Fundamentals of heat transfer

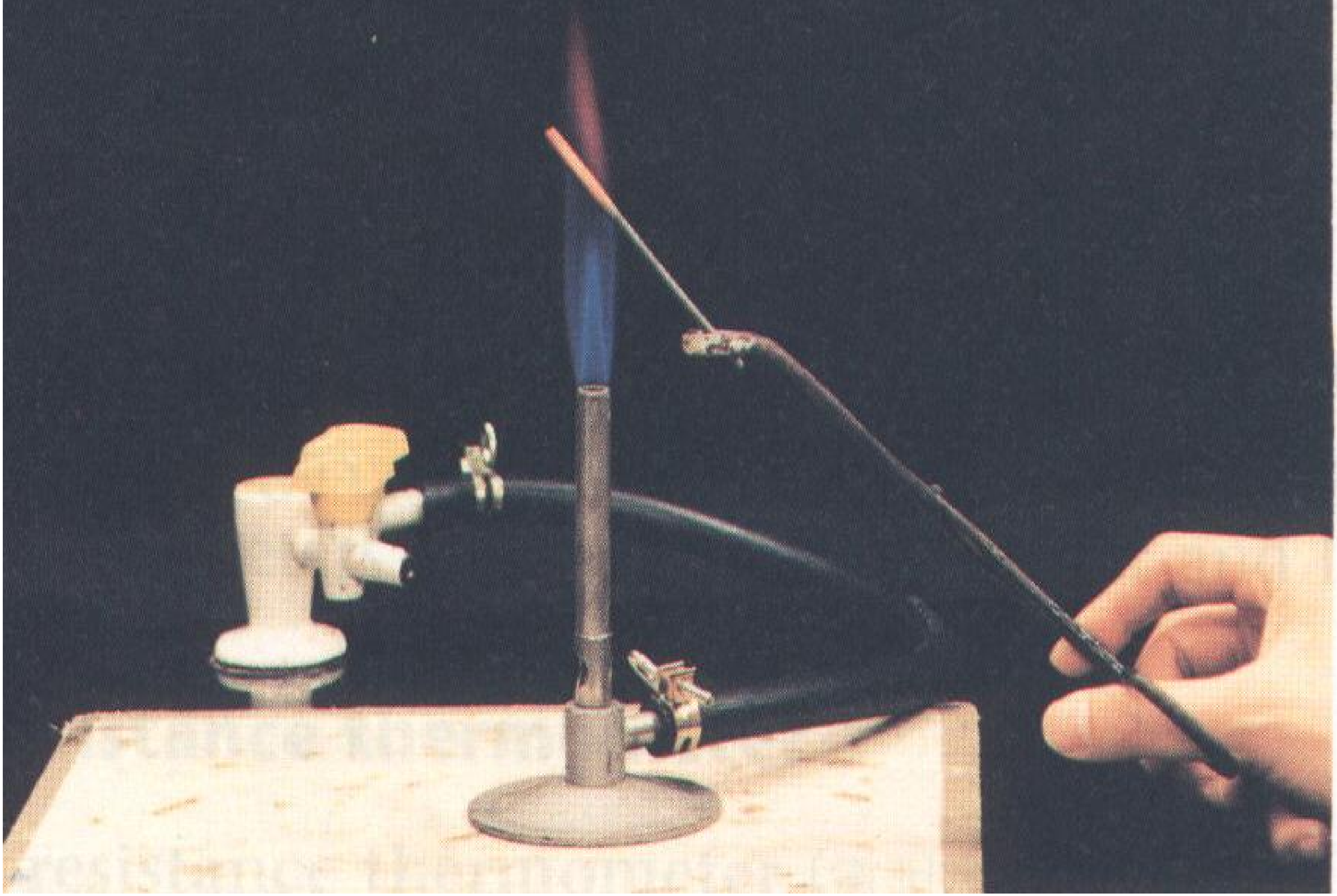
Å State basic laws of heat transfer

Å Estimate heat transfer rates by different modes

Å Use the concept of thermal resistance to solve steady state heat transfer problems

Å State and use the analogy between heat, mass and momentum transfers

Conduction, Convection and Radiation



Basic modes of heat transfer

There are three basic modes of heat transfer

(i) Conduction

(ii) Convection

(iii) Radiation

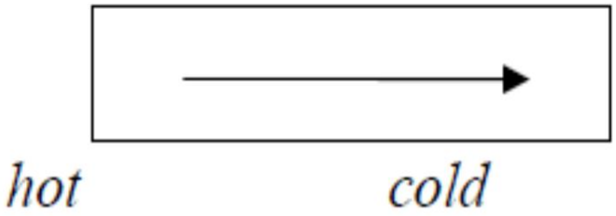
Exchange of heat between bodies occurs through **one of these modes or a combination of them**.

They have in common that **temperature difference** must exist and that **heat is always transferred in the direction of decreasing temperature**.

But they differ entirely in the **physical mechanism and laws** by which they are governed.

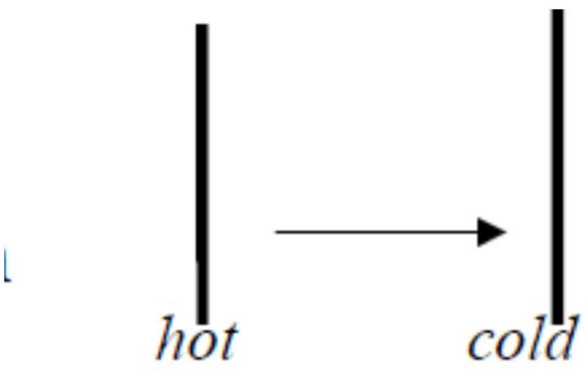
Basic modes of heat transfer

Conduction
Through solid bodies and still fluid



Convection
Through moving fluids
(also boiling and condensation)

Radiation
Between surfaces through gas or vacuum



Examples

The instructor giving a test to the students in a class room, may cause the question paper to reach the farther most student in a row by any of three possible methods mentioned below

Question paper : Heat energy

Students: Heat transfer medium (molecules of the substance)

(1) He could deliver the paper to the students nearest to him who delivers the same to the next and so on till it finally reaches the last students. This is analogous to heat conduction in solid.

Examples

2) He could also carry the paper himself to the other end of the row.

   Heat convection in liquid and gases

3) As a last alternative, he could throw the question paper so that it reaches the last student.

   Thermal radiation in vacuum or most gases

Examples

Consider that a house has caught fire which is being extinguished by people who carry water from well to the site of fire.

Water: Heat

People: Heat transfer medium

(1) A person at the well delivers the water bucket to a person nearest to him who delivers the same to the next and so on till finally the bucket reaches the fire site. Here the water goes from the well to the site through the medium. This is analogous to heat conduction in solid.

Examples

2) The person at the well becomes the single runner (represent the medium) and carries the water from the well to the site.

Heat convection in liquid and gases

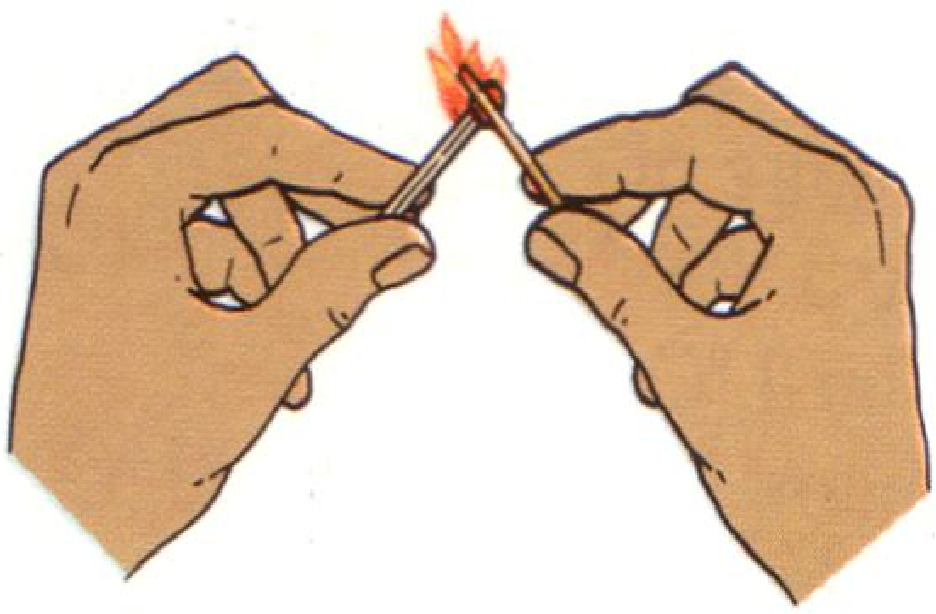
3) The person with the help of a hose directs the water from the well to the house independently of the medium.

Thermal radiation in vacuum or most gases

Conduction

Å Get a piece of stiff copper wire about the same length as a match.

Å Strike the match and hold the copper wire in the flame.



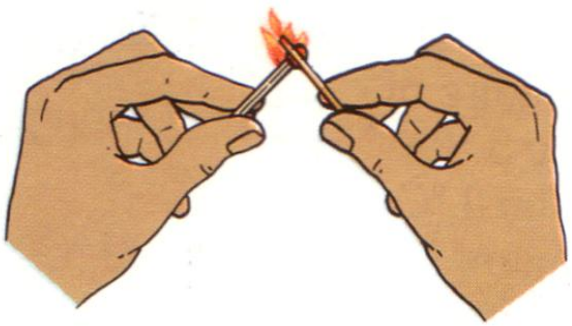
Conduction

Å What happens?

The copper wire is heated up.

Å Does the energy get to your hand quicker through wood or through copper?

Å We say that copper is a better conductor than wood. The energy has traveled from atom to atom through the copper.



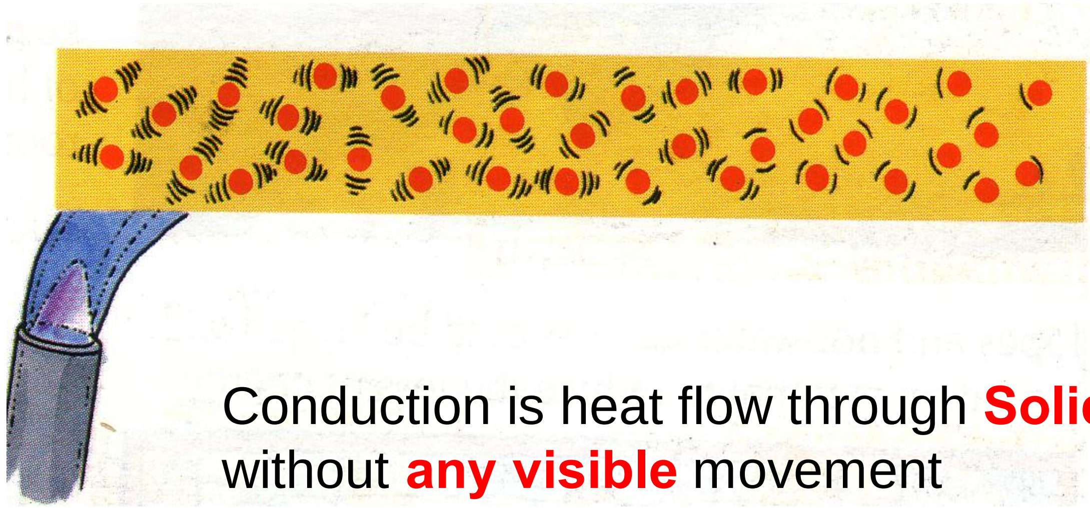
Conduction

Heat conduction is a mechanism of heat transfer from a region of high temperature to a region of low temperature within a medium (solid, liquid or gas) or between different mediums in **direct physical contact**.

OR

If the flow of heat is a result of transfer of internal energy from one molecule to another, the process is called conduction.

