10 Transfer of Heat and Its Effects

Heat can be transferred within and across bodies, and to improve our daily lives, humans depend heavily on new discoveries and technologies to monitor and keep our surroundings at an optimal temperature. The understanding of how heat is transferred can lead to increase in the efficiency of energy use, reducing the demand for additional energy.

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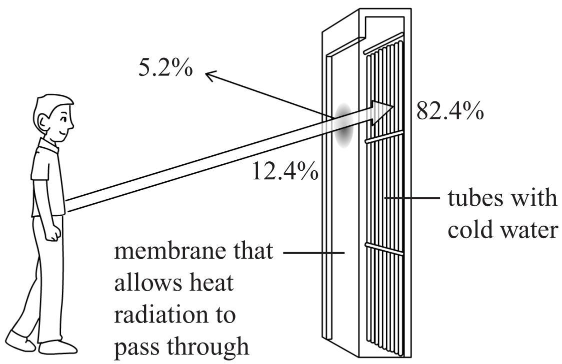
- What effects does heat transfer have on an object? (10.1)
- How is heat transferred in our daily lives? (10.2)

10.1 What Effects does Heat Transfer have on an Object?

Earth lies within a habitable zone where there is sufficient transfer of heat from the Sun to keep it warm, and also provide sufficient light and heat for life to exist. However, climate change indicators have shown that Earth's temperature is increasing rapidly over the past 100 years, leading to warming of the planet's oceans and the melting of snow and ice on Earth's surface. This has led to changes in volume of ice and water on land, and expansion of ocean water.



Emerging technology

Fig 10.1 Air-conditioners cool air which is circulated within a room or building potentially spreading airborne viruses such as the coronavirus. Scientists are developing large panels of thin tubes that carry cold water to absorb heat. These cooling panels can be used with open windows or doors reducing the spread of airborne viruses.

Heat and Temperature

1. Temperature is the degree of hotness or coldness. Its SI unit is the kelvin (K) but we commonly use the degree Celsius (°C).

   Temperature in K = 273.15 + temperature in °C

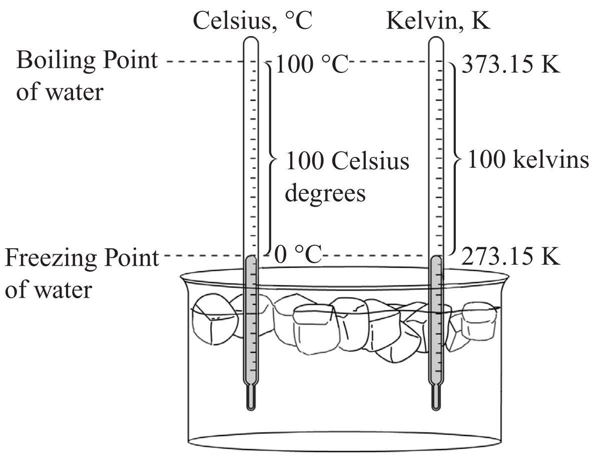


Fig 10.2 Relationship between degree Celsius and Kelvin. In the Celsius scale, the freezing point of water is used as the lower fixed point while the boiling point of water is used as the upper fixed point. Note that a change in 1 K is the same as a change in 1 ºC.

> **Note**
> What is the difference between the Celsius scale and the Kelvin scale? While the zero point of the Celsius scale is the freezing point of water, the zero point of the Kelvin scale is 0 K or –273.15 °C which is called the absolute zero. This is the point at which the motion of particles has completely stopped.

2. The temperature of an object gives an indication of how much heat, or energy, an object has.
3. There are various kinds of thermometers to help us measure temperature. In the laboratory, we commonly use the liquid-in-glass thermometer which has a range of –10 °C to 110 °C.

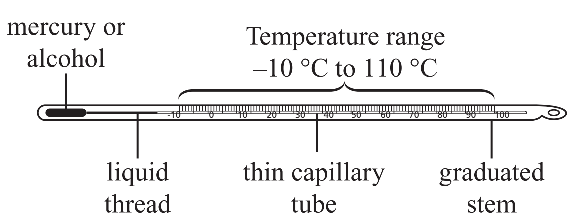


Fig 10.3 A laboratory liquid-in-glass thermometer

> **Note**
> The capillary tube is made thin so that there is a great change in the length of the mercury thread for each unit temperature change. This means that when the temperature changes by one degree celcius, the change in length of the coloured liquid in the tube will be visible when liquid expands or contracts.

4. Heat is the amount of energy that is transferred from a region of higher temperature to a region of lower temperature. Like all forms of energy, the SI unit of heat is the joule (J).

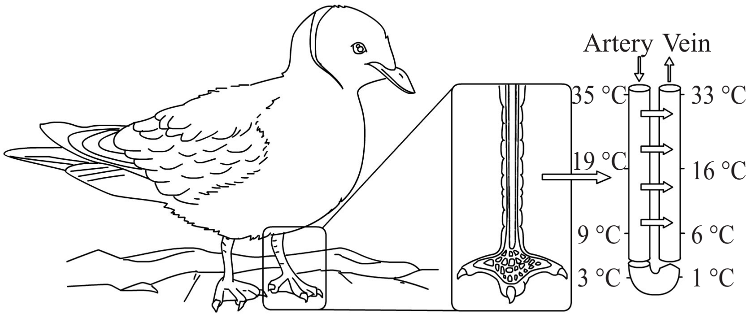


Fig 10.4 This bird lives in an environment that can be as cold as –16 ºC. In its leg, the blood vessel (artery) that carries warmer blood from the heart to the feet runs beside the blood vessel (vein) that carries cooler blood from the feet to the heart. This proximity allows heat from the warmer artery to be transferred effectively to the cooler vein.

5. Heat in a substance depends on its temperature and mass.

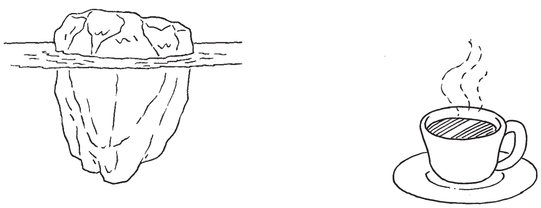


Fig 10.5 The iceberg can contain more heat than the cup of hot coffee although the iceberg is cooler. This is because the iceberg has a much greater mass than the coffee.

