Chapter 10 – Transfer of Thermal Energy

Subject content

Content

- Conduction
- Convection
- Radiation

Learning outcomes

(a) show understanding that thermal energy is transferred from a region of higher temperature to a region of lower temperature
(b) describe, in molecular terms, how energy transfer occurs in solids
(c) describe, in terms of density changes, convection in fluids
(d) explain that energy transfer of a body by radiation does not require a material medium and that the rate of energy transfer is affected by:
  (i) colour and texture of the surface
  (ii) surface temperature
  (iii) surface area
(e) apply the concept of thermal energy transfer to everyday applications

Thermal equilibrium

Objects in contact have same temperature → no net transfer of heat

10.1 Modes of Heat Transfer

<table>
<tr><th>Mode</th><th>Medium</th><th>Theory</th><th>Explanation</th><th>Figure</th></tr>
<tr><td>1. Conduction</td><td>Solid</td><td>Molecular movement</td><td>1) Vibrating molecules
Molecules at hot region gain KE
Vibrate more vigorously + collide with neighbouring molecules
Transfer energy → molecules → cooler region
2) Free electron diffusion (metals)
Free e^- near hot region gain KE
Move freely b/w atoms → collide with other atoms & electrons
Transfer energy → atoms & electrons → cooler region</td><td></td></tr>
<tr><td>2. Convection</td><td>Fluids (liquids + gases)</td><td>Density changes</td><td>Fluids:<table><tr><th>Hotter region</th><th>Colder region</th></tr><tr><td>Lower density</td><td>Higher density</td></tr><tr><td>Rise upwards</td><td>Sink downwards</td></tr></table>
Difference in densities of fluids → set up convection current</td><td></td></tr>
<tr><td>3. Radiation</td><td>Vacuum (no medium required)</td><td>Energy transfer</td><td>Transfer of thermal energy by infrared radiation
Rate of energy transfer affected by:
colour & texture of surface
surface area
surface temperature</td><td></td></tr>
</table>

10.2 Applications of Thermal Energy Transfer

Conduction:

Application	Explanation
1. Polyester fibres & wool: make winter wear	Pockets of air → good heat insulator ● Reduce heat transfer to colder environment by conduction
2. Double-glazed windows: reduce heat transfer	Layer of air trapped b/w sheets of glass → good heat insulator ● Summer: house kept cool (less heat conducted into house) ● Winter: house kept warm (less heat conducted out of house)

Convection:

Application	Explanation
1. Air conditioners installed near room ceiling	● Air around air conditioner is cooled → contract ○ Cold air: denser → sink ○ Warmer air below: less dense → rise ● Continuous cycle forms convection current → cool room
2. Heating coils of electric kettles at bottom of kettle	● Water around heating coil is heated → expand ○ Warm water: less dense → rise ○ Cooler water at top: denser → sink ● Continuous cycle forms convection cycle → heat up water

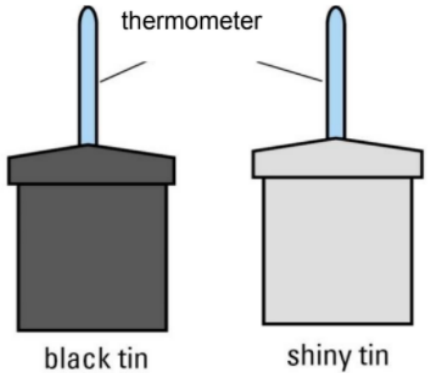
Radiation:

Application	Explanation
1. Cooling fins at back of refrigerator: paint black	**Black**: good emitter of IR ● Thermal energy from refrigerator radiate to surroundings at high rate ● Fins lose heat at slow rate → increase amt of infrared radiation lost by fins
2. Fire-fighting suits: shiny + silver-coloured outer surface	**Shiny + silver**: good reflector of IR ● Thermal energy from surroundings radiated to suit at low rate ● Suit gain heat at slow rate → reduce amt of infrared radiation gained by fireman

Experimental procedures (radiation)

Black & dull surface	Shiny & silver surface
better emitter of IR	poor emitter of IR
better absorber of IR	poor absorber of IR