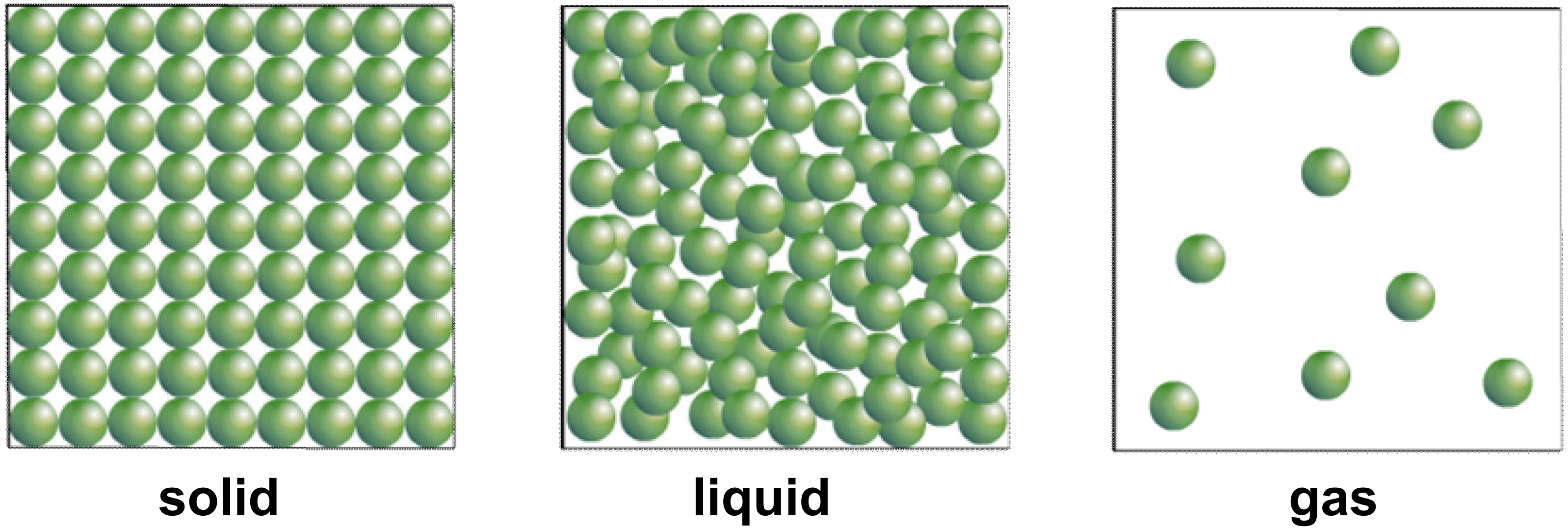
1. Molecular activity
2. Electron drift



Conduction is heat flow through **Solids** without **any visible** movement

Conduction

How are the particles arranged in a solid, a liquid and a gas?

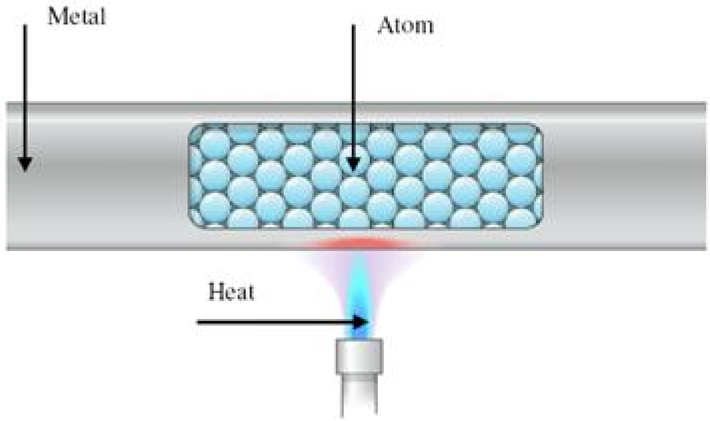


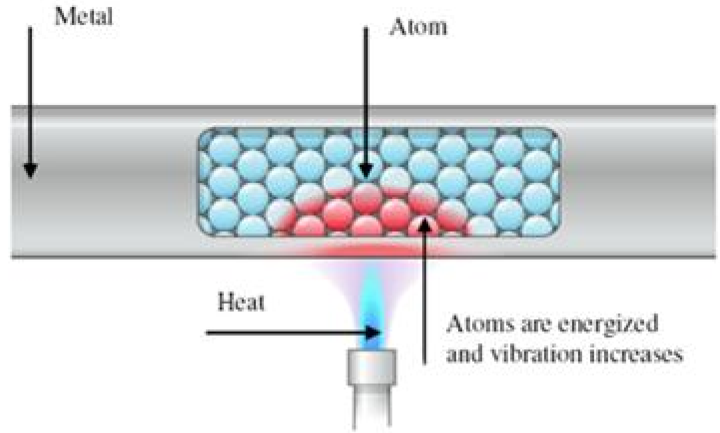
Particles that are very close together can transfer heat energy as they vibrate. This type of heat transfer is called **conduction.**

Conduction is the method of heat transfer in **solids** but not liquids and gases. Why?

What type of solids are the best conductors?

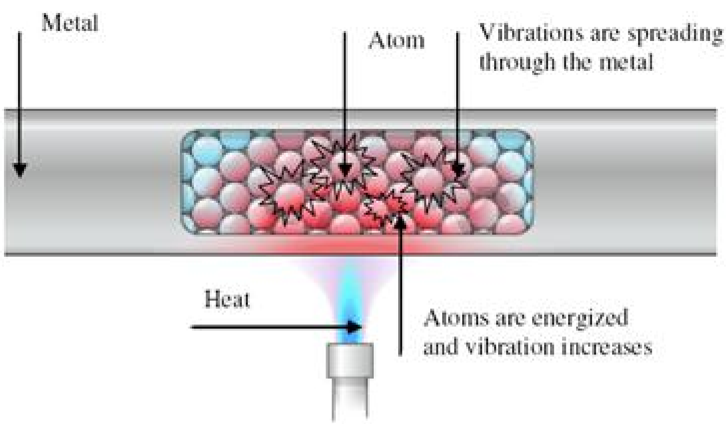
Conduction





The metallic rod is being heated

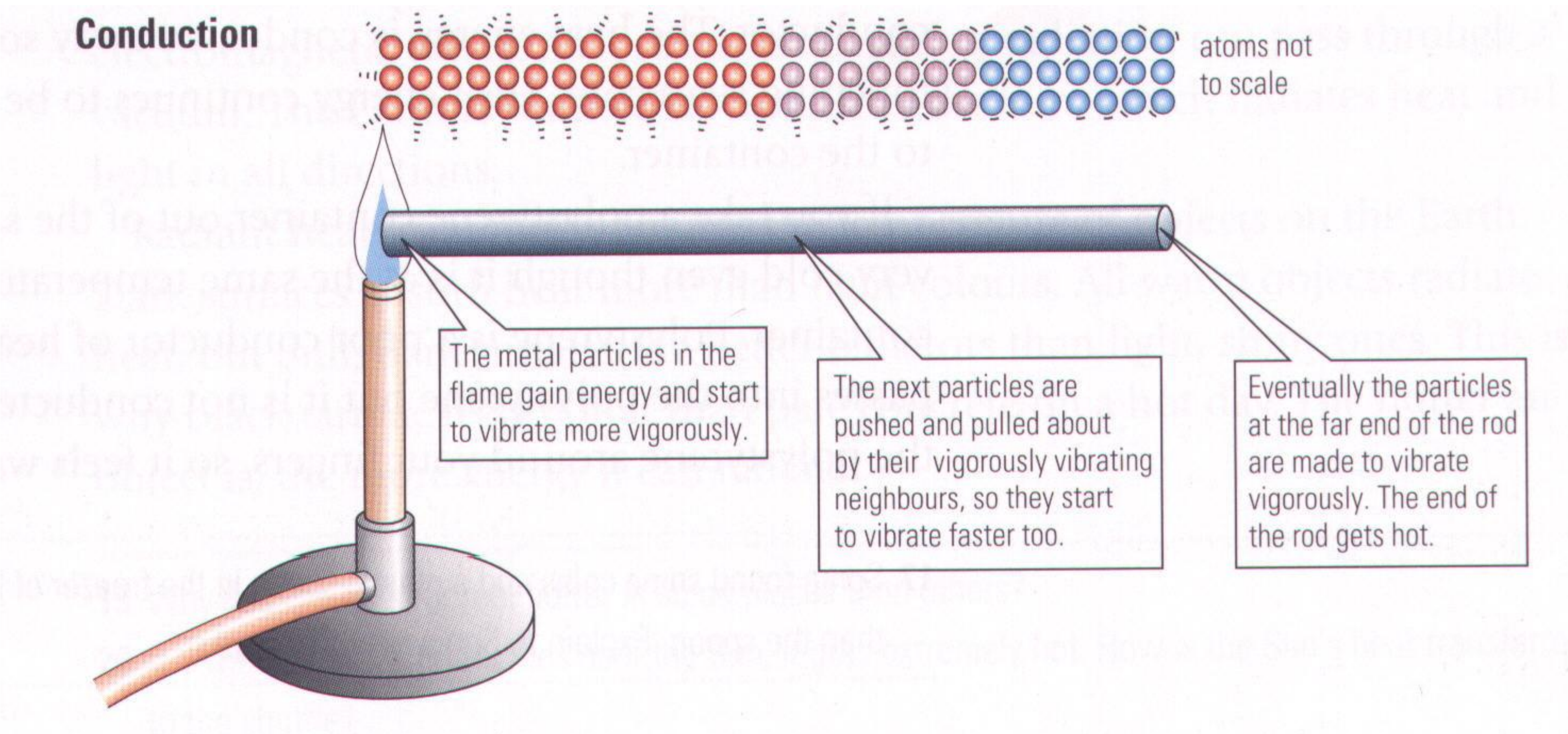
The energy is transferred to the atoms and vibration of the atoms started



As more energy is transferred to the atoms, the vibration increases as well as transferred to the other atoms

Conduction

Conduction is the process by which heat is transmitted through a medium from one particle to another.



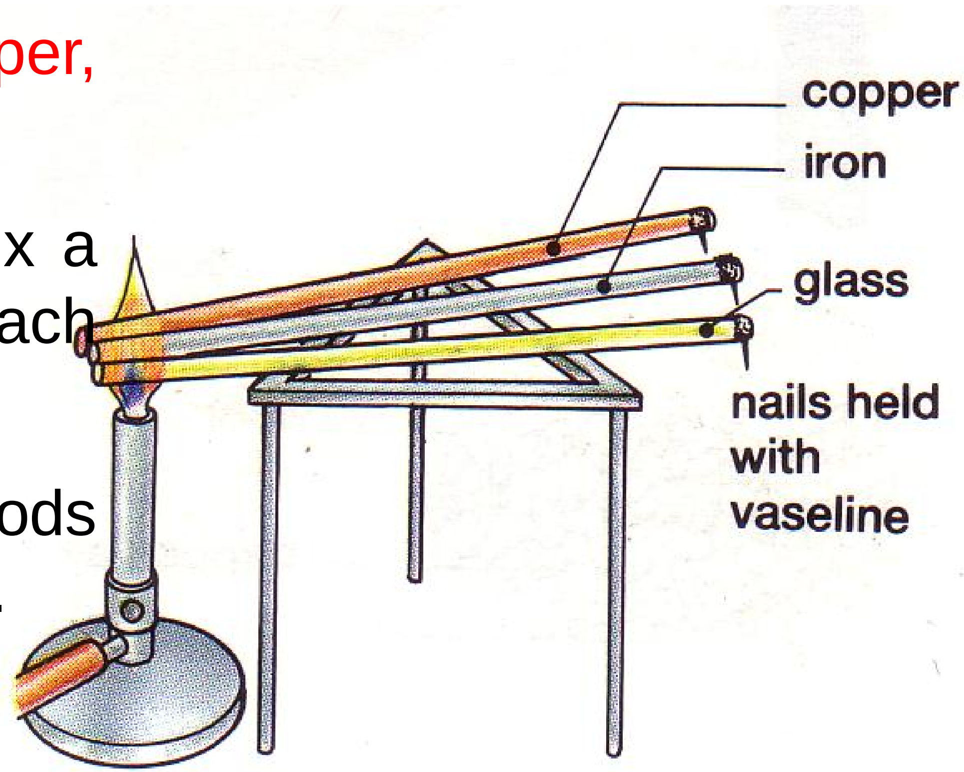
Conduction

Get three rods of the same size.

The rods are made of copper, iron and glass.

Rest them on a tripod and fix a small nail at one end of each rod.

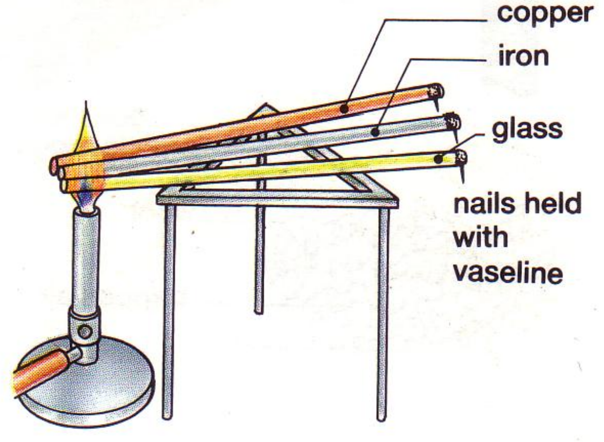
Heat the other ends of the rods equally with a Bunsen Burner.