6. **Extension Knowledge**

In upper secondary Physics, you will learn about specific heat capacity of substances. It is the amount of energy needed to raise the temperature of a unit mass of a substance by one unit temperature.

Specific heat capacity of substance

$$= \frac{\text{heat gain or heat loss by the substance}}{\text{mass} \times \text{temperature change}}$$

Where temperature change
= final temperature – initial temperature
SI unit of specific heat capacity: J/(kg ºC) or J/(kg K)

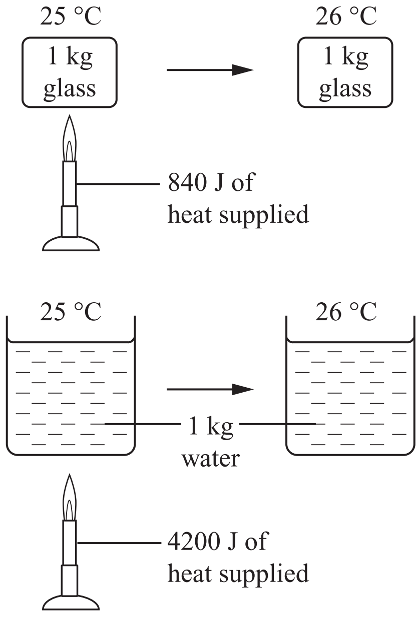


Fig 10.6 Water (4200 J/(kg ºC)) has a higher specific heat capacity than glass (840 J/(kg ºC)).

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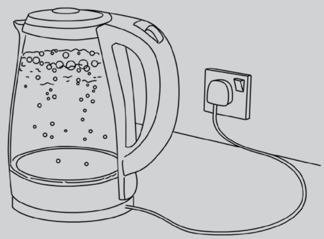
Extension Knowledge

The diagram shows an electric kettle. How much electrical energy is needed to increase the temperature of 600 g of water from 20 ºC to its boiling point? (specific heat capacity of water = 4200 J/(kg ºC))



ANSWER

Electrical energy is converted to heat.

Heat

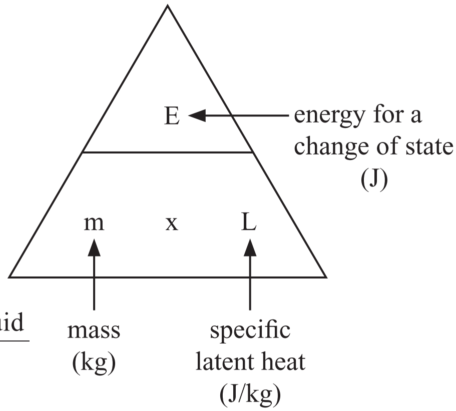
= mass × specific heat capacity of water × (final temperature – initial temperature)

= 0.6 kg × 4200 J/(kg °C) × (100 – 20) °C

= 201 600 J

7. **Extension Knowledge**

In upper secondary Physics, you will learn about specific latent heat of substances. It is the amount of energy needed to change the state (melting or boiling) of 1 kg of the substance without changing its temperature.



Specific latent heat of fusion =

$$\frac{\text{energy needed to change the state of a substance from solid to liquid}}{\text{mass of substance}}$$

Specific latent heat of vaporization =

$$\frac{\text{energy needed to change the state of a substance from liquid to gas}}{\text{mass of substance}}$$

SI unit of specific latent heat: J/kg

SCIENCE AROUND US

Extension Knowledge

Huiying places an ice cube with a mass of 10 g at 0 ºC outside under direct sunlight. She measures that it takes 5.56 minutes for the ice to completely melt. The specific heat of fusion of water is 334 J/kg. Calculate the rate of energy (energy per unit time) in W at which the ice cube receives heat from the sunlight and hot air around.

ANSWER

Energy needed to heat the ice cube = mass × specific latent heat of fusion

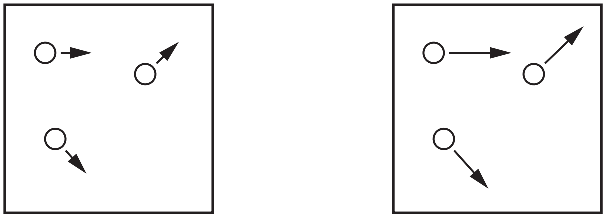
= 0.010 kg × 334 J/kg

= 3.34 J

Rate of energy (or power) $= \dfrac{3.34 \text{ J}}{(5.56 \times 60) \text{ s}}$

= 0.0100 W (3 s.f.)

8. Explanation using Kinetic Theory:
   The heat in a substance is the sum of all the kinetic energy of the particles (e.g. atoms, molecules) in the substance.



Lower average kinetic energy
Lower temperature

Higher average kinetic energy
Higher temperature

Fig 10.7 The greater the average kinetic energy of particles in a substance, the higher the temperature of the substance.

Effects of Heat

1. Heat can cause a substance to change its temperature or physical state.

Effect of substance gaining heat	Explanation using the Kinetic Theory
The temperature of a substance increases when it is heated.	The heat supplied to the substance goes into increasing the speed of particles and hence, their average kinetic energy.
Optional for **N(A)** At the melting point of a substance, the substance changes from solid state to liquid state as heat is supplied.	The heat supplied goes into weakening the forces of attraction between the particles in solid and breaking down their regular arrangement.
Optional for **N(A)** At the boiling point of a substance, the substance changes from liquid state to gaseous state as heat is supplied.	The heat supplied goes into overcoming the forces of attraction between the particles in liquid and increasing the spaces between them.

2. Heat can cause matter to undergo thermal expansion and contraction.
   - Matter (solids, liquids and gases) expands when heat is absorbed, and contracts when heat is given out.
   - Thermal expansion of a substance results in an increase in volume and hence a decrease in the density of the substance.

Note

Recall the formula density $= \frac{\text{mass}}{\text{volume}}$. When a heated substance expands, its volume increases while its mass (amount of matter) remains the same. Therefore, its density decreases.