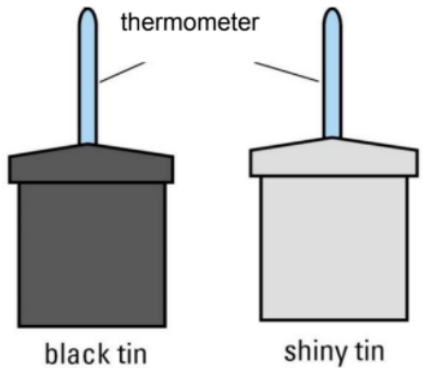
Emitter of IR



1. Fill 2 same-sized metal tins with same amount of hot water at 90°C
2. Place thermometers into hot water, ensure do not touch bottom
3. Thermometer inside black tin shows greater temperature drop than shiny tin

- Black + dull surface: better emitter
- Silver + shiny surface: poor emitter

Absorber of IR



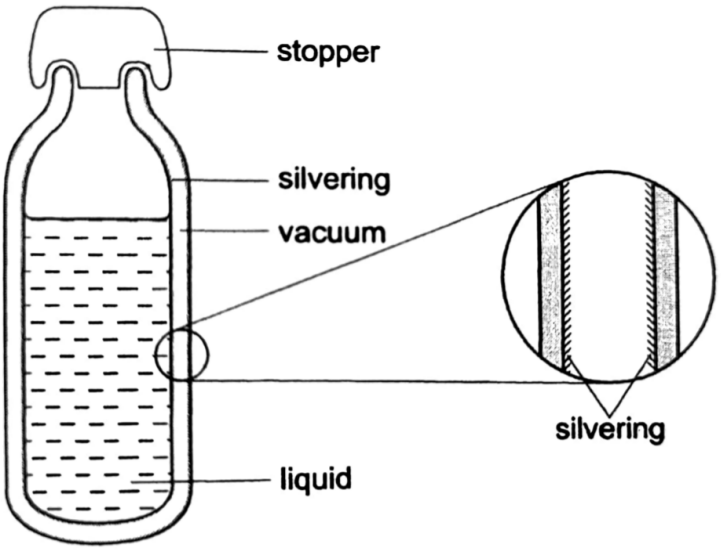
1. Fill 2 same-sized metal tins with same amount of hot water at 5°C
2. Place thermometers into hot water, ensure do not touch bottom
3. Place both tins in hot sun
4. Thermometer inside black tin shows greater temperature rise than shiny tin

- Black + dull surface: better absorber
- Silver + shiny surface: poor absorber

Typical questions

Multiple choice questions

1 The diagram shows a vacuum flask and an enlarged view of a section through the flask wall.



The main reason for the silvering is to reduce heat transfer by (2011 P1 Q16)

A conduction only
B conduction and convection
C radiation only
D radiation and convection

2 A house, built in a country with a hot, sunny climate, stays cool in the day.
Which material for the wall and which outside colour keeps the house the coolest?
(2013 P1 Q21)

	wall material	outside colour
A	bad conductor	dark
B	bad conductor	light
C	good conductor	dark
D	good conductor	light

3 Which surface is the best absorber of heat radiation? (2014 P1 Q17)

A dull black
B dull white
C shiny black
D shiny white

4 A beaker of water is heated at the bottom to form a convection current in the water.
An explanation of the convection current contains four statements.

1 The water at the bottom becomes warmer.
2 The density of the water decreases.
3 Less dense water rises and cold water moves in to replace it.
4 Water expands.

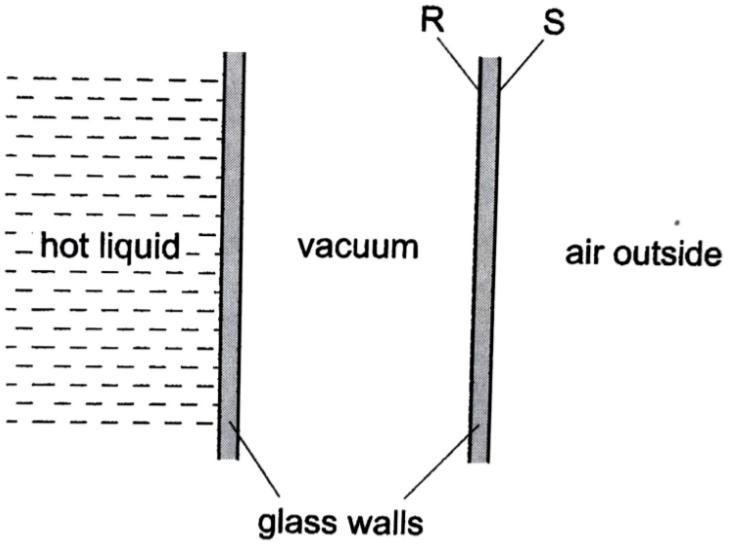
What is the correct order of these statements? (2016 P1 Q22)