What happens?

The nails from different materials dropped off from the rod at different time.

Conduction



Material	Time taken for pin to drop(s)
copper	14
iron	73
glass	Did not drop

From the experiment it shows that nail from the copper drops off first at 14 seconds.
This is because heat travels faster through copper than iron and glass.
We say that copper is a good conductor of heat.

Conductor

Good conductors of heat refer to objects that can conduct heat very fast.

All metals are good conductors of heat.

Examples:
Copper, silver, iron, mercury are good conductors.

Insulators

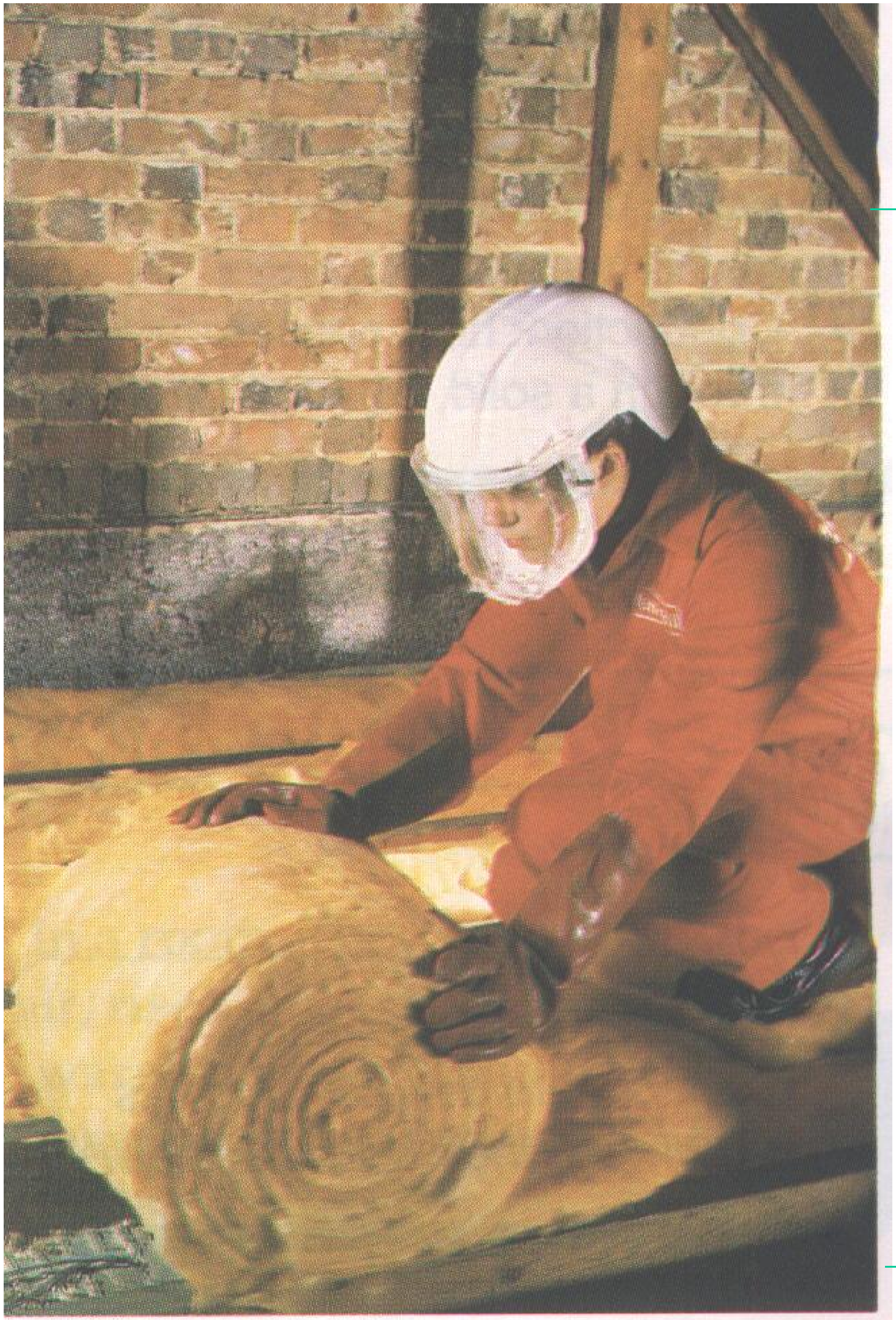
Insulators are materials that heat cannot travel through.

They are poor conductors of heat.

Poor conductors are good insulators.

Non-metals, such as plastic and air, are poor conductor.

Liquids and gases are usually poor conductors
The poorest conductor is vacuum.



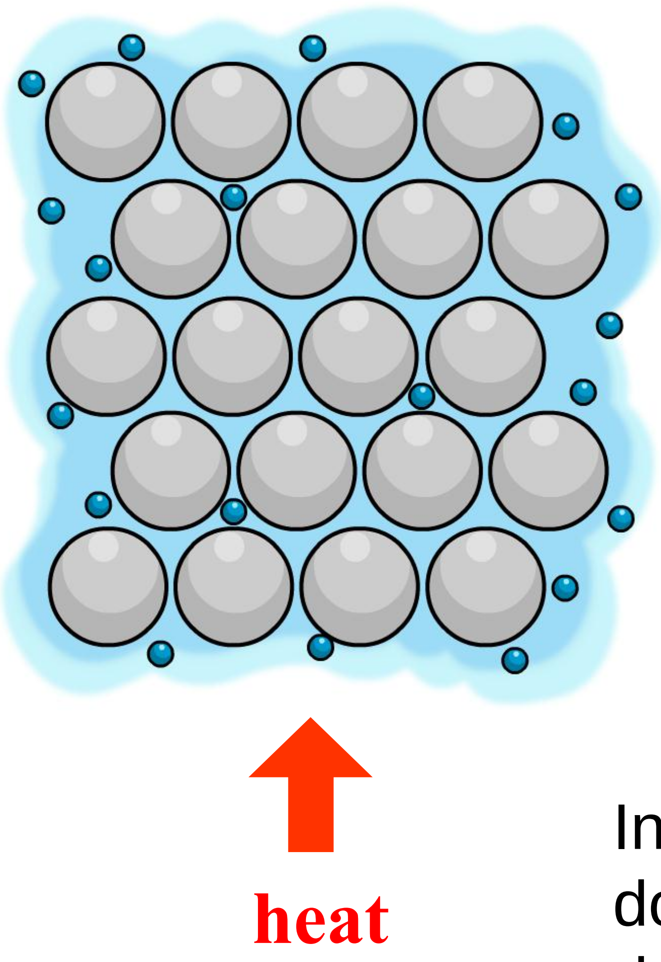
Insulators

Insulators are used to lag pipes, lofts, hot water tanks and many other objects.

Fiber glass insulation is a popular choice for home insulations.

Conduction

The outer electron of metal atoms drift and are free to move.



Metals are good conductors of heat. The outer electrons of metal atoms are not attached to any particular atom. They are free to move between the atoms.

When a metal is heated, the free electrons gain kinetic energy.

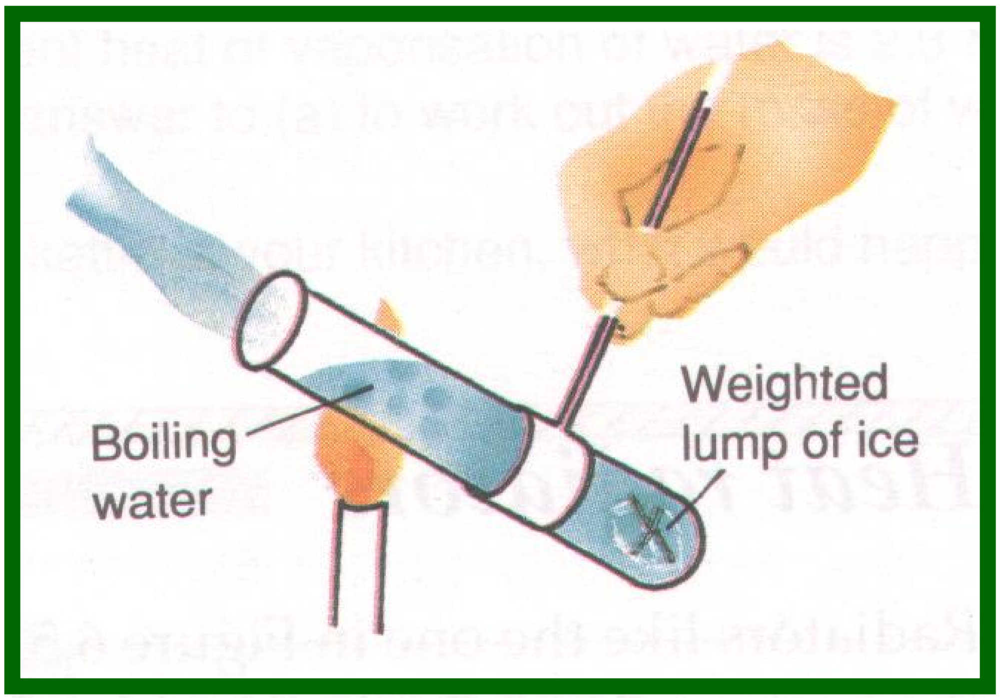
This means that the free electrons move faster and transfer the energy through the metal.

This makes heat transfer in metals very efficient.

Insulators such as wood and plastics do not have free electrons and so they do not conduct heat as metals.

Test Yourselves

Å Heat a test tube of water near the top with a óweightedô ice cube near the bottom. Even when the water at the top starts boiling, the ice cube does not melt. Why ?

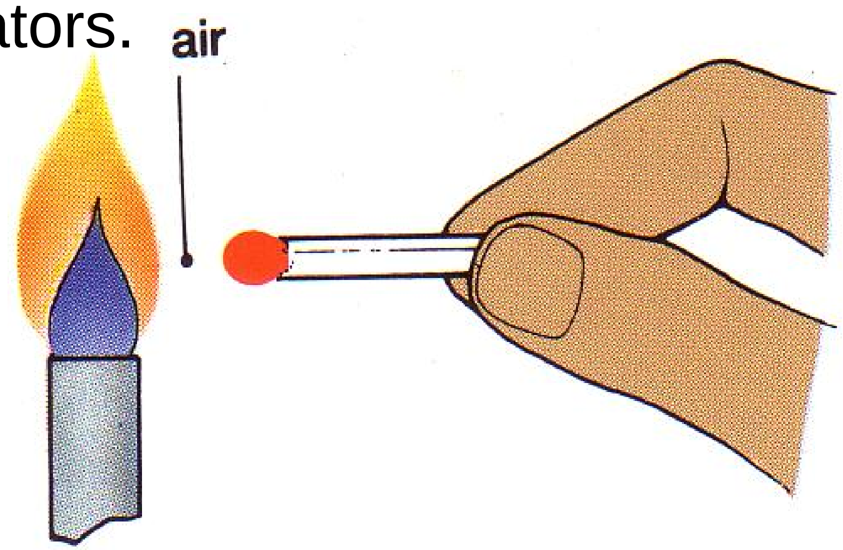


Ans.: Water is a poor conductor of heat.

Is air good conductor or insulator

Hold a match about 1 cm away from a very hot Bunsen flame.
Does the match get hot enough to burst into flame?

This shows that air is a very poor conductor ï it is a very good insulators.



All gases are poor conductors.

Conduction

Å In gases and liquids, conduction is due to the collisions and diffusion of the molecules during their random motion.

Application of conduction

Soldering iron

Å Iron rod is a good conductor of heat with copper tip.

Å The handle is made of plastic which is a good insulator.

Application of conduction

Home electrical appliances

Å The handles of kettles, hot iron, cooking utensils are made of wood and plastics which are the good insulators of heat.

Insulation

Å The air trapped in the fur and feather to keep animals warm.

Å Birds fluff up their feathers in winter to trap more air.

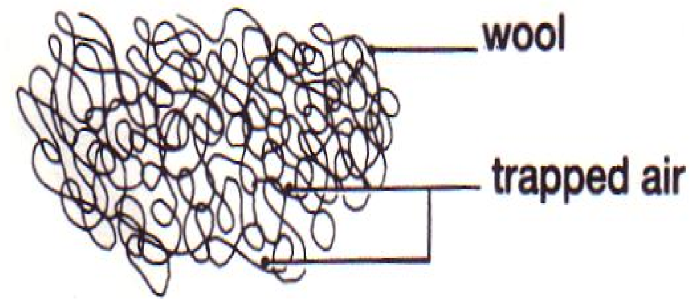
Å Polar bears have thick fur to trap more air and keep them warm.

