse in trapping heat radiated from the Earth's surface. This has serious implications for the global climate. For the average temperature of the Earth to remain constant, a balance must be achieved between the incoming radiation and the radiation emitted from the Earth's surface.

If there is a build-up of carbon dioxide and methane gases in the atmosphere, the balance between incoming radiation from the Sun and the average power emitted from the Earth will be upset.

Rate of cooling of an object

If the surface temperature of an object is higher than its surroundings, it emits radiation at a faster rate than it absorbs radiation from its surroundings. As a result, it cools until the two rates become equal and a constant temperature is reached. The higher the surface temperature of the object above its surroundings, and the larger its surface area, the greater the quantity of radiation it emits and the greater its rate of cooling.

Practical work

Rate of cooling

For safe experiments/demonstrations related to this topic, please refer to the *Cambridge IGCSE Physics Practical Skills Workbook* that is also part of this series.

Safety

- Eye protection must be worn.
- Take care when handling hot water and its containers.

Place a thermometer in some hot water and wait until the temperature reaches a steady temperature above 80°C. Remove the thermometer from the water, and quickly wipe it dry with a paper towel. Record the temperature on the thermometer every 30 s as it cools away from draughts or any source of heat. Use your results to plot a graph of temperature against time.

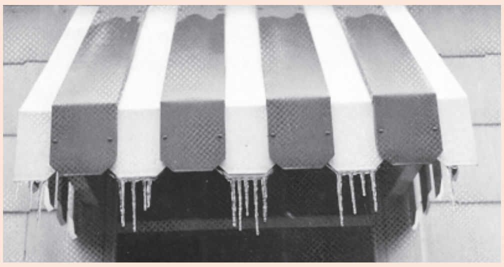
1 In the above experiment a student recorded the following temperatures on the thermometer as it cooled in air.

Time/s	0	30	60	90	120	150	180
Temperature/°C	80	63	51	42	36	31	28

a Plot a graph of temperature against time using the values given in the table.
b Calculate the temperature drop
  i between 0 and 90 s
  ii between 90 s and 180 s.
c State the temperature range over which the thermometer cools most quickly.
d Does the thermometer emit radiation at a higher rate at the higher or lower temperatures?

Test yourself

5 The door canopy in Figure 2.3.11 shows clearly the difference between white and black surfaces when radiation falls on them. Explain why.



▲ **Figure 2.3.11**

6 What type of radiation is thermal radiation?

7 **a** The Earth has been warmed by the radiation from the Sun for millions of years yet we think its average temperature has remained fairly steady. Why is this?
b Why is frost less likely on a cloudy night than a clear one?

2.3.4 Consequences of thermal energy transfer

FOCUS POINTS

★ Explain everyday applications and consequences of thermal energy transfer by conduction, convection and radiation.

★ Explain complex applications and consequences of conduction, convection and radiation involving more than one type of thermal energy transfer.

You have now encountered the three ways in which thermal energy can be transferred from one place to another: conduction, convection and radiation. Such transfers occur in many different situations in everyday living. Transfer of thermal energy by conduction from an external source enables us to heat cooking pots. Convection is often used in water and convector heaters in our homes. Radiation from the Sun can be felt directly and an infrared thermometer allows us to read temperature from a distance. In this topic you will learn more about the uses of both good conductors and poor conductors (insulators).

Applications in which more than one type of thermal energy transfer is involved are explained.

Uses of conductors

Good conductors

These are used whenever heat is required to travel quickly through something. Saucepans, boilers and radiators are made of metals such as aluminium, iron and copper which are all good conductors that transfer thermal energy quickly.

Bad conductors (insulators)

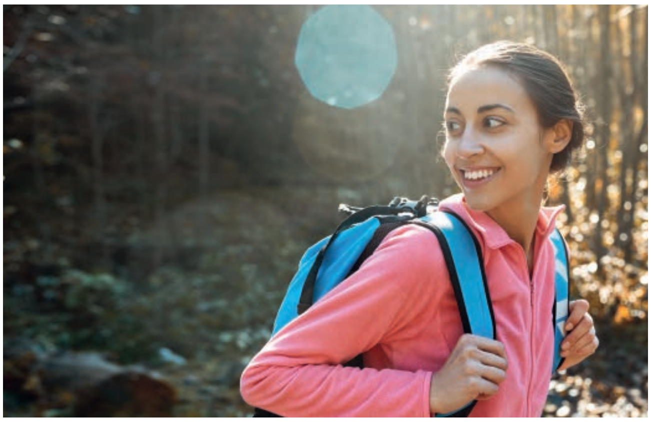
The handles of some saucepans are made of wood or plastic. Cork is used for table mats. These are insulating materials that transfer thermal energy only very slowly.

Air is one of the worst conductors and so one of the best insulators. This is why houses with cavity walls (two layers of bricks separated by an air space) and double-glazed windows keep warmer in winter and cooler in summer.