A 1 → 2 → 3 → 4
B 1 → 3 → 4 → 2
C 1 → 4 → 2 → 3
D 1 → 4 → 3 → 2

5 The following objects all lose heat.
Which object loses all of its heat by radiation? (2017 P1 Q20)

A a concrete block with white surfaces at 100°C, in air
B a metal block with black surfaces at 40°C, in air
C a shiny metal satellite at 30°C, in space
D the heating element of a kettle at 150°C, in water

6 A vacuum flask contains a hot liquid. The diagram shows a section of the double wall.



What colour for surface R and for surface S most reduces the heat loss from the flask?
(2018 P1 Q20)

	R	S
A	black	black
B	black	silver
C	silver	black
D	silver	silver

7 Four bars, all of exactly the same size, are each placed with one end in boiling water.
The times taken for the temperature of the other end to increase by 2°C are measured.

Material of bar	**Time for 2°C rise / s**
aluminium	10
copper	5
cork	800
styrofoam	1200

To make a large metal tank with the least heat loss, which material should be used for the walls of the tank and its insulation?

	Tank	**Insulation**
A	aluminium	cork
B	aluminium	styrofoam
C	copper	cork
D	copper	styrofoam

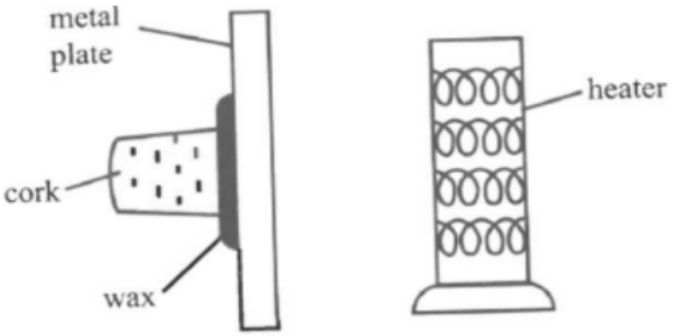
8 The main mechanism for conduction in a typical metallic conductor involves

A atoms near the hot end vibrating about their fixed positions and transferring their energy to neighbouring atoms located in cooler regions by knocking against them.
B the diffusion of atoms in the conductor from the hot end to the cooler end.
C the diffusion of free electrons from the hot end to the cooler end of the conductor carrying their energy with them.
D the atoms near the hot end sending out energy to atoms near the cooler end.

9 Which of the following statements about the vacuum flask is incorrect?

A Loss of thermal energy by radiation is minimised by keeping hot water in a double-walled glass container.
B Loss of thermal energy is minimised by using a cork or plastic stopper to close up the neck of the glass container.
C The vacuum in the double-walled glass container effectively prevents conduction and convection.
D The walls of the glass container are silvered to reduce radiation.

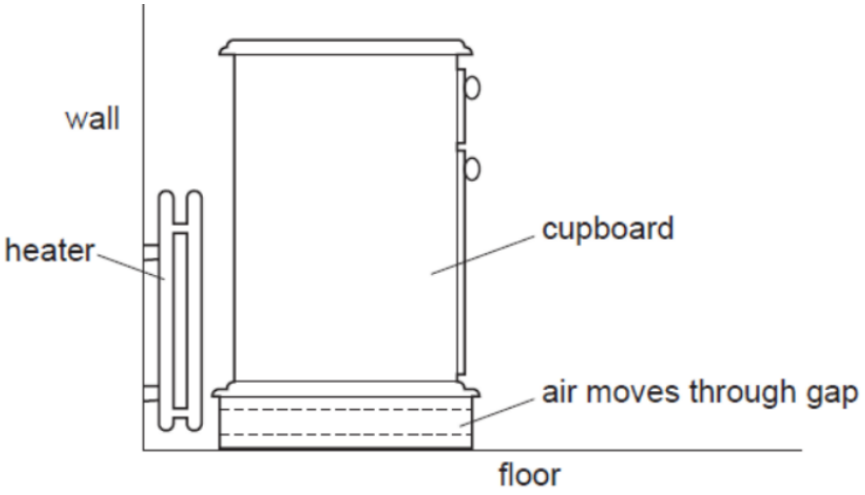
10 A small cork is fixed with wax to a metal plate. An electric heater is placed close to the plate. After some time, the wax melts and the cork drops off.