Insulation

Å A refrigerator has insulation material round it to keep it cold.

Å The insulation reduces the amount of heat conducted to the inside from the warmer room.

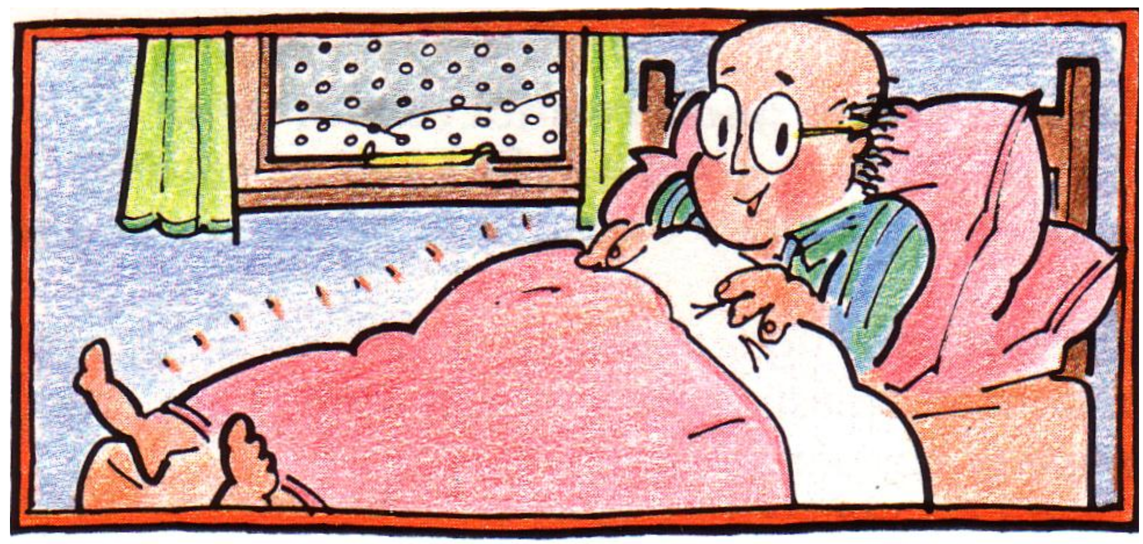
Insulation



Å Many insulators contain tiny pockets of trapped air to stop heat conducted away.

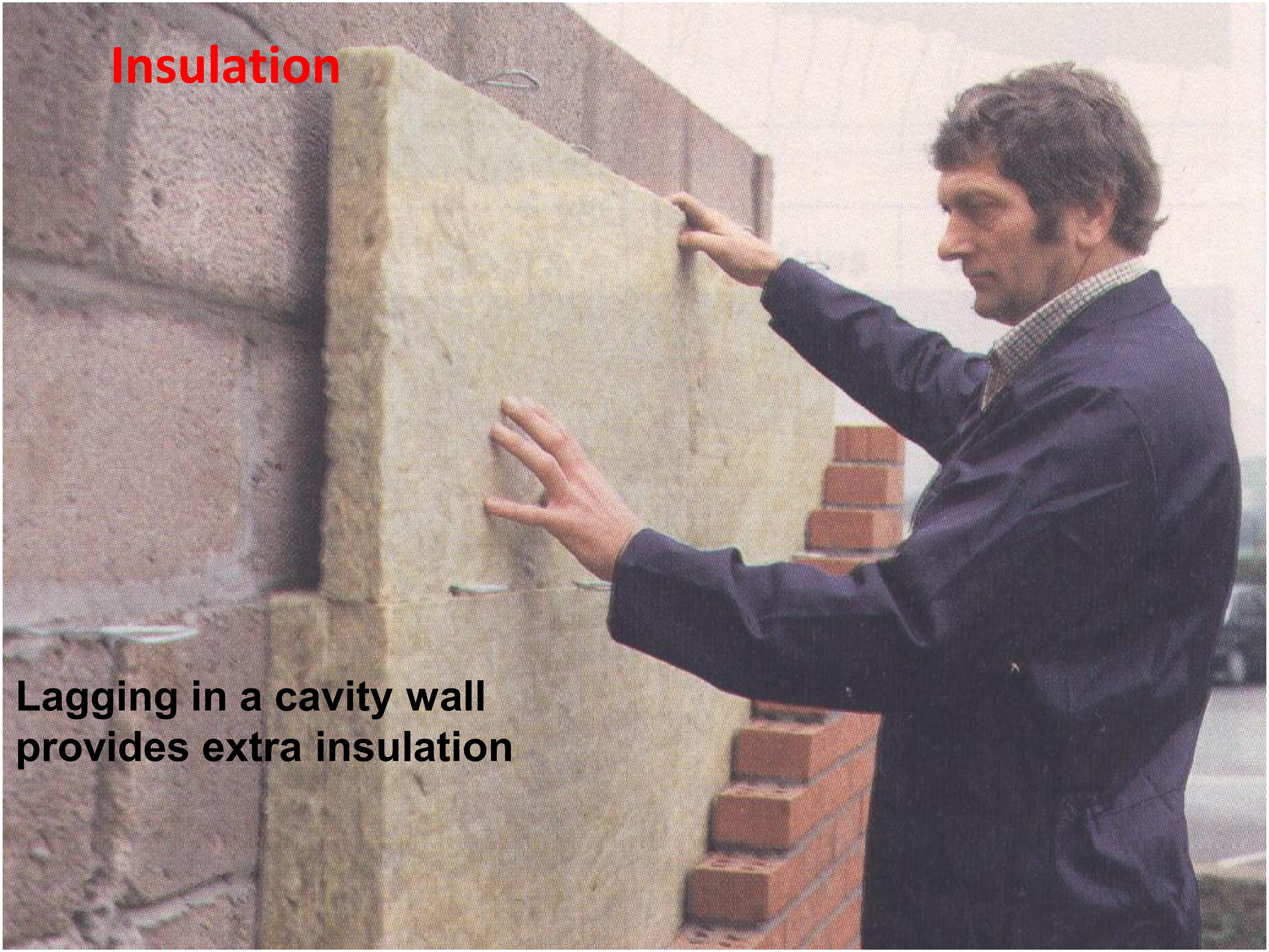
Å Wool feels warm because it traps a lot of air.

Å The air trapped in and between our clothes and blankets keeps us warm.



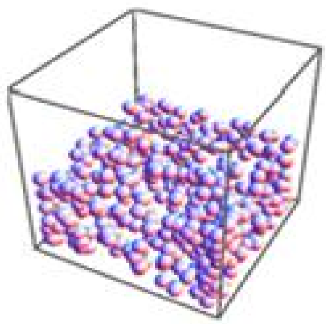
Insulation

Pipes and hot-water tanks are lagged with insulation material to reduce the loss of **energy.**

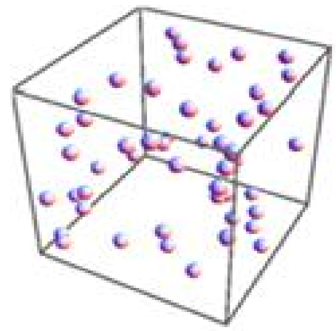

Insulation
Lagging in a cavity wall
provides extra insulation

Convection

In liquid and gases, the molecules are no longer confined to a certain point put constantly change their positions even if the substance is at rest. The heat energy is transported along with the motion of these molecules from one region to another. This process is called convection.

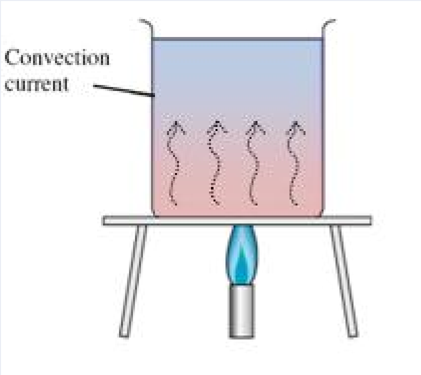
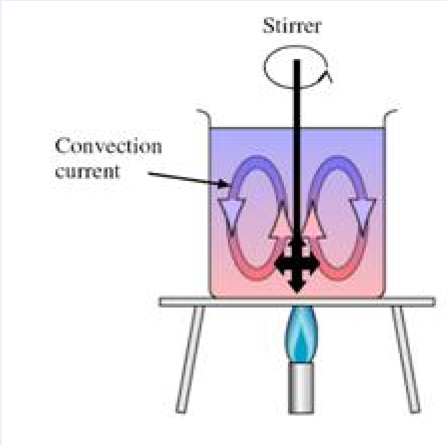


(a) Liquid

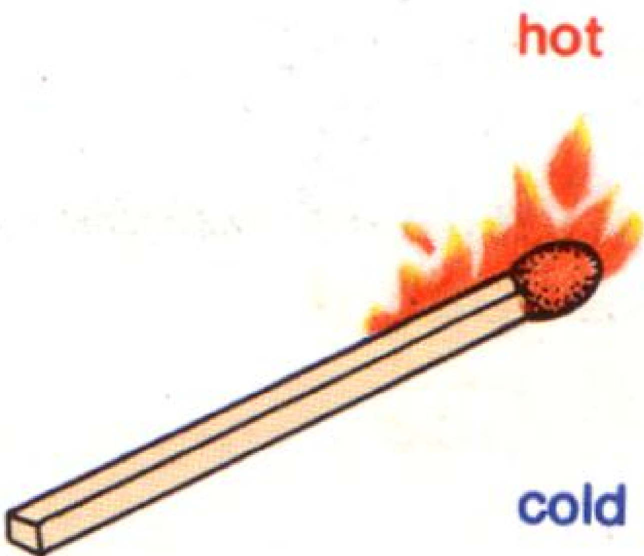


(b) Gas

Convection is the transfer of heat by the actual movement of the warmed matter

Free convection	Force Convection
In natural convection, the movement of the fluid particles is due to the buoyancy forces generated due to density difference of heated and colder region of the fluid	in forced convection the movement of fluid particles from the heated region to colder region is assisted by some mechanical means too (e.g. stirrer)
	

Convection



Hold your hand over and under the flame of a match.

What do you notice?

Why?

Hot air expands, becomes less dense and then rises.

Heat is convected upwards.

Convection

Convection is the process by which heat is transmitted from one place to another by the movement of heated particles of a gas or liquid.

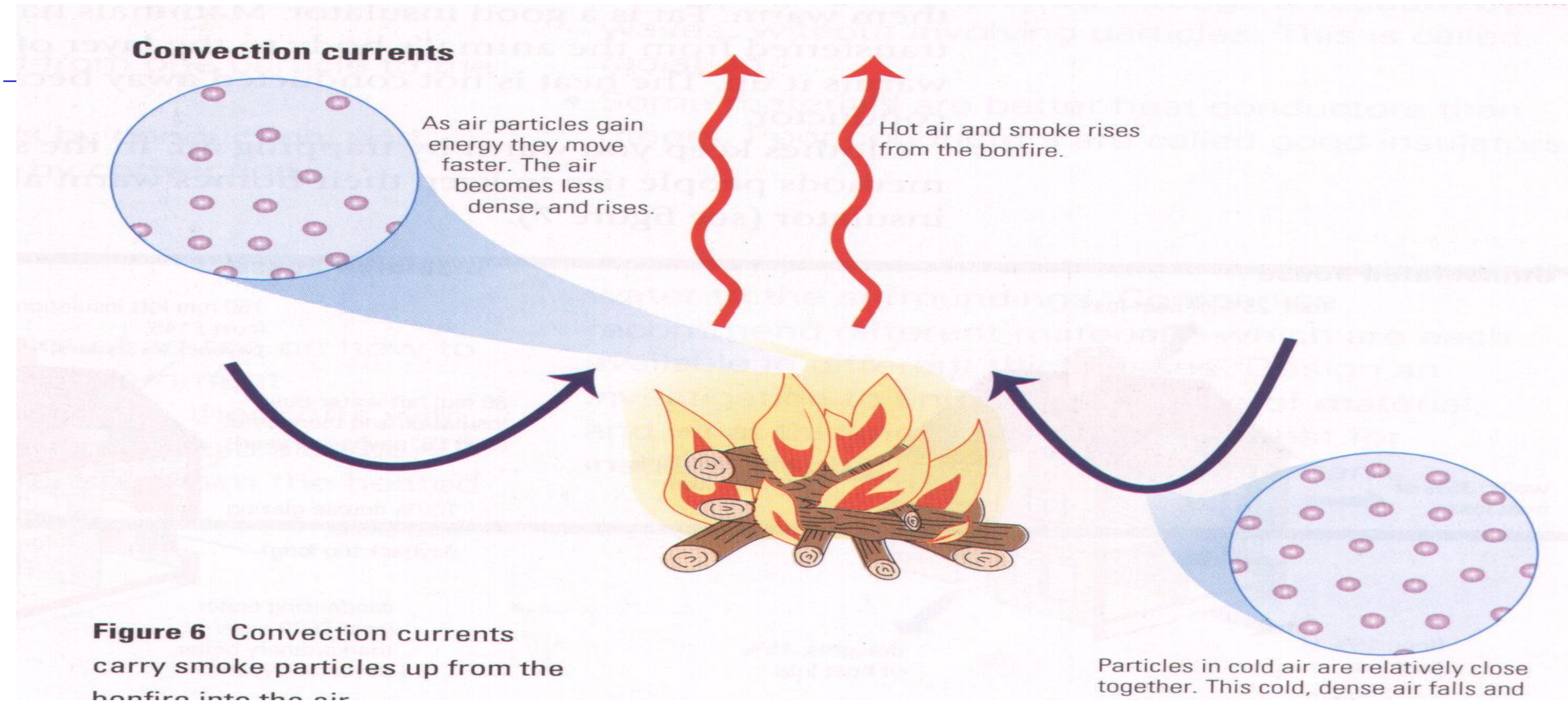
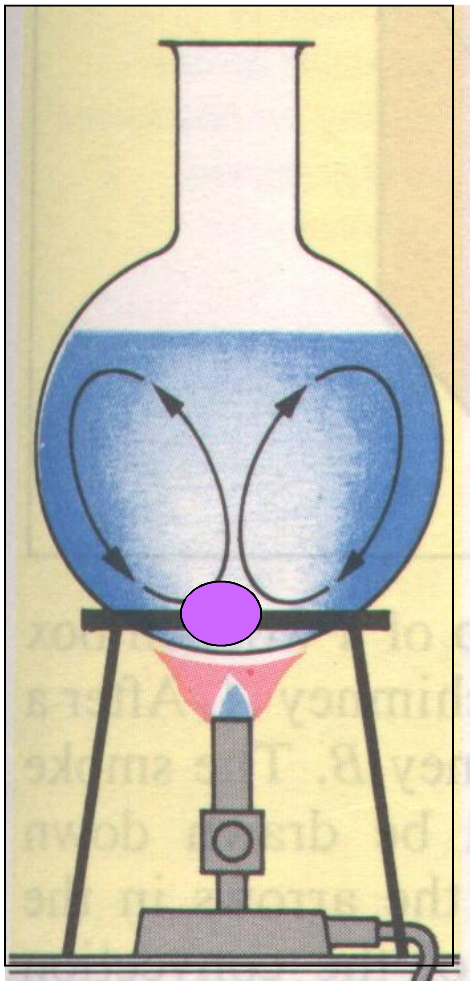


Figure 6 Convection currents carry smoke particles up from the bonfire into the air

Convection in Liquid



Å To demonstrate convection in water, drop a few tiny crystals of potassium permanganate into a flask filled with water.

Å Gently heat the flask, purple streaks of water will rise upwards and then fan outwards.

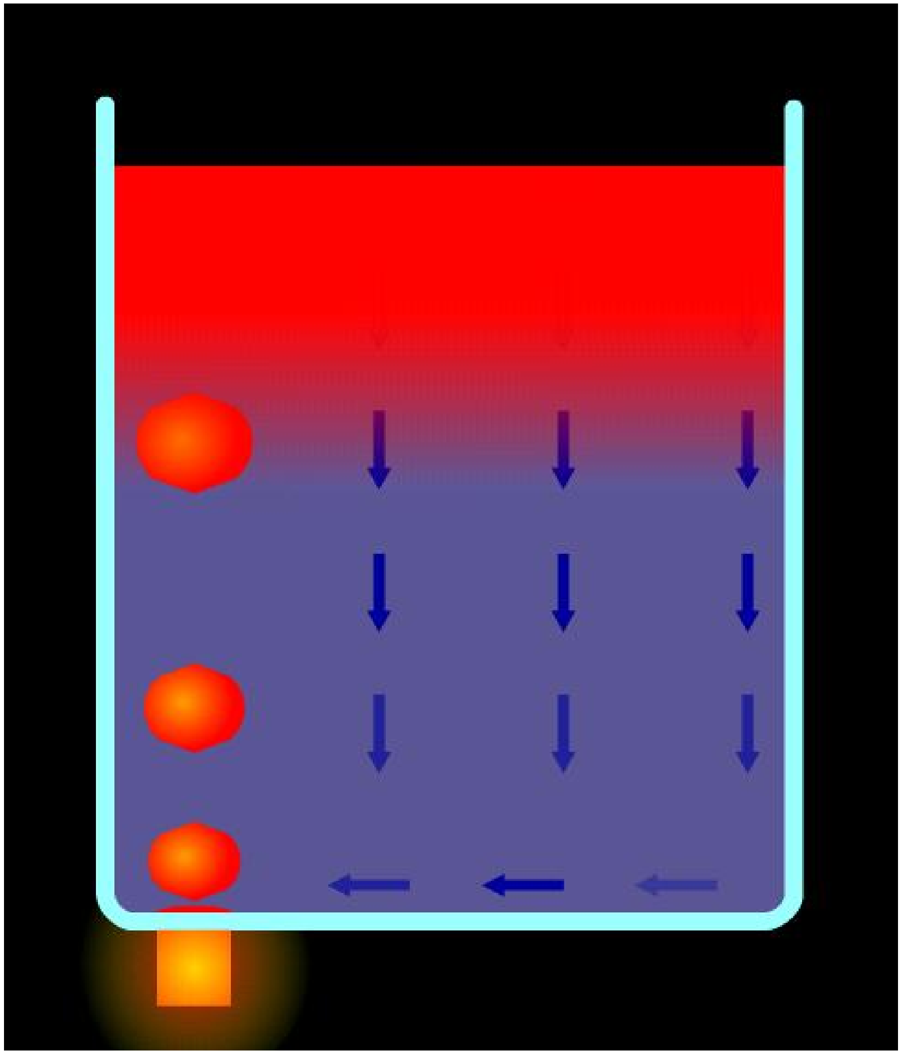
Å The water becomes uniformly purplish after some time.

Å The circulation of a liquid in this matter is called a convection current.

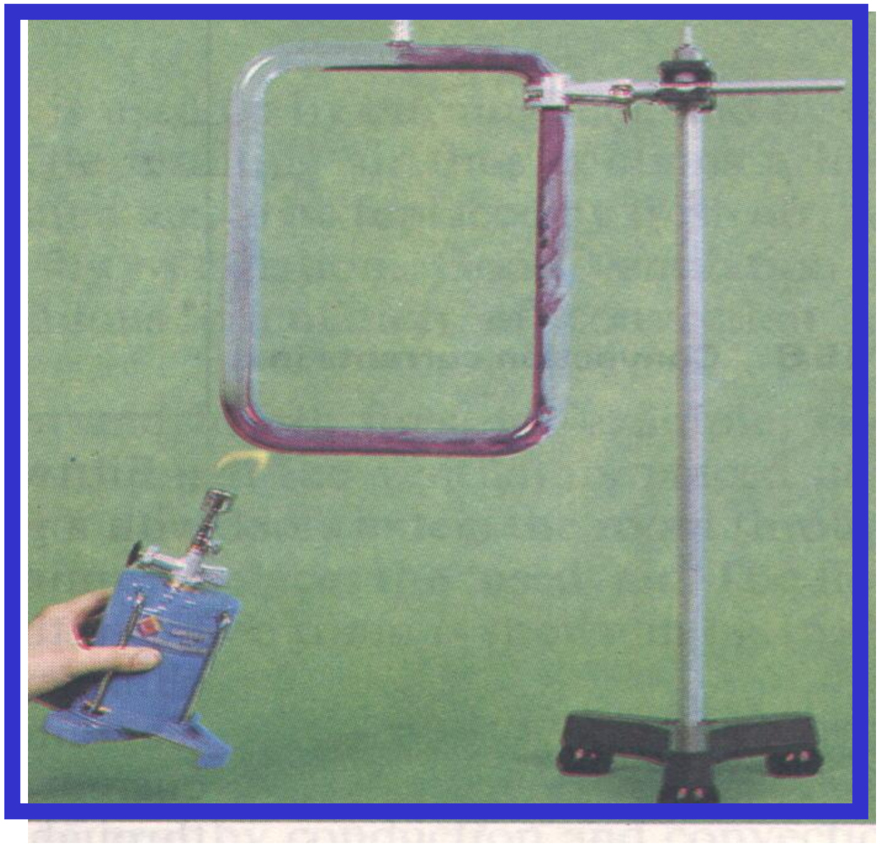
Thinking :

Why hot water rises and cold water sinks ?

Convection in Liquid

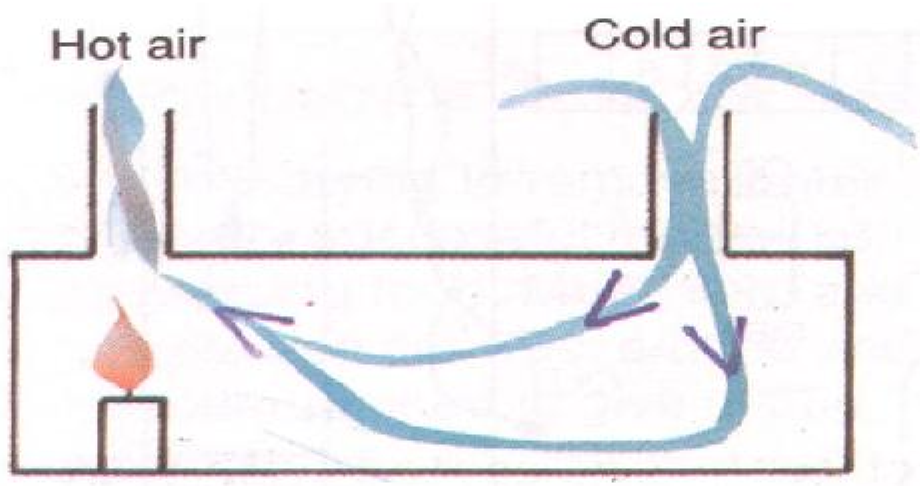


Convection in Liquid

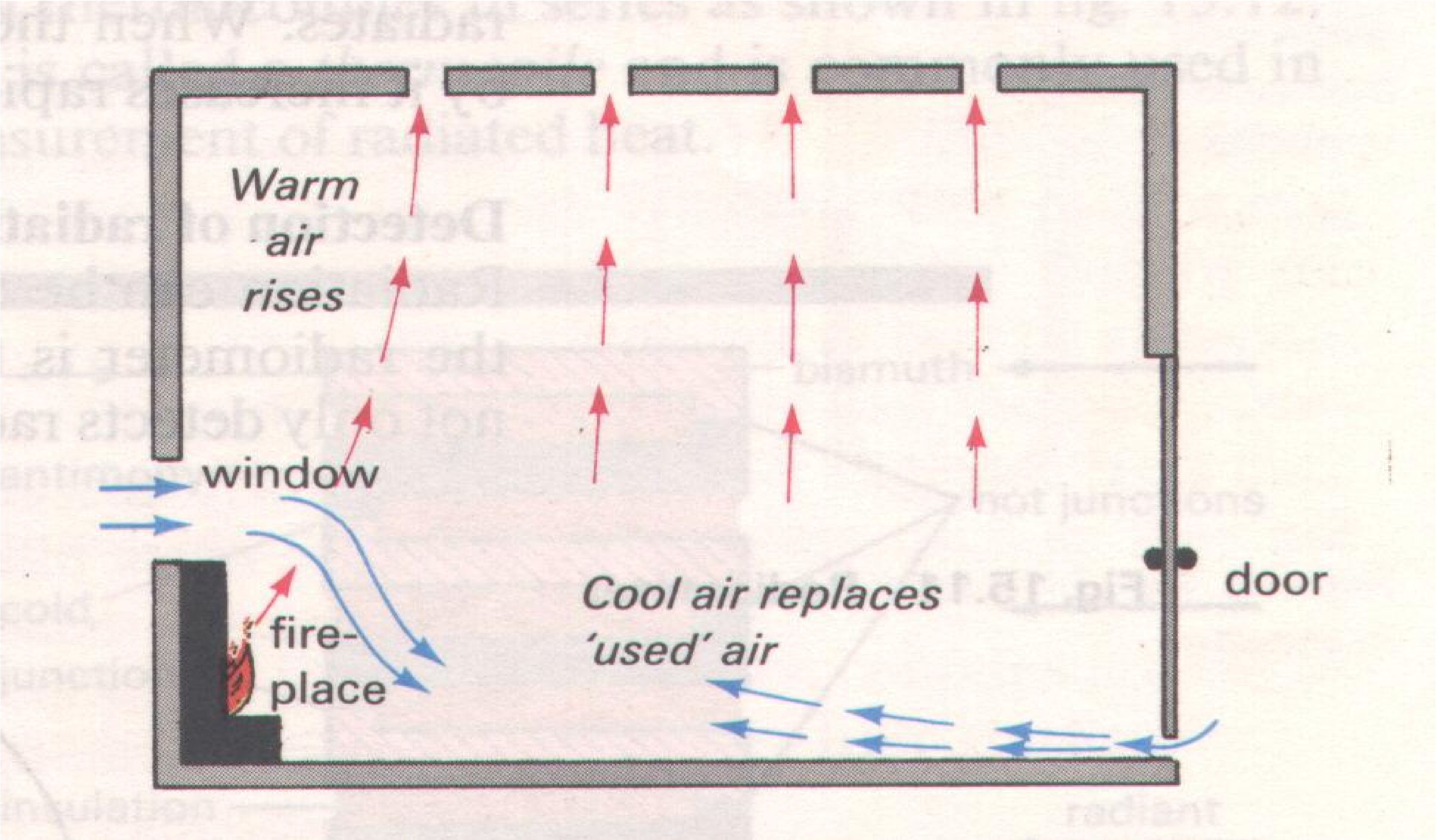


Convection in Gases

The fig. shows a simple demonstration of convection of gas. The hot gases from the burning candle go straight up the chimney above the candle. Cold air is drawn down the other chimney to replace the air leaving the room.



Concept on ventilation of a room with fire place

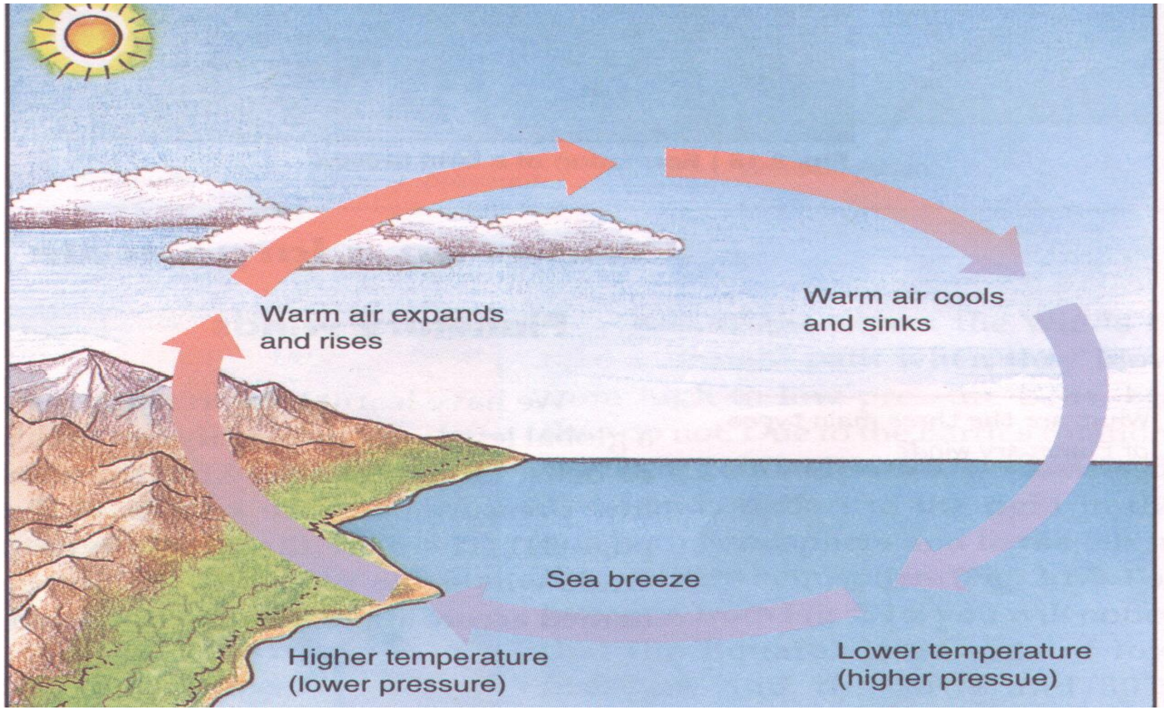


Test Yourselves

1. Usually, it is better to install air conditioner in the higher portion of the wall. Please explain this statement with reasons.

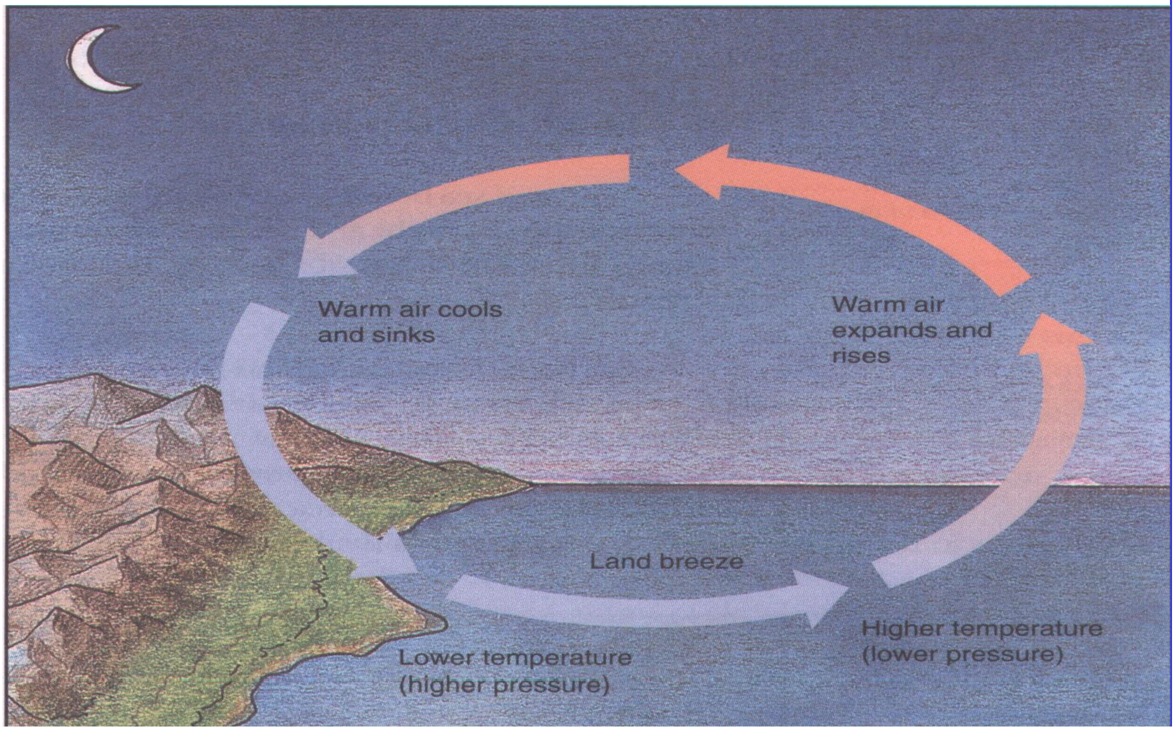
2. How are winds forms ?

3. Why is the heating coil of an electric kettle placed near the bottom of the vessel ?



Application of convection

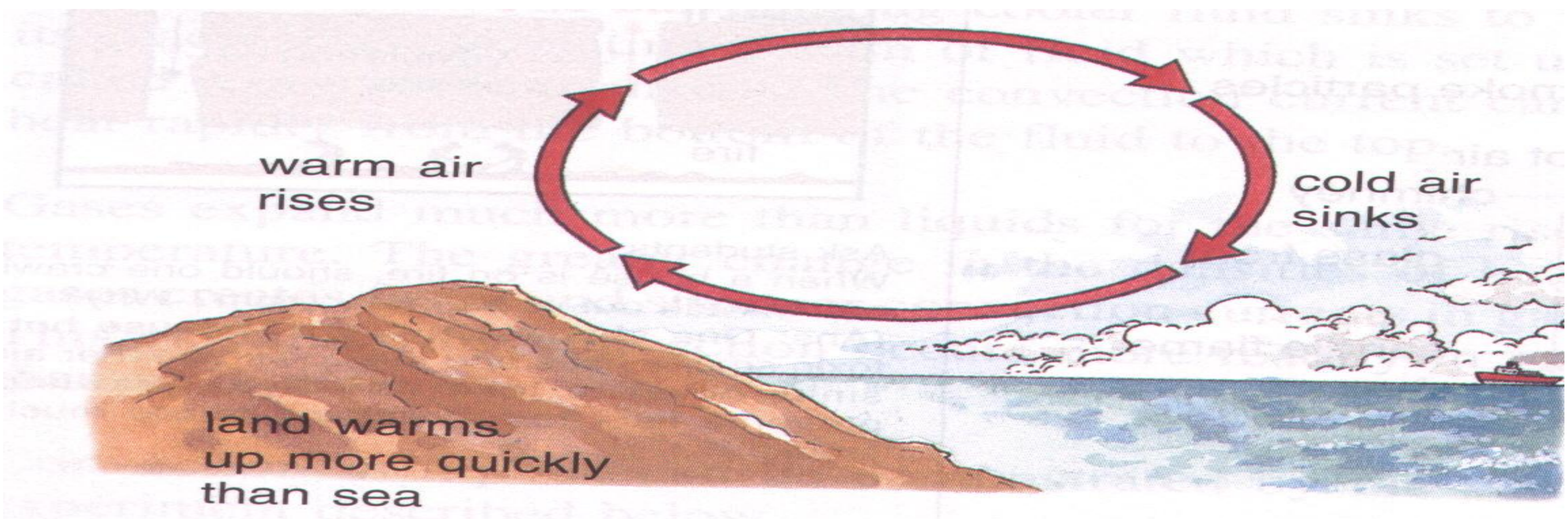
Sea Breeze



Land Breeze

Sea Breeze

Å During the day the sun heats the land much faster than the sea.
Å The air above the land is heated, expands and rises.
Å Cold air from the sea moves inland to take its place.
Å Hence, sea breeze is obtained.



Discussion : How land breeze is produced ?

Land Breeze

At night:

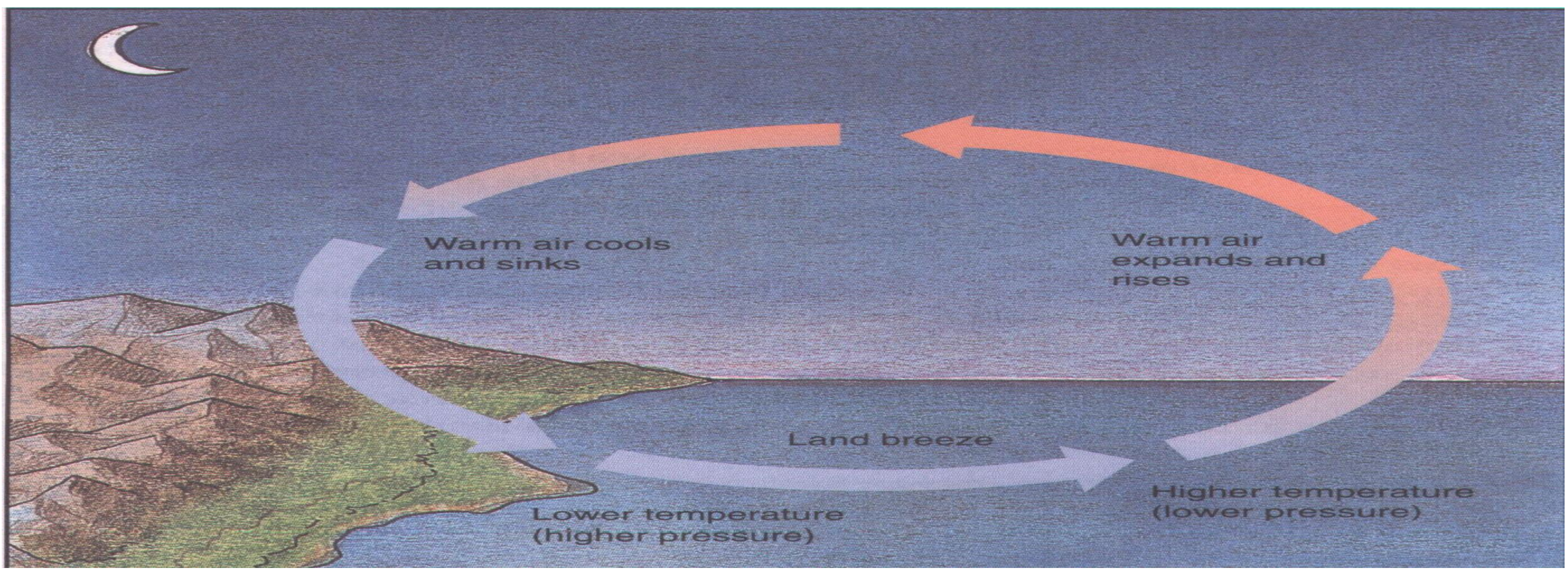
Å Land loses heat faster than the sea.

Å Hot air above the sea which is less dense, expands and rises.

Å Cold air from the land moves towards the sea.

Å Convection current is formed.

Å Land Breeze is obtained.



Application of convection

Electric kettle

- Å The heating element is always placed at the bottom of the kettle.
- Å So that hot water at the bottom which is less dense will rise up.
- Å Cooler water at the top which is denser will sink to the bottom.
- Å Convection current is set up to heat up the water.

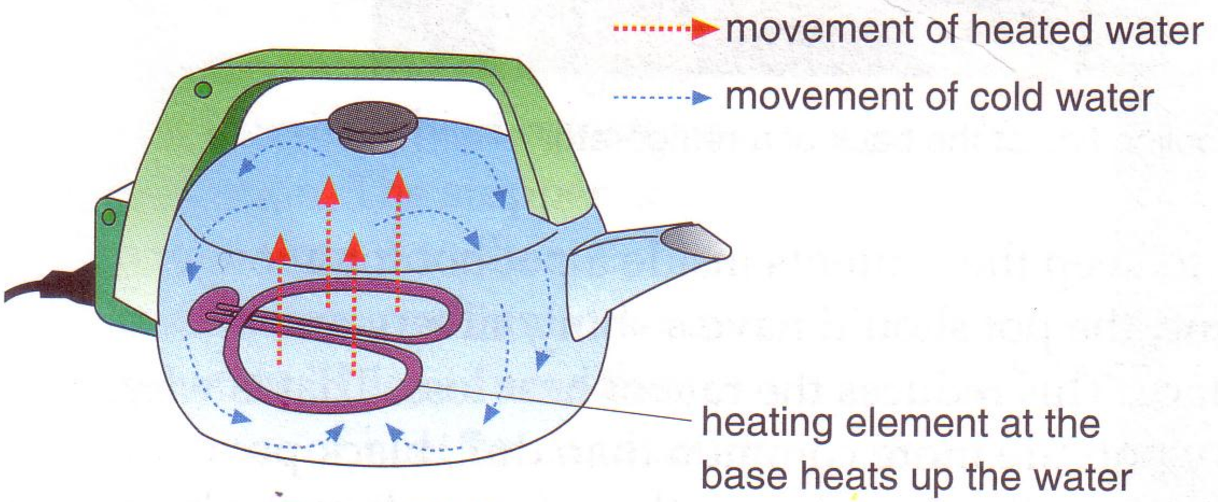


Figure 9.9 Kettle

Application of convection

Refrigerator

- Å The freezer is always placed at the top of the refrigerator.
- Å So that cold air at the top will sinks to the bottom.
- Å Warmer air at the bottom will rise to the top.
- Å Convection current
- Å is set up to cool down the refrigerator.

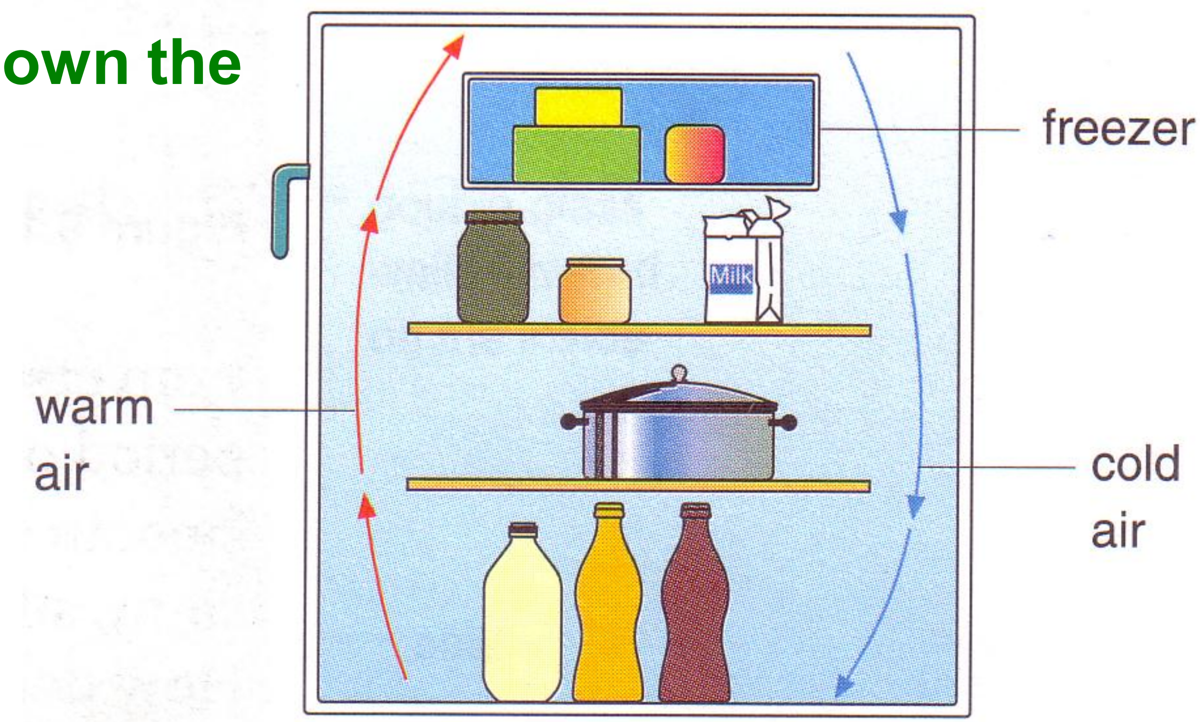
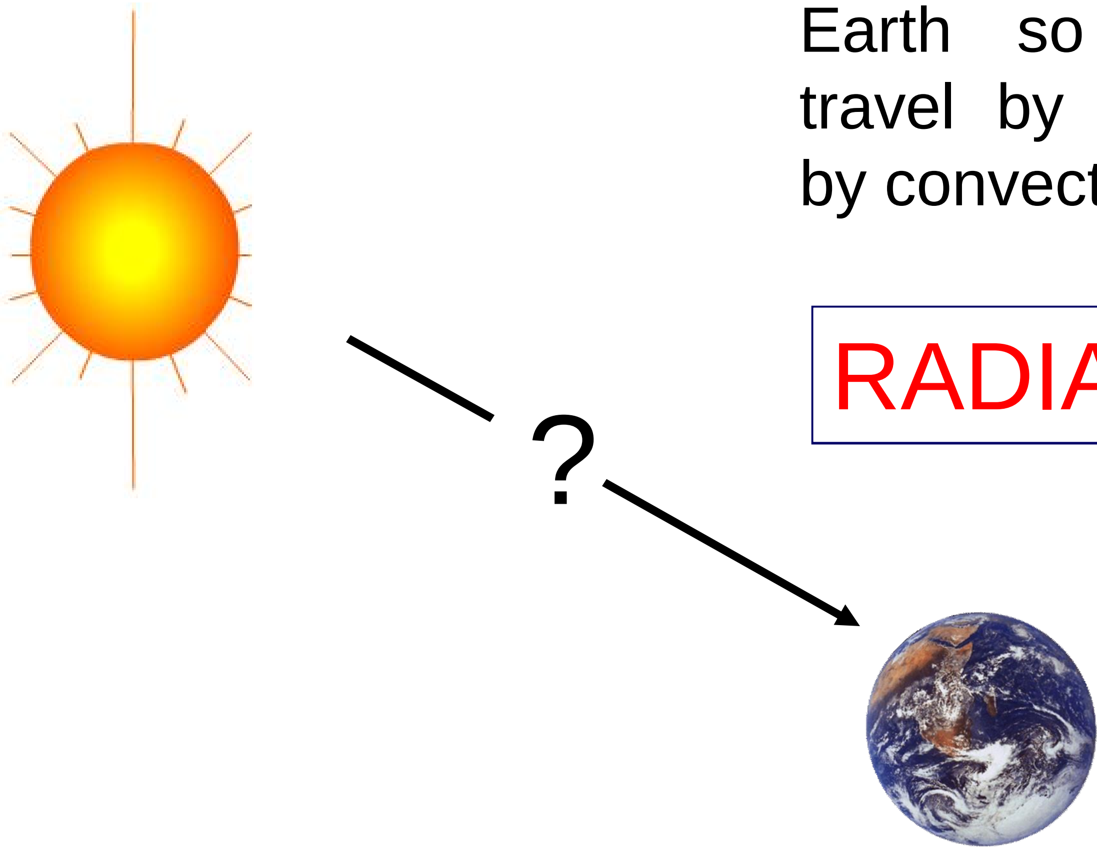


Figure 9.10 Refrigerator

Radiation

How does heat energy get from the Sun to the Earth?



There are no particles between the Sun and the Earth so it CANNOT travel by conduction or by convection.

RADIATION

Radiation

All solid bodies as well as liquid and gases have a tendency of radiating thermal energy in the form of electromagnetic waves and absorbing similar energy emerging from the neighbouring bodies.

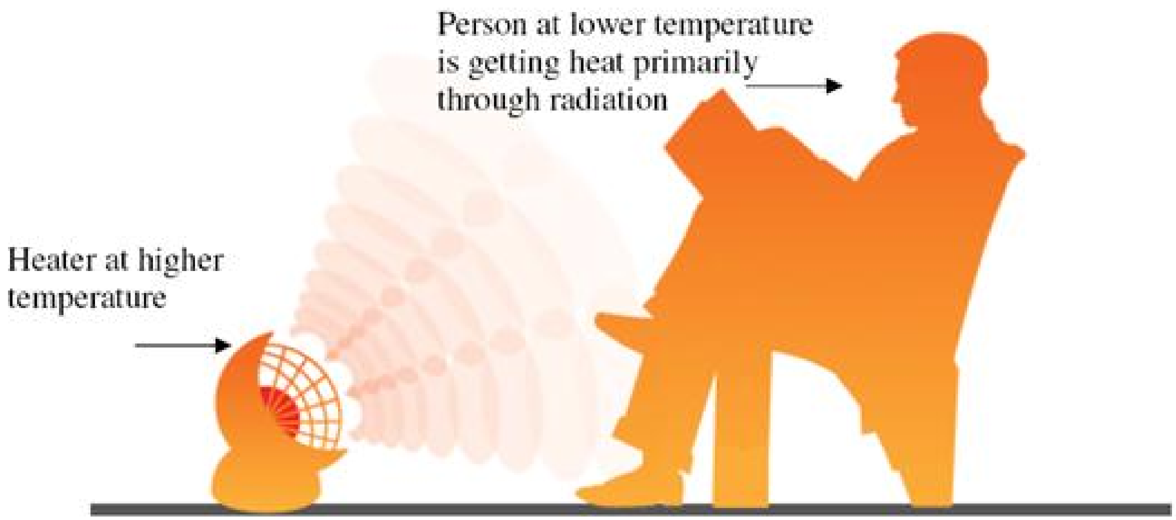
This type of heat transport is known as thermal radiation.

OR

Radiation is a process by which heat flows from a high temperature body to a body at lower temperature in the form of electromagnetic waves when the bodies are separated in space even when a vacuum exists between them (when the bodies are not in direct physical contact with each other).

Radiation

There will be a continuous interchange of energy between two radiating bodies, with a net exchange of energy from the hotter to the colder body.



Heat transfer through radiation

The source of energy can be far away

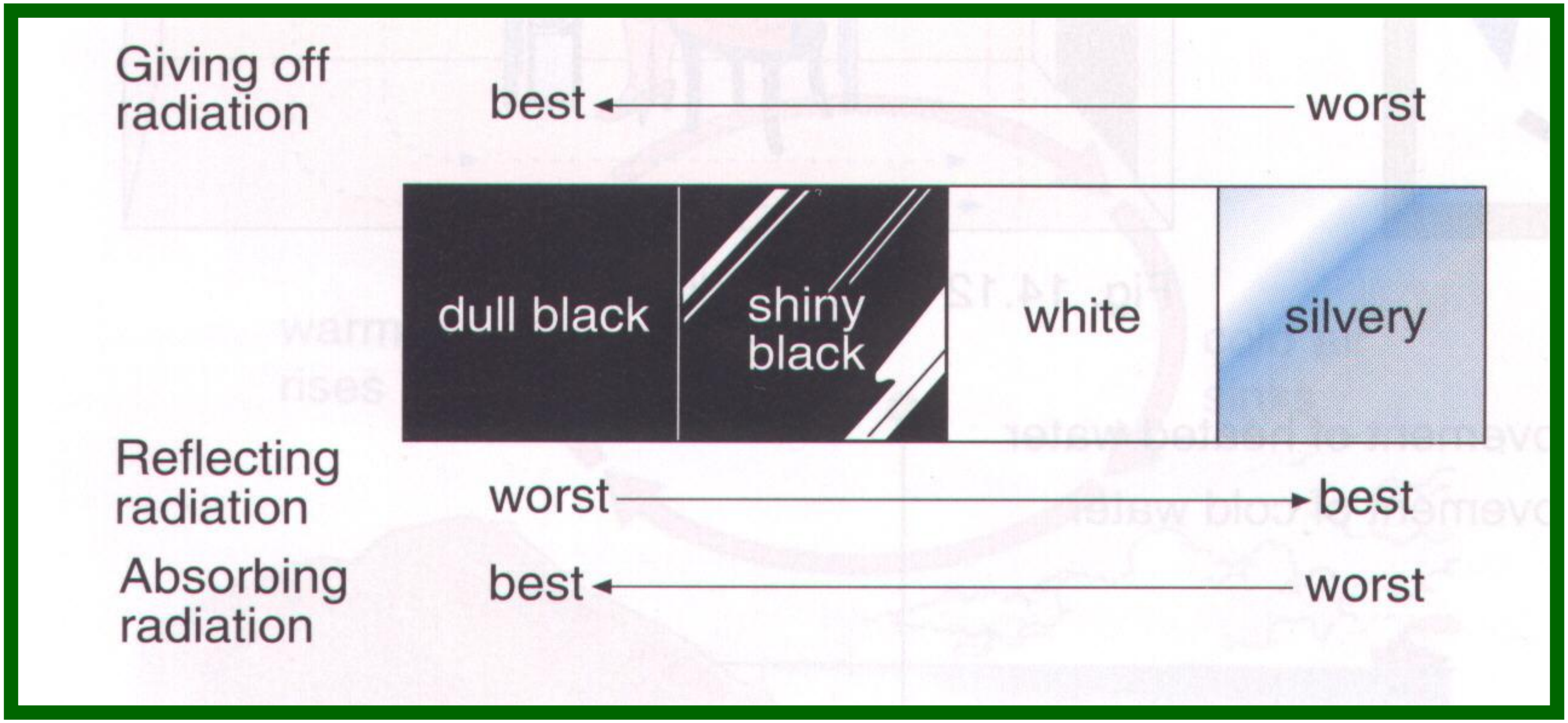
No material medium is require for heat transfer.

At ordinary temperature, the energy transferred by radiation can be neglected.

Radiation

Å The heat energy from the sun is radiated to us.

What type of surface is the best absorber of heat



Test Yourselves

1. **Brightly polished kettle do not lose much energy by radiation. Why ?**

Silvery surface is the worst radiator of heat

2. **The cooling fins on the back of a refrigerator, in a car radiator should be dull black. Why ?**

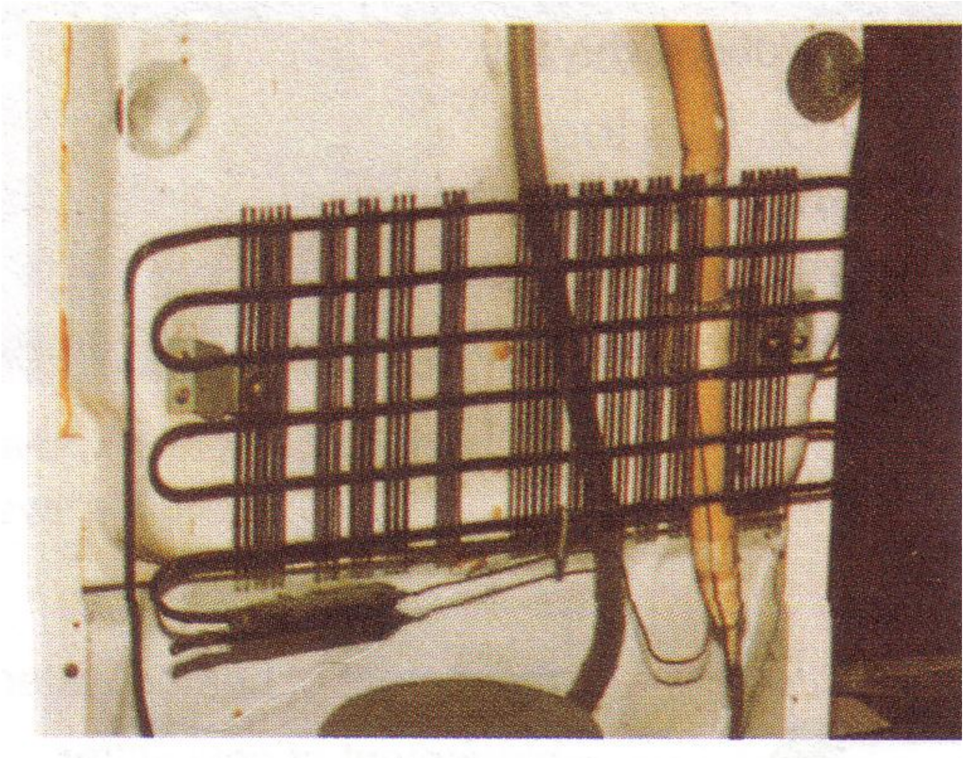
Application of Radiation

Cooling fins at the back of a refrigerator

Å Is rough and painted in black.

Å A black and rough surface is a good radiator of heat.

Å The motor of the refrigerator can be cooled down quickly by the cooling fins.



Application of Radiation

Teapot

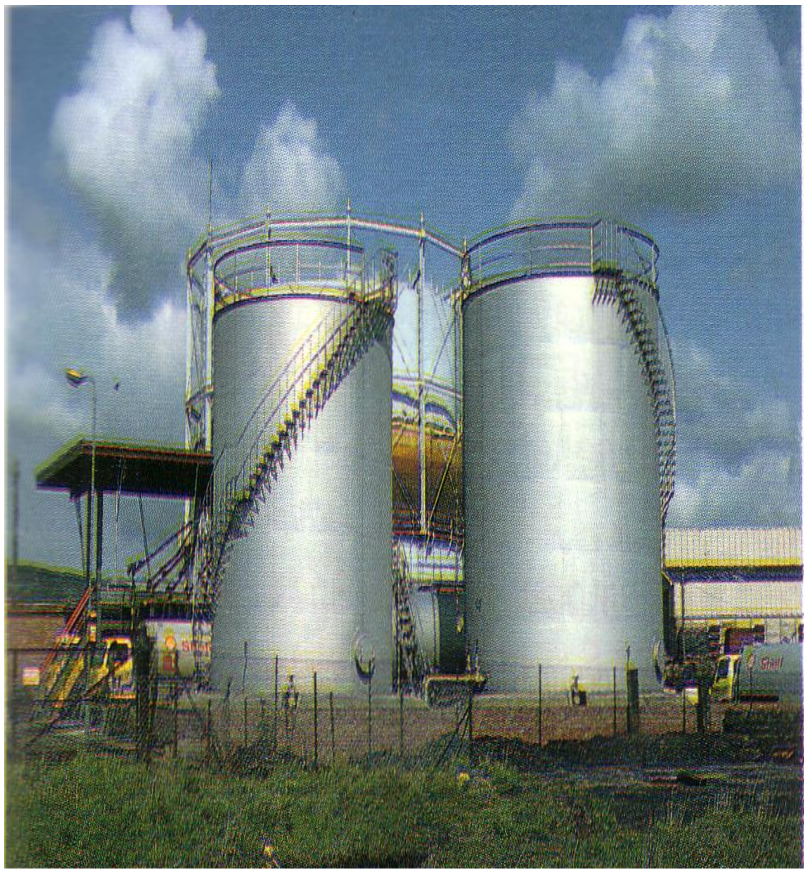
- Has smooth, shiny and silvery surface.
- Smooth, shiny and silvery surface is a bad radiator of heat.
- This reduces rate of heat loss. Tea or coffee can be kept warm in the teapot.

Application of Radiation

White paint for houses

Å In hot countries, houses are painted in white to reduce absorption of heat energy from the Sun

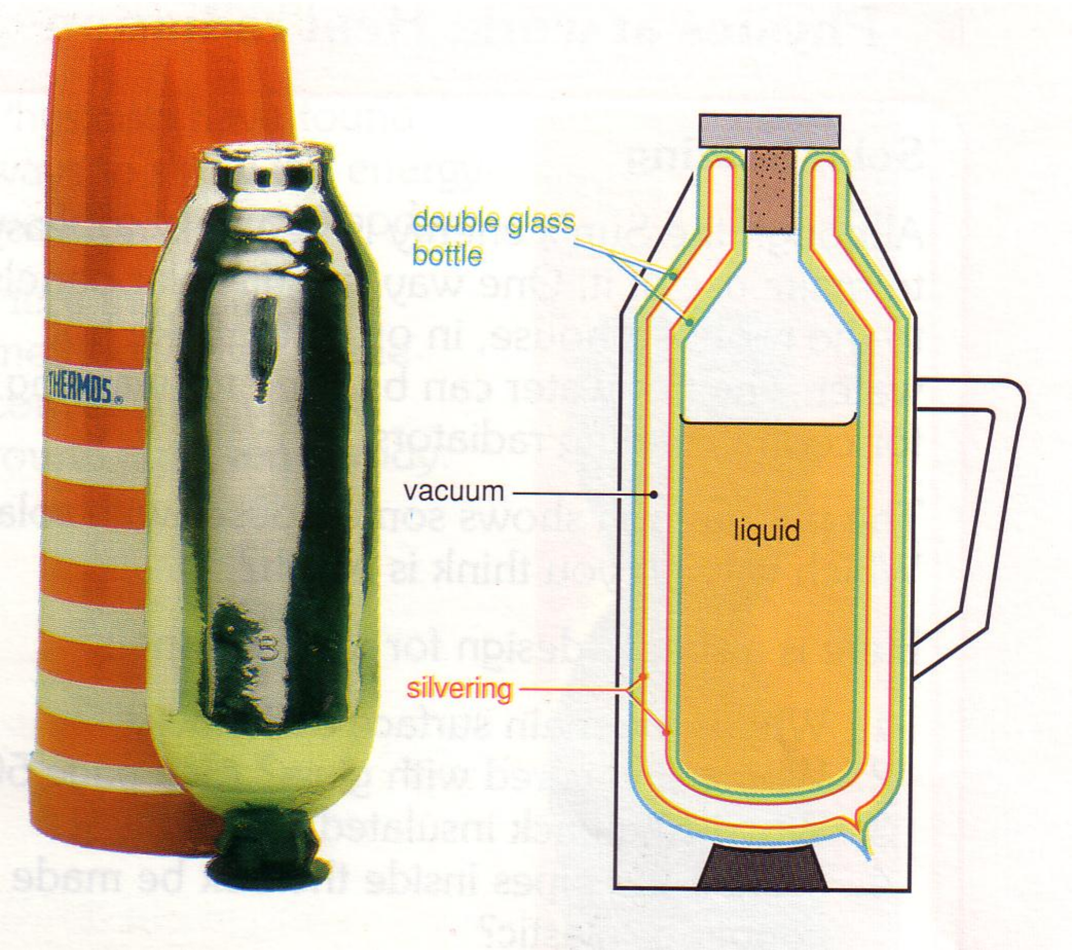
Application of Radiation



Application of Radiation