3. **Explanation using the Kinetic Theory:**
   Particles gain kinetic energy and move further apart.

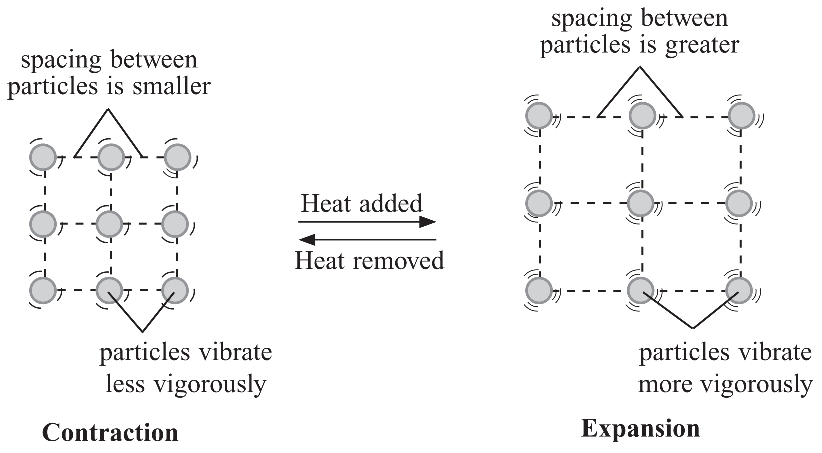


Fig 10.8 How can the Kinetic Theory Model of Matter explain thermal contraction and thermal expansion of matter?

4. Gases expand and contract the most (compared to solids and liquids) when heated and cooled respectively. Solids expand and contract the least when heated and cooled respectively.
5. Effects of expansion and contraction in everyday life:
   - The concrete used to build bridges and buildings is strengthened by steel rods. The steel used to make the rods are carefully selected to expand and contract at the same rate as the concrete. Otherwise, the structure is susceptible to cracks and will fail over time.
   - **Climate change**
     Studies have shown that Earth's temperature has been increasing over the past 100 years, leading to warming of the planet's oceans. As ocean volume increases, sea level at coastal areas rises, leading to an increase in floods in low-lying areas.

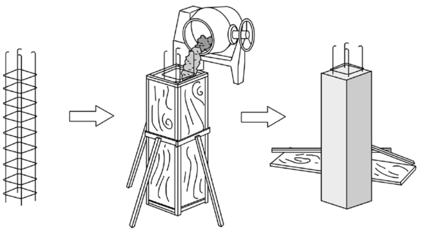
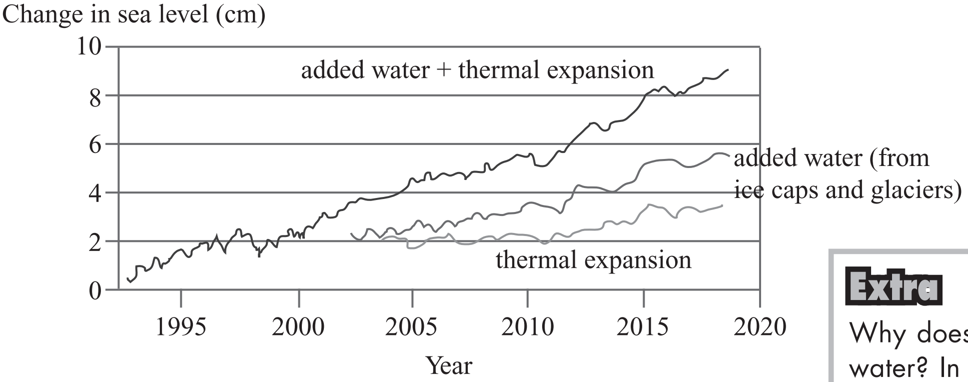


Fig 10.9 By combining concrete and steel, engineers create a composite material that is much stronger than the concrete alone. However, engineers must make sure that the two materials have similar expansion rates especially in places with extreme temperatures. Otherwise, the two materials would crack and create stresses against each other, weakening the building structure.



Climate change

Fig 10.10 On average, global sea level rises at about 1 mm to 2 mm per year due to melting glaciers and ice sheets that add water to the oceans, and increasing volume of water as water warms. In addition, places near the equator such as Singapore will experience greater rise in sea level due to greater gravitational pull at the equator than at the poles. Currently, Singapore's coastlines are protected by structures such as sea walls.

6. Applications of expansion and contraction in everyday life:
   - A bimetallic strip consists of two layers of different metals which expand at different rates when heated. Since they can bend, bimetallic strips are used in electric circuits (e.g. electric iron, fire alarm, circuit breakers) as a switch to interrupt the circuit when the strips heat up and bend. The circuit can be reset when the bimetallic strip cools down.

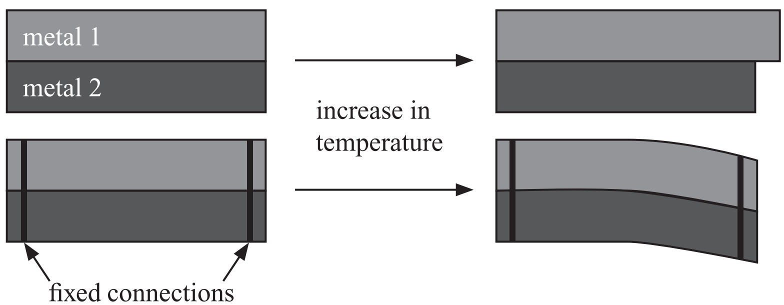
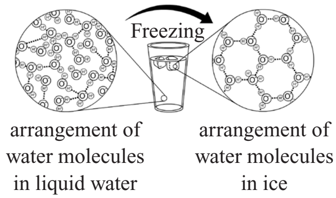


Fig 10.11 Two different metals are rivetted together to form a bimetallic strip. When the bimetallic strip is heated, it bends because one metal expands more than the other.

Extra

Why does ice float on water? In ice, the water molecules are regularly arranged. However, the water molecules in solid state (ice) are further apart than in liquid water as shown in the diagram. As a result, ice takes up more space and it is less dense than water.