How does heat reach the wax?

A by conduction only
B by conduction and radiation
C by convection and radiation
D by conduction and convection

11 A cupboard is placed in front of a heater. Air can move through a gap under the cupboard.



Which of the following best describes the temperature and the direction of the air that moves through the gap?

	air temperature	air direction
A	cool	away from the heater
B	cool	towards the heater
C	warm	away from the heater
D	warm	towards the heater

Structured questions

1 Avani and Nabil offer different explanations for the cooling effect of ice on a soft drink.
Avani: The soft drink cools down because the ice transfers its coldness to the soft drink.
Nabil: The soft drink cools down because heat is transferred from the soft drink to the ice.

(a) State (with reasons) whether Avani's explanation is correct.

Avani is incorrect.
Nothing can transfer its 'coldness' to anything else. Just as dark is the absence of light, cold is simply the absence of heat.
For example, air conditioners do not supply 'coldness'. Instead, they draw heat out of the air that circulates around the evaporative coils (part of an air-conditioner that removes thermal energy from the air as the air flows around them) inside the air conditioners.

(b) State (with reasons) whether Nabil's explanation is correct.

Nabil is correct.
Thermal energy is always transferred from a region of higher temperature to a region of lower temperature.
Since the soft drink has a higher temperature than the ice, its thermal energy is transferred to the ice. As a result, the temperature of the soft drink decreases.

2 Min Dee touches a metal spoon and a plastic spoon that has been placed in an air-conditioned room that has been maintained at 25°C for a long time.
'When I touch the spoons, the metal spoon feels colder than a plastic spoon because metals generally have lower temperatures than plastics.'
Explain why Min Dee's statement above is incorrect.

Both spoons will be cooled to the same temperature of the air-conditioned room (25°C) because they have been placed there for a long time.

Since Min Dee's hand (37°C) is warmer than both spoons (25°C), thermal energy is transferred from her hand to the spoons (by conduction).

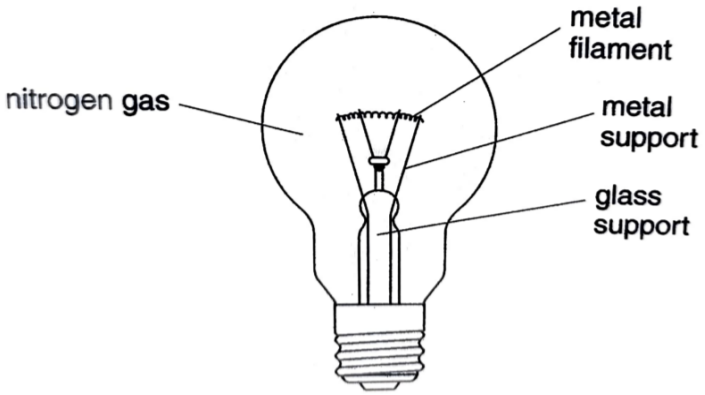
Even though both spoons are at the same temperature, the metal spoon feels colder than the plastic one because it conducts thermal energy away from her hand more quickly than the plastic spoon.

3 When Avani uses a flame to heat one end of a copper rod, she finds that the opposite end of the copper rod quickly becomes hot as well. She makes an incorrect conclusion.
'The flame supplies highly energetic electrons which transport energy to the copper rod.'
Explain why Avani's statement (above) is incorrect.

The flame does not supply electrons.

- Metals such as copper already contain delocalised free-moving electrons.
- When conduction in metals takes place, in addition to the process that takes place in non-metals, free electrons at the heated end of the rod gain energy and move faster towards the cooler regions of the rod.
- The electrons collide with other electrons and atoms, transferring energy to them.
- The transfer of thermal energy via the motion of free electrons causes the cooler end of the rod to become hot. This process is much faster than the vibration of atoms that takes place in non-metals.