Because air is such a bad conductor, materials that trap air, such as wool, felt, fur, feathers, polystyrene foam and fibreglass, are also very bad conductors. Some of these materials are used as 'lagging' to insulate water pipes, hot water cylinders, ovens, refrigerators and the walls and roofs of houses (Figures 2.3.12a and 2.3.12b). Others are used to make warm winter clothes like fleece jackets (Figure 2.3.12c on the next page).

▲ **Figure 2.3.12a** Lagging in a cavity wall provides extra insulation.

▲ **Figure 2.3.12b** Laying lagging in a house loft



▲ **Figure 2.3.12c** Fleece jackets help to retain your body warmth.

Wet suits are worn by divers and water skiers to keep them warm. The suit gets wet and a layer of water gathers between the person's body and the suit. The water is warmed by body heat and stays warm because the suit is made of an insulating fabric, such as neoprene (a synthetic rubber).

Energy losses from buildings

The inside of a building can only be kept at a steady temperature above that outside by heating it at a rate which equals the rate at which it is losing energy. The loss occurs mainly by conduction through the walls, roof, floors and windows. For a typical house where no special precautions have been taken, the contribution each of these makes to the total loss is shown in Table 2.3.1a.

As fuels (and electricity) become more expensive and the burning of fuels becomes of greater environmental concern (Topic 1.7.3), more people are considering it worthwhile to reduce heat losses from their homes. The substantial reduction of this loss which can be achieved, especially by wall and roof insulation, is shown in Table 2.3.1b.

▼ **Table 2.3.1** Energy losses from a typical house

a Percentage of total energy loss due to				
walls	**roof**	**floors**	**windows**	**draughts**
35	25	15	10	15
b Percentage of each loss saved by				
insulating walls	**insulating roof**	**carpets on floors**	**double glazing**	**draught excluders**
65	80	≈30	50	≈60
Percentage of total loss saved = 60				

Going further

Ventilation

In addition to supplying heat to compensate for the energy losses from a building, a heating system has also to warm the ventilated cold air, needed for comfort, which comes in to replace stale air.

If the rate of heat loss is, say, 6000 J/s, or 6 kW, and the warming of ventilated air requires 2 kW, then the total power needed to maintain a certain temperature (e.g. 20°C) in the building is 8 kW. Some of this is supplied by each person's 'body heat', estimated to be roughly equal to a 100 W heater.

Uses of convection

Convection currents set up by electric, gas and oil heaters help to warm our homes. Many so-called 'radiators' are really **convector** heaters. Warm air produced by the heater rises because it is less dense than the colder air above. The cold air sinks, is warmed by the heater and itself rises. A convection current is set up which helps to warm the whole room.

Convection currents also form in the water being heated in hot water tanks, kettles and kitchen pans, allowing water to be heated quickly.

Uses of radiation: infrared thermometer

An infrared thermometer detects the thermal radiation emitted by an object and converts it into an electrical signal. The temperature of the object can be determined from the **radiant** power detected and the value is shown on a digital display. It is a non-contact method and allows temperature to be measured at a distance. Infrared thermometers are frequently used to monitor the health of passengers arriving at an airport.

Applications involving more than one type of thermal energy transfer

Car radiator

Both conduction and radiation occur in a car radiator which acts to dissipate the heat generated in the engine. It contains a fluid which circulates between the engine block and the radiator. Thermal energy is transferred to the fluid by conduction as it passes over the engine block. When the fluid enters the radiator, thermal energy is transferred by conduction to the radiator which then radiates energy in the infrared to the surroundings. The metal radiator is black and has a large surface so is a good emitter of radiation. In this way the fluid is cooled before it circulates back to the engine block.

Wood or coal fire

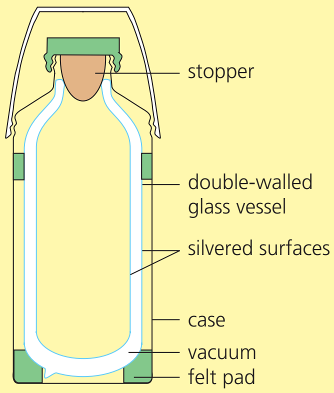
Radiation and convection occur when a room is heated by a wood- or coal-burning fire.

Thermal energy is radiated from the burning wood or coal and heats up objects in the room which absorb it. Air in contact with the hot wood or coal is warmed and rises upwards because it is less dense than the cold air above. Cooler air is drawn down to take its place and a convection current is set up which also serves to transfer heat into the room.

Vacuum flask

A vacuum or Thermos flask keeps hot liquids hot or cold liquids cold. It is very difficult for heat to travel into or out of the flask.