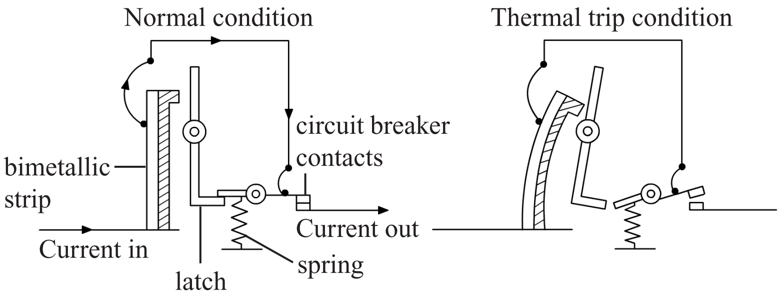


Fig 10.12 In this circuit breaker, when there is an excessive amount of electric current passing through the bimetallic strip, it heats up. Since one metal expands more than the other, the bimetallic strip bends and moves the latch causing the contact to break. Thus, the electric current stops flowing.

- Liquid-in-glass thermometer has a narrow capillary tube that contains a fixed mass of liquid. The volume of the liquid in the bulb expands or contracts when temperature changes and can be read off on a calibrated scale.

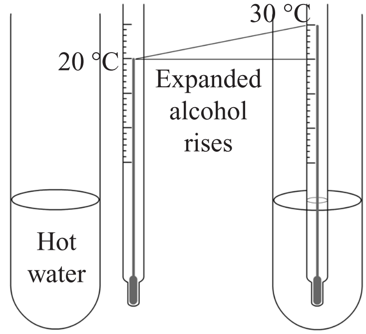
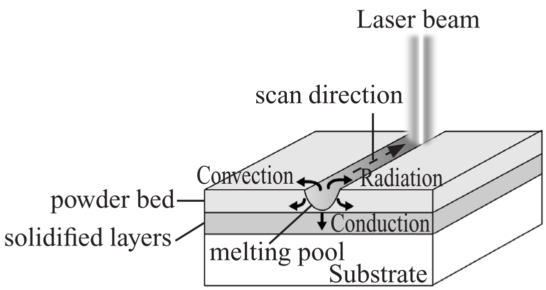


Fig 10.13 When the bulb of the thermometer is placed in warm water, the alcohol level may drop a little at first because the glass bulb absorbs heat and expands. When the alcohol absorbs the heat, the alcohol level rises because the liquid expands more than the solid.

10.2 How is Heat Transferred in Our Daily Lives?

Heat transfer is explored by thermal engineers as they study the generation, use, conversion and exchange of heat between physical systems. Many systems involve the transfer of heat when in operation, and a thermal engineer strives to improve the system by finding ways to make it more efficient. There are different processes that heat can be transferred from one place to another: conduction, convection and radiation.



Emerging technology

Fig 10.14 In this 3D printing technology, a laser beam is used to selectively melt a layer of metal powder. The melted metal is allowed to cool and solidify by conduction, convection and radiation. A new layer of the metal powder is then applied and the process is repeated. A 3D metal object can be formed through melting layers after layers of metal powder.

Conduction

1. **Conduction** is the transfer of heat through a medium without the transfer of medium from one place to another.
2. Explanation using the Kinetic Theory:
   - Particles at the hot end gain kinetic energy and vibrate more vigorously about their fixed positions.
   - The more energetic particles collide with the neighbouring less energetic particles, thereby transferring their kinetic energy.
   - Eventually, heat will be transferred to the cooler end of the rod without the transfer of the medium.
3. Metals are better conductors of heat than non-metals.
4. Explanation using the Kinetic Theory:
   - Metal atoms are surrounded by free-moving electrons.
   - These free-moving electrons absorb heat and gain kinetic energy to move at greater speeds to the cooler regions of the rod.
   - Electrons collide with neighbouring particles and transfer some kinetic energy to the particles, heating the metal up quicker than non-metals.
5. Conduction in solids is more efficient that in liquids (water) and gases (air) as particles in solids are arranged more closely to one another. This enables transfer of heat to occur more quickly with more frequent collisions.
6. Air and water are poor conductors of heat.
7. **Experiment to compare heat conductivity of solids:** The longer the length of melted wax on the rod, the better the heat conductivity of the material.

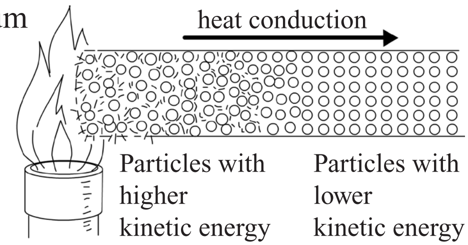


Fig 10.15 Heat is conducted in a solid through the transfer of kinetic energy from more energetic particles to less energetic particles.

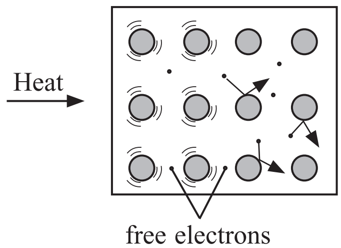


Fig 10.16 Metals are better conductors of heat than non-metals due to the presence of delocalized electrons which move faster over great distances.

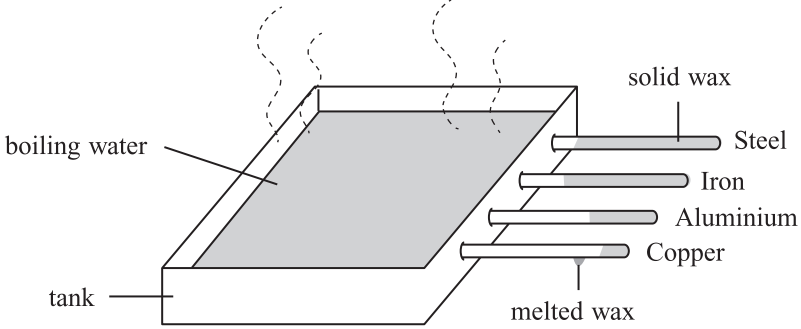


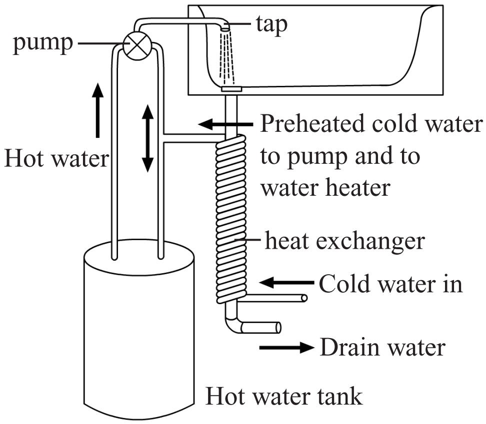
Fig 10.17 Based on the diagram, can you arrange the metals in order from the poorest conductor of heat to the best conductor of heat?

Independent variable: Different metals

Dependent variable: Length of melted wax in a fixed period of time

Fixed variable: Length and cross-sectional area of rod. Experimental time (time for wax to melt)

8. **Everyday examples**:
   - Good conductor of heat: Metals to make cooking pans and copper tubings in heat exchangers.
   - Poor conductor of heat: Winter clothings trap a layer of air to keep people warm, double-glazed windows trap air to reduce heat transfer through the windows.



Sustainability

Fig 10.18 The cold water flows through the copper spiral tube (a heat exchanger) and absorbs heat from the waste water before being heated up further in the hot water tank. By preheating the cold water through recovering the waste heat, less energy is required by the hot water tank to heat the cold water. Note that copper is selected as the material to make the heat exchanger as it is a good conductor of heat, allowing heat from the waste water to be transferred to the cold water quickly.

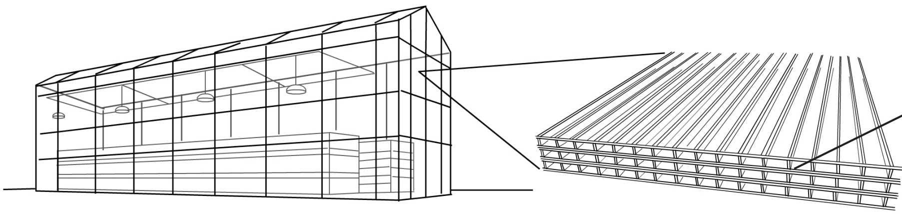
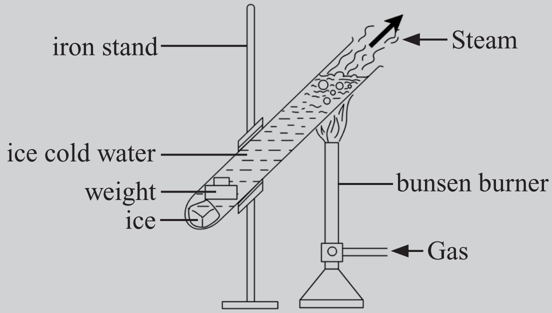


Fig 10.19 Temperature is an important factor that affects the rate of photosynthesis. In cold Northern climates, greenhouses may use air trapped in double-glazed glass panes or multi-walled polycarbonate sheets (shown) to reduce heat loss.

SCIENCE AROUND US

The following shows an experiment performed in school laboratories to show that water is a poor conductor of heat. In the experiment, the ice cube must be kept at the bottom of the test tube.



(a) Why is a weight placed on the ice cube? [1]

(b) The water at the top of the test tube is heated until it boils. Why does the hot water not flow down to the bottom of the test tube? [1]

(c) (i) Through what process does the heat from the top flow down to the bottom of the test tube? [1]

(ii) What would you observe and conclude? [2]

ANSWER

(a) *The weight is to prevent the ice cube from rising to the surface of the water.*

(b) *Hot water is less dense than cold water, so it tends to remain at the top.*

(c) (i) *Conduction*

(ii) *The ice cube takes a long time to melt even when the water started to boil. We can conclude that water is a poor conductor of heat.*

Note

Ice is less dense than water.

Convection

1. **Convection** is the transfer of heat through a medium by the movement of fluid (liquid or gas) due to difference in density.

2. **Experiments to show convection in fluids (gas, liquid):**

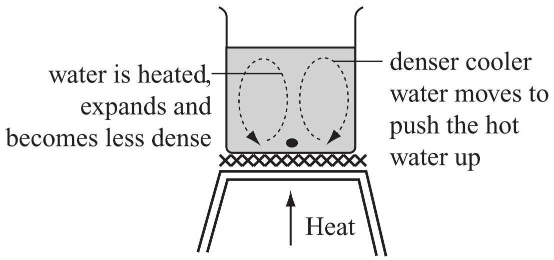


Fig 10.20 Experiment to show convection in liquid

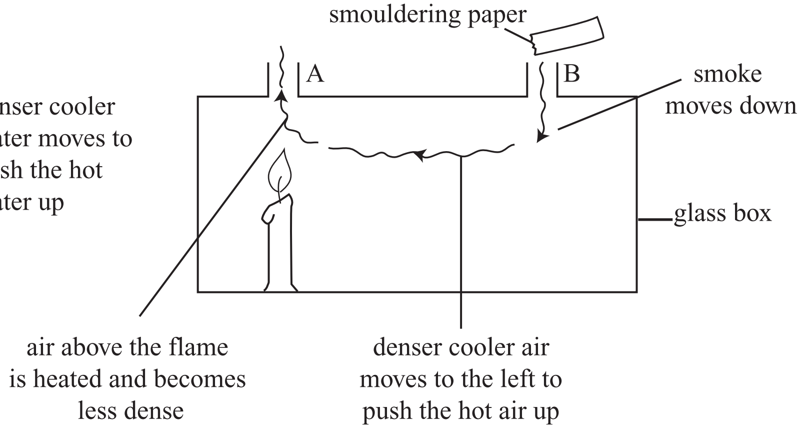


Fig 10.21 Experiment to show convection in gas

3. **Explanation:**
   - When a fluid (liquid or gas) is heated, the heated part of the fluid expands, increasing its volume and lowering its density.
   - The heated and less dense fluid rises to the top.
   - The surrounding cooler, denser fluid sinks to the bottom.
   - This goes on continuously and a convection current is set up, to transfer heat throughout the fluid.
4. Convection only occur in fluids (liquids or gases) and not solids. This is because particles are in fixed positions in solids, and are unable to move like fluids to transfer heat.
5. **Everyday examples:**

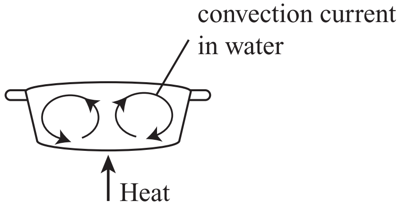


Fig 10.22 Convection currents in a pot when water is heated

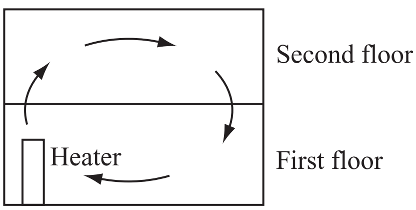
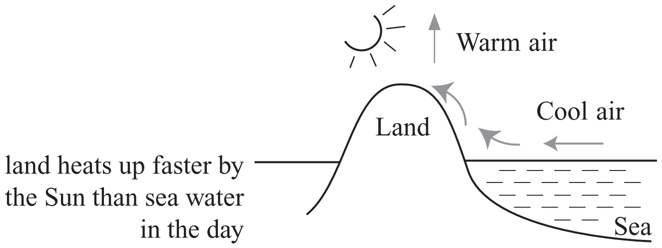
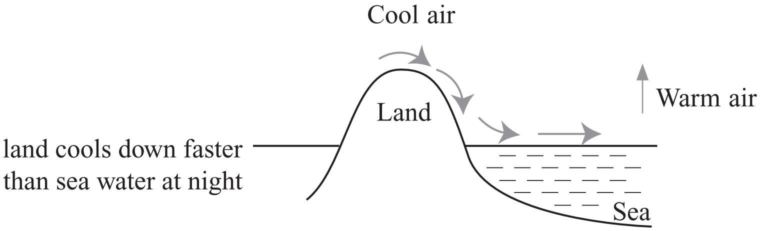


Fig 10.23 Air circulation in a house caused by heater



Sea breeze

Fig 10.24a The denser cooler air above the sea moves to the land and pushes the less dense warmer air up.



Land breeze

Fig 10.24b The denser cooler air above the land moves to the sea and pushes the less dense warmer air up.

Extra

The specific heat capacity of water is about four times the specific heat capacity of most rocks and earth materials. This is why the seas heat up slower than the land during the day. At night, both the land and water lose heat but the land cools down faster than the sea.

Radiation

1. Energy (or internal energy) stored in an object can be transferred to the surroundings as heat radiation.
   The heat radiation is also called infrared, which we can feel with our skin but cannot see with our eyes.
   All objects including animals give out heat radiation from their surfaces.
2. **Radiation** is the transfer of heat from a hotter to a cooler body in the form of heat (infrared) radiation from the surface of a body in all directions, without the need of a medium.
3. **Explanation:**
   Atoms or molecules are in constant motion and collision with one another. During collision, the particles lose kinetic energy, and radiation is emitted.
4. Unlike conduction and convection, radiation does not require a medium for heat transfer. That is how heat radiation travels from the Sun to Earth.

Extra

In upper secondary Physics, you will learn that the internal energy of particles in objects is the sum of the microscopic kinetic energy (motion of particles) and microscopic potential energy (due to intermolecular forces between particles) of the particles.

5. We can detect heat radiation from animals using an infrared camera. We measure our body temperature using an infrared thermometer.

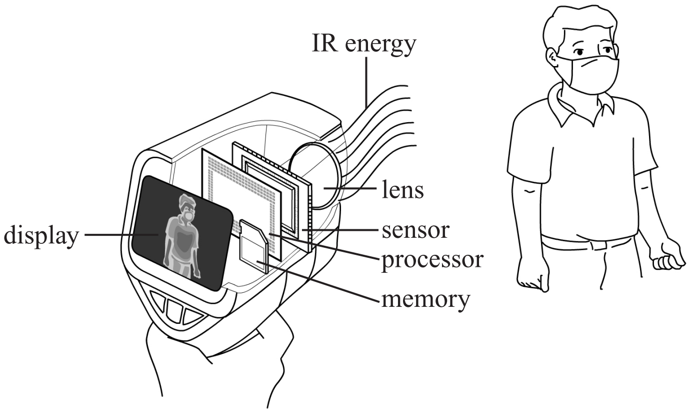


Fig 10.25 An infrared camera has a special detector chip sensor that converts infrared energy (IR energy) to electrical energy. The electronic signals produced are then processed to generate a thermal image on the display.

6. Like light, heat radiation (infrared radiation) is part of the electromagnetic (EM) spectrum, and travels in vacuum at 3×10^8 m/s.
7. All objects emit radiation. Hotter objects emit more radiation than colder objects.
Example:
Suppose a piece of iron is heated. The hot iron emits infrared radiation that is invisible to the naked eye. When it is hot enough at about 460 ºC, it emits visible light and glows red in colour.

Extra

Stars have different colours which help scientists to tell their temperatures. For examples, a red star such as Betelgeuse has a surface temperature of 3000 K, a yellow star such as the Sun has a surface temperature of 6000 K while a blue star such as the supergiant Rigel has a surface temperature of 20 000 K.

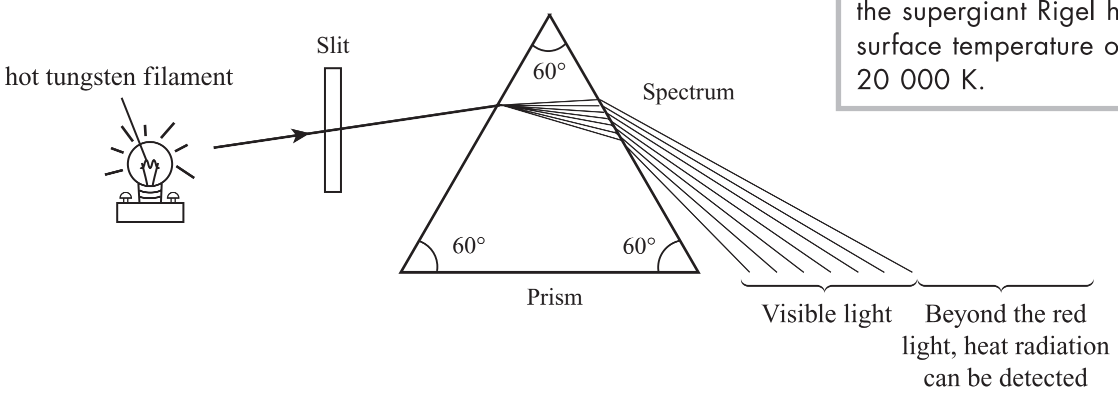


Fig 10.26 The filament wire in the filament lamp is made of tungsten which is a metal of very high melting point. When an electric current passes through the filament lamp, it heats up and produces more infrared. The tungsten begins to produce not only infrared, but also visible light only when it is at a very high temperature.

8. **Factors affecting rate of radiation:**
   - Surface area of the object: A greater surface area emits heat radiation faster than a smaller surface area.
   - Surface temperature of the object: The greater the temperature of the object, the more heat radiation it gives out.
   - Colour and texture of the surface: Black and dull surfaces are better absorbers and emitters of heat radiation than white and shiny surfaces.

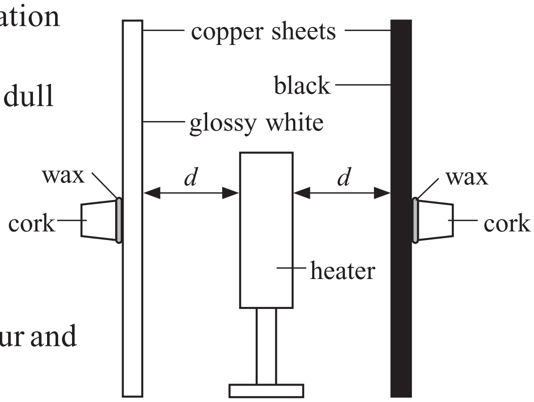
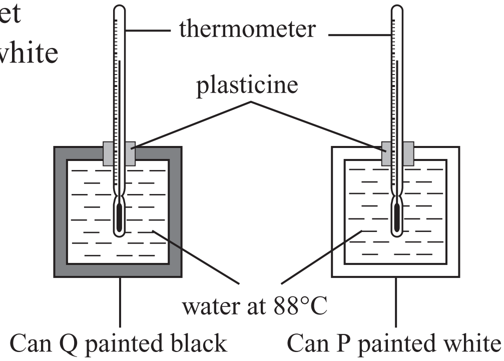


Fig 10.27 The corks are attached to the copper sheets by solidified wax. Which cork will drop first? Why?

9. **Experiment to find out what type of surface absorbs heat radiation better:**
   - Independent variable: Type of surface (the colour and texture of the surface)
   - Dependent variable: Time taken for cork to drop
   - Fixed variables: Distance between heater and sheets, size/thickness of copper sheets, amount of wax, size and mass of cork
   - Results: The cork behind the black copper sheet drops earlier than the cork behind the glossy white copper sheet.
   - Conclusion: Black and dull surfaces are better absorbers of infrared than white and shiny surfaces.
10. **Experiment to find out what colour of surface emits heat radiation better:**
    - Independent variable: Type of surface of can (the colour and texture of the surface)
    - Dependent variable: Rate of heat loss
    - Fixed variables: Size of can, volume of water, initial temperature of water
    - Results from graph: The temperature of water in can Q decreases faster than that in can P.
    - Conclusion: A black surface is a better emitter of infrared than a white surface.



Results:

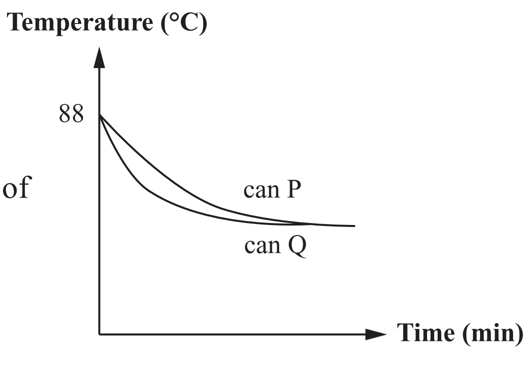
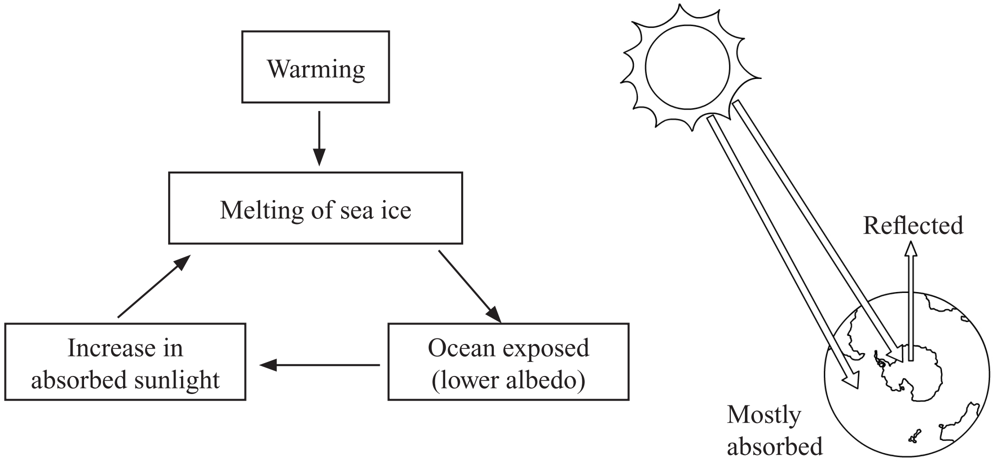


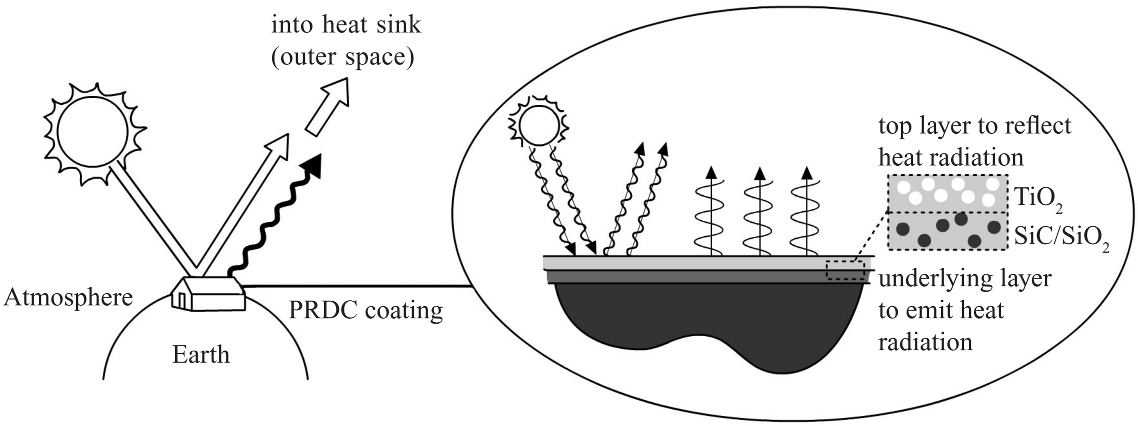
Fig 10.28 Which can of hot water will cool down faster? Why?

11. **Everyday examples:**
    - Shiny and silvered surfaces are used for cooking utensils such as kettles and pots to minimise heat loss by radiation.
    - Black and dull surfaces are used for cooling fins on radiators in cars to maximise heat loss by radiation.



Climate change

Fig 10.29 Light surfaces reflect more heat while dark surfaces absorb more heat. Due to global warming, Arctic ice melts causing the area of light surfaces (Arctic ice) to decrease and the area of dark surfaces (water) to increase. More heat from the Sun is absorbed and less heat is reflected into outer space worsening global warming. This is called the Albedo effect.

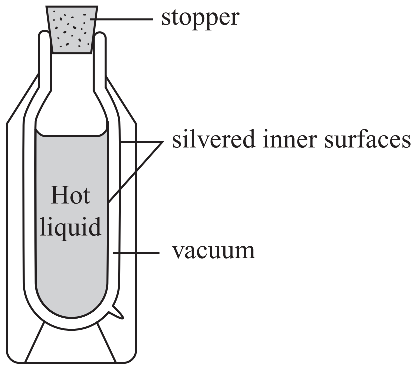


Emerging technology **Sustainability**

Fig 10.30 Is there a surface or material that reflects heat like a shiny surface and emits heat like a black surface? Scientists are developing nanoparticle-embedded coatings that consist of a top reflective layer and underlying emissive layer. Such coatings can help to cool down buildings during the day reducing the use of air-conditioners.

Applications of Heat Transfer

The vacuum flask keeps a hot liquid hot (or keeps a cold liquid cold) for a long time as it prevents heat loss (or heat gain) through conduction, convection and radiation.



Part	Description
Stopper	• made of a poor heat conductor • convection and evaporation can occur only when it is removed
Silvered inner surfaces	• reflect heat radiation back to the contents of the flask
Vacuum	• prevents conduction and convection

Fig 10.31 How does a vacuum flask prevent heat transfer?

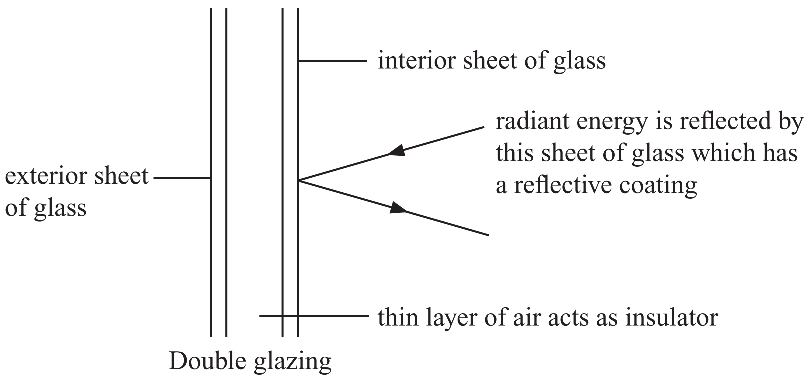
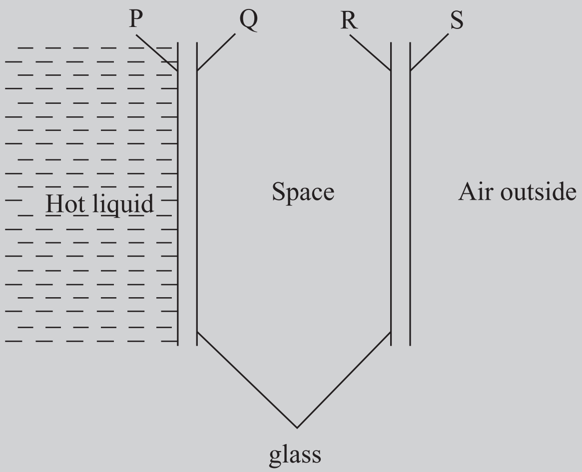


Fig 10.32, In addition to using the layer of trapped air in the double-glazed greenhouse (mentioned in Fig 10.19), a special reflective coating can be used on the inner glass pane to reflect heat radiation back to the air inside the greenhouse to further reduce heat loss.

SCIENCE AROUND US

A flask containing hot liquid consists of a double-layered glass to keep a liquid hot for as long as possible.



(a) Explain why the surfaces P, Q, R and S should be shiny. [1]
(b) Explain why the space between the glass walls should be a vacuum. [1]

ANSWER

(a) To reflect heat radiation back to the content of the flask.

(b) To prevent heat loss through conduction and convection.