4 When switched on, the filament lamp shown in the figure below loses energy by conduction, convection and radiation.



The radiation emitted is part of the electromagnetic spectrum.
Describe how energy is lost from the metal filament (2012 P2A Q3c)

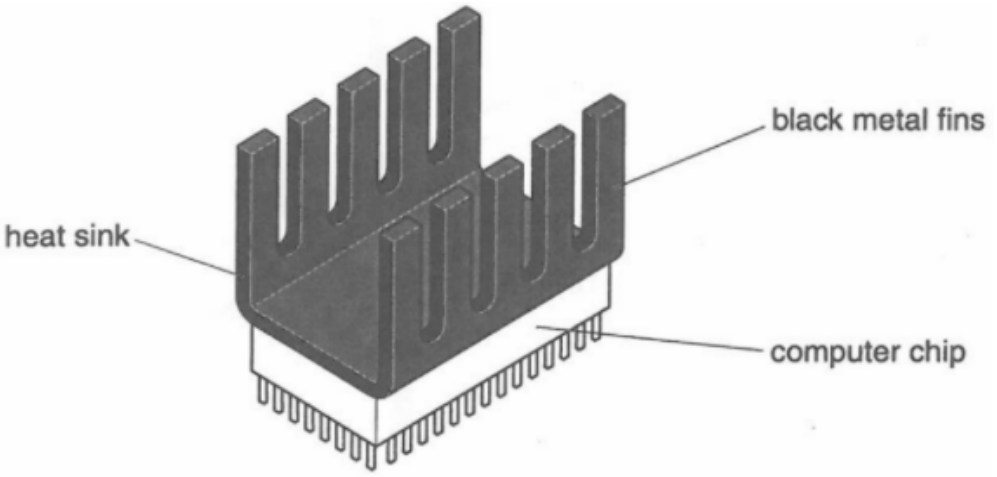
(a) by conduction [1]

Thermal energy is conducted down the metal support, through the glass support and lost through the base of the filament lamp.

(b) by convection [2]

- The nitrogen gas around the filament lamp heats up, expands, becomes less dense and rises.
- The heated nitrogen gas, upon rising, comes into contact with the glass casing of the bulb and transfers the energy to the glass casing, which in turn, heats up the air around the filament lamp, which also expands and rises, causing the thermal energy to be lost to the surroundings.
- The convection currents in and around the filament bulb cause energy to be lost.

5 The figure below shows a computer chip fitted with a heat sink with black metal lines.



The heat sink keeps the computer chip cool. Thermal energy (heat) is transferred away from the chip by conduction, convection and radiation. (2013 P2A Q4)

(a) Explain the difference between conduction and convection. [2]

CONDUCTION:

The transfer of thermal energy due to collisions / vibrations of particles. There is no movement of the medium in conduction.

CONVECTION:

The transfer of thermal energy due to the movement of the medium itself, and happens only in fluids (liquids and gases).

(b) Explain the features of the heat sink that allow thermal energy to be transferred easily away from the chip. [3]

(N2013/P2/Q4b)

CONDUCTION:

Material is metal.

- The heat sink is made of metal which is a good conductor of heat.
- Heat is removed from the chip quickly through conduction.

CONVECTION:

Design of the fins is vertical.

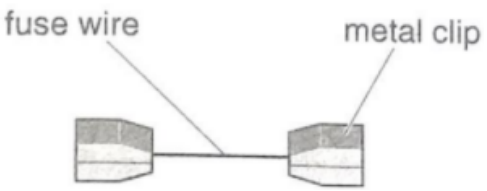
- The fin design is vertical, which increases the rate of heat loss as more effective convection currents are formed.

RADIATION:

Colour is black. Surface area is large.

- The surface area of the heat sink is large and it is painted black which is a good emitter of radiation.
- Thus, the rate of heat loss via radiation to the surrounding is increased.

6 A length of fuse wire is cut into two pieces X and Y. Each piece of wire is clamped, in turn, between two metal clips, as shown in the figure below.



The length of the wire between the clips is 1.5 cm for wire X and 0.4 cm for wire Y.
Just before each wire melts, the middle of the wire in the figure above becomes red hot.

(2015 P2B Q9c)

(a) Describe **two** ways in which thermal energy (heat) is lost from the middle of the wire. [2]

CONDUCTION:

The thermal energy from the hotter middle of the wire is conducted along the wire to the colder ends, and eventually to the metal clips.

RADIATION:

The thermal energy could be lost through emission of infrared radiation from the middle of the wire.

CONVECTION:

Thermal energy is lost through convection. The hotter middle of the wire heats the air around it. The heated air expands. The expanded air rises as it is less dense than the surrounding air. Colder air from the surroundings flows in to take its place. Thus, a convection current is set up.

(b) Explain why the ends of the wire are colder than the middle. [1]

The ends of the wire are connected to the metal clips which are good conductors of heat, and would be able to conduct the heat generated in the wire away quickly, thus they are colder.

7 The figure below shows a refrigerator which contains a freezing compartment at the top.

Placing the freezing compartment at the top cools all of the air in the refrigerator.
Explain why. [3]

(N2014/P2A/Q5)

- The freezing compartment cools the air around it, causing its density to decrease. The cool air sinks to the bottom of the refrigerator,
- while the warmer, less dense air rises up to the freezing compartment and is cooled by it.
- The cycle continues, cooling all the air in the refrigerator.

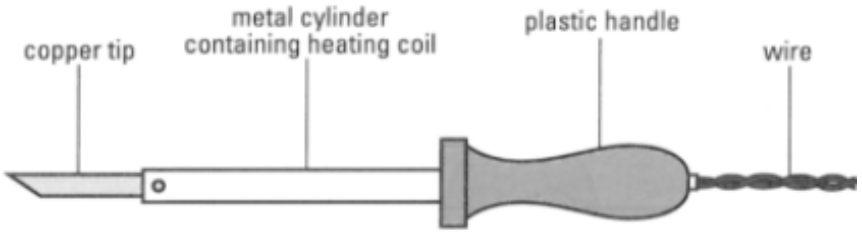
8 A burning candle is positioned directly below a chimney in a box, as shown in the diagram below.

(a) Indicate clearly with arrows the direction of the convection current in the air. [2]

(b) Describe how the convection current is set up. [2]

Air around the candle flame is heated. Hot air expands and becomes less dense, thus it rises out of the chimney. Cooler air that is denser, sinks in the other chimney to replace the air that has left. A convection current is set up.

9 Solder is a type of metal which can be melted and used to join wires in an electrical circuit. The figure below shows a soldering iron used to melt solder. The metal cylinder of the soldering iron contains a heating coil to heat the copper tip.



(a) Suggest and explain why the tip is made of copper. [2]

Copper is a metal, which is a good conductor of thermal energy. Thus, it allows the copper tip to be heated up quickly.

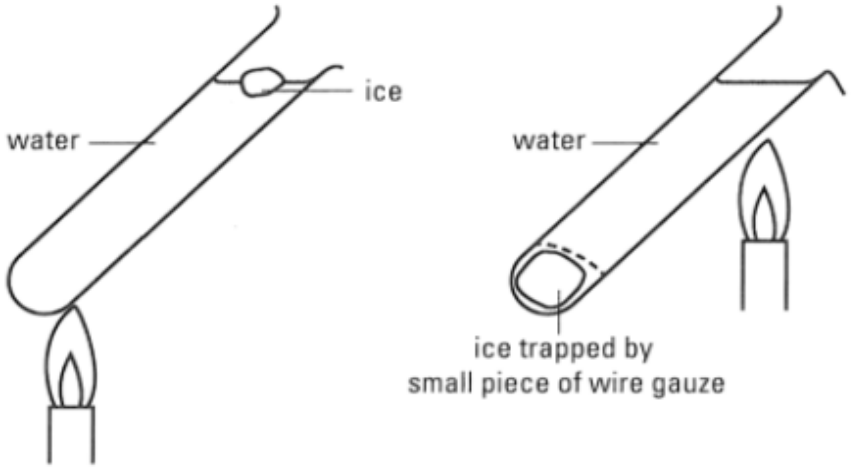
(b) Suggest and explain why the handle is made of plastic. [2]

Plastic is a poor conductor / good insulator of thermal energy. Thus, it prevents the user from getting burnt.

(c) When the soldering iron is used, its tip is put in contact with the solder to melt the solder. State the process by which the thermal energy is transferred from the copper tip to the solder. [1]

Conduction

10 Two experiments are conducted to investigate the transfer of thermal energy in water.
Experiment 1: Cold water at the bottom of the test tube is gently heated while the ice floats on the water.
Experiment 2: Cold water near the top of the test tube is gently heated while the ice is trapped at the bottom of a small piece of wire gauze.



experiment 1 **experiment 2**

(a) What will you observe in experiments 1 and 2? [2]

Experiment 1:

The ice floating on the water melts before the water boils.

Experiment 2:

The ice trapped at the bottom of the test tube remains solid, even when the water near the top of the test tube begins to boil.

(b) Name the process by which thermal energy transfers through the glass. [1]

Conduction

(c) In experiment 1, name the main process by which thermal energy is transferred from the heated water at the bottom of the test tube to the water at the upper part of the test tube. [1]

Convection

(d) Describe how the process in (c) occurs. [2]

When water at the bottom is heated, its volume expands and its density decreases.

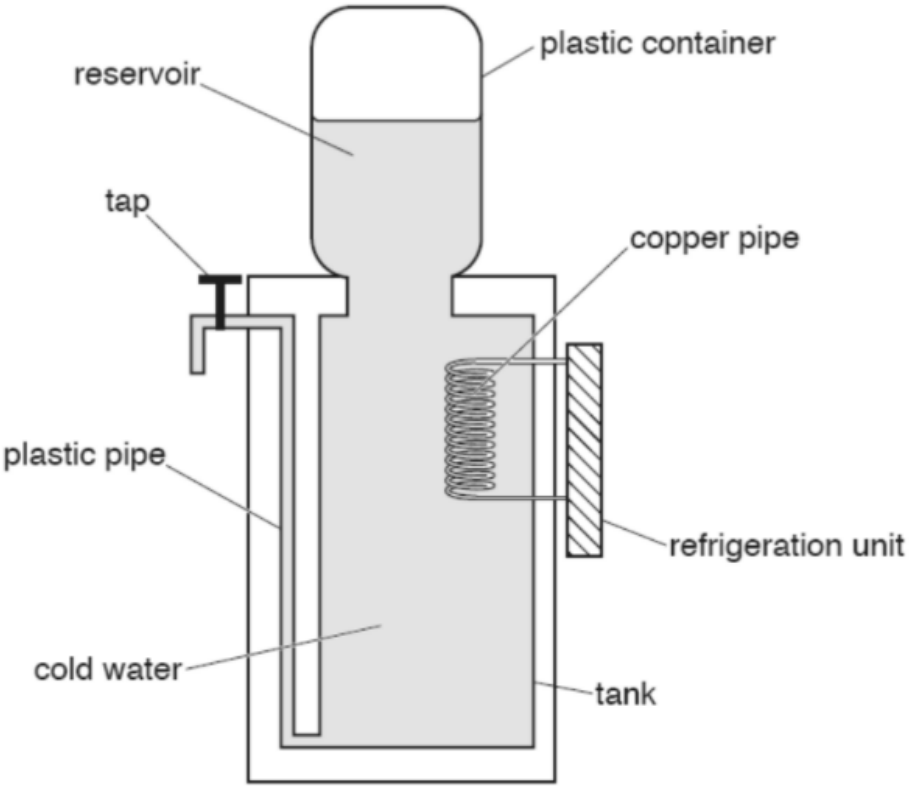
The heated water will rise to the upper part of the test tube.

(e) Explain why the ice in experiment 2 does not melt, even when the water near the top of the test tube boils. [2]

In experiment 2, convection currents are limited to the water near the top of the test tube as the heated water stays at the top.

As water is a poor conductor of thermal energy, very little thermal energy is transferred to the ice at the bottom of the test tube.

11 The figure below shows the structure of a water cooler that is used to supply cold water to the workers in a hot office.

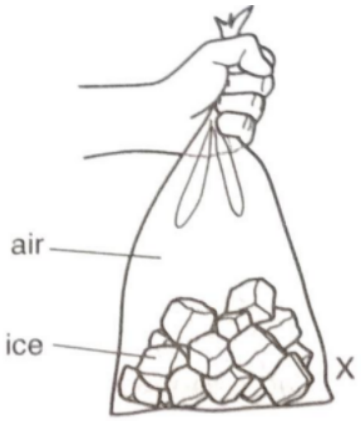


The reservoir of water in the plastic container is at room temperature. It does not mix with the cold water in the tank below.

Explain why. [2]

- It is less dense than the cooler water.
- It floats on the cooler water, and cooler water remains on the bottom.

12 The figure below shows ice in a plastic bag being carried by a nurse from a freezer to the operating theatre in a hospital.

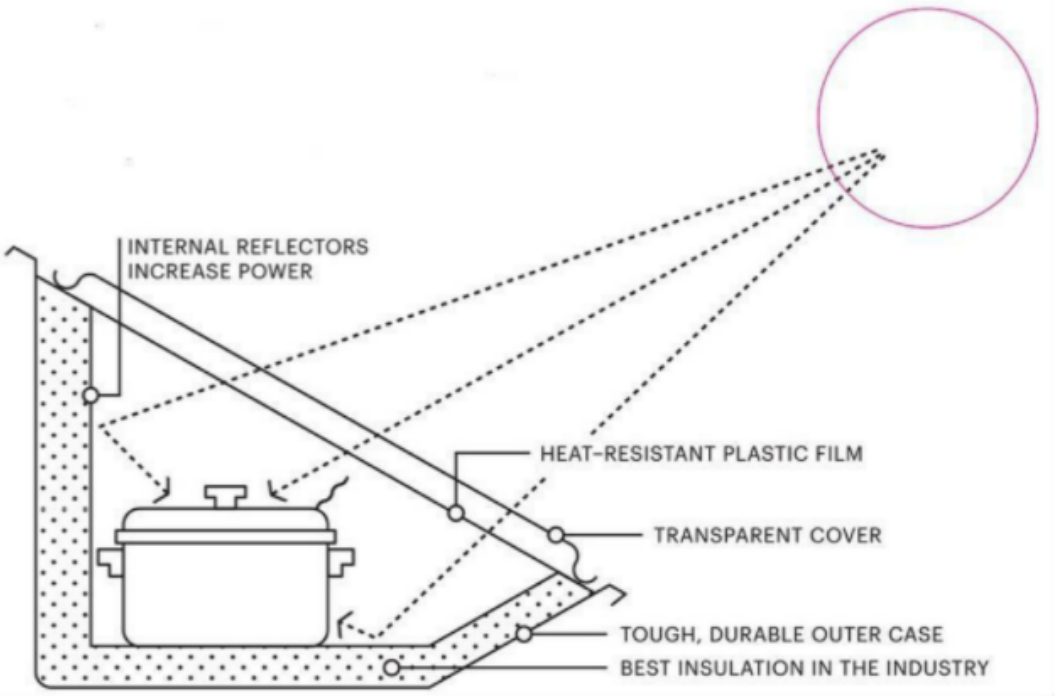


The nurse notices that the ice melts too quickly. She puts the plastic bag containing the ice into a second plastic bag. There is a layer of air between the two bags.
Explain how this layer of air helps to stop ice from melting. [2]

Air is a poor conductor of heat.

This reduces the rate of heat transfer from the warmer surroundings to the ice by conduction (reduces heat gain).

13 The figure below shows a solar oven that is used to heat a pot of water.



State three design characteristics of the solar oven and explain how these factors allow the water to be heated up quickly. [3]

- The transparent cover allows thermal radiation / infrared radiation / radiant heat to enter the pot and heat up the food.
- The infrared reflectors increase the rate of infrared radiation absorption by the pot.
- The insulation at the base / plastic film reduces the rate of heat loss by conduction from the pot.
- The transparent cover reduces heat loss via conduction.

14 The figure below shows a metal coffee cup on a metal warming plate.

There is a small electrical heater inside the warming plate that keeps the plate hotter than the coffee.

(a) Describe how heat is transferred through the metal and then to all the liquid in the cup. [3]

CONDUCTION:

The metal is a good conductor of heat and conducts heat quickly. Heat is transferred from the metal to the liquid at the bottom.

CONVECTION:

The liquid there becomes hotter and rises as it is less dense. The cooler liquid at the top sinks as it is denser.

A convection current is set up throughout the liquid that allows thermal energy to be transferred from the metal to the liquid.

(b) A cup of a different shape is placed on the same heater, as shown in the right figure. The two cups are made of the same metal and contain the same amount of coffee.
Explain why the coffee in the cup in the right figure is not kept as warm as the coffee in the cup in the left figure. [1]

Air is a poor conductor of heat (OR good insulator of heat via conduction),
thus the energy from the metal warming plate is conducted slowly to the cup in right figure, making it less warm.