Transfer of thermal energy by conduction and convection is minimised by making the flask a double-walled glass vessel with a vacuum between the walls (Figure 2.3.13). Radiation is reduced by silvering both walls on the vacuum side. Then if, for example, a hot liquid is stored, the small amount of radiation from the hot inside wall is reflected back across the vacuum by the silvering on the outer wall. The slight heat loss that does occur is by conduction up the thin glass walls and through the stopper. If the flask is to be used to store a cold liquid, thermal energy from outside the flask is reflected from the inner wall.



▲ **Figure 2.3.13** The structure of a vacuum flask

Test yourself

8 Explain why on a cold day the metal handlebars of a bicycle feel colder than the rubber grips.

9 Name the energy transfers which occur
  a when a radiator is used to cool the engine of a car
  b when a room is heated by a coal fire.

Revision checklist

After studying Topic 2.3 you should know and understand:

- ✔ that thermal energy transferred by radiation does not require a medium and that thermal radiation is infrared radiation emitted by all objects
- ✔ that for an object at a constant temperature, the rate at which it receives radiation equals the rate that it transfers radiation
- ✔ the rate of radiation emission increases as the temperature of the object increases
- ✔ how thermal insulation is used to keep liquids cool and to reduce heat loss from buildings.

After studying Topic 2.3 you should be able to:

- ✔ describe experiments to show the different conducting powers of various substances and name good and bad conductors
- ✔ explain conduction using the kinetic particle model
- ✔ describe experiments to show convection in fluids (liquids and gases) and relate convection in fluids to density changes
- ✔ describe the effect of surface colour and texture on the emission, absorption and reflection of radiation and recall that good absorbers are also good emitters
- ✔ describe experiments to study factors affecting the absorption and emission of radiation
- ✔ explain how a greenhouse acts as a 'heat-trap' and the consequence for the balance between incoming and emitted radiation at the Earth's surface
- ✔ explain some simple uses and consequences of conduction, convection and radiation
- ✔ explain applications involving more than one type of thermal energy transfer.

Exam-style questions

1 Describe an experiment to demonstrate the properties of good and bad thermal conductors. [Total: 4]

2 Explain in terms of particles how thermal energy is transferred by conduction in solids. [Total: 4]

3 **a** Explain how thermal energy is transferred by convection. [3]
b Describe an experiment to illustrate convection in a liquid. [3]
[Total: 6]

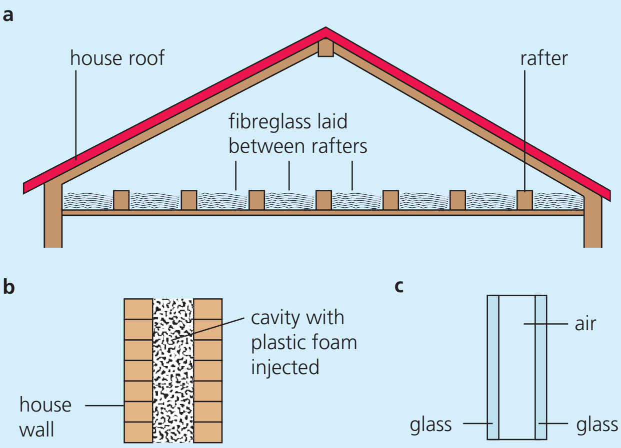
4 The following statements relate to the absorption and emission of radiation.
State which of the statements are *true* and which are *false*.
A Energy from the Sun reaches the Earth by radiation only. [1]
B A dull black surface is a good absorber of radiation. [1]
C A shiny white surface is a good emitter of radiation. [1]
D The best heat insulation is provided by a vacuum. [1]
[Total: 4]

5 Describe the effect of surface colour and texture on the
a emission of radiation [2]
b reflection of radiation [2]
c absorption of radiation. [2]
[Total: 6]

6 **a** Describe an experiment to show the properties of good and bad emitters of infrared radiation. [4]
b Describe an experiment to show the properties of good and bad absorbers of infrared radiation. [4]
[Total: 8]

7 Explain why
a newspaper wrapping keeps hot things hot, e.g. fish and chips, and cold things cold, e.g. ice cream [1]
b fur coats would keep their wearers warmer if they were worn inside out [2]
c a string vest helps to keep a person warm even though it is a collection of holes bounded by string. [2]
[Total: 5]

8 Figure 2.3.14 illustrates three ways of reducing heat losses from a house.
a Explain how each of the three methods reduces heat losses. [4]
b Why are fibreglass and plastic foam good substances to use? [2]
c Air is one of the worst conductors of heat. What is the advantage of replacing it by plastic foam as shown in Figure 2.3.14? [1]
d A vacuum is an even better heat insulator than air. Suggest one (scientific) reason why the double glazing should not have a vacuum between the sheets of glass. [1]
[Total: 8]



▲ **Figure 2.3.14 a** Roof insulation; **b** cavity wall insulation; **c** double glazing

Alternative to Practical

9 The manufacturers of roof insulation suggest that two layers of fibreglass are more effective than one. Describe how you might set up an experiment in the laboratory to test whether this is true.
[Total: 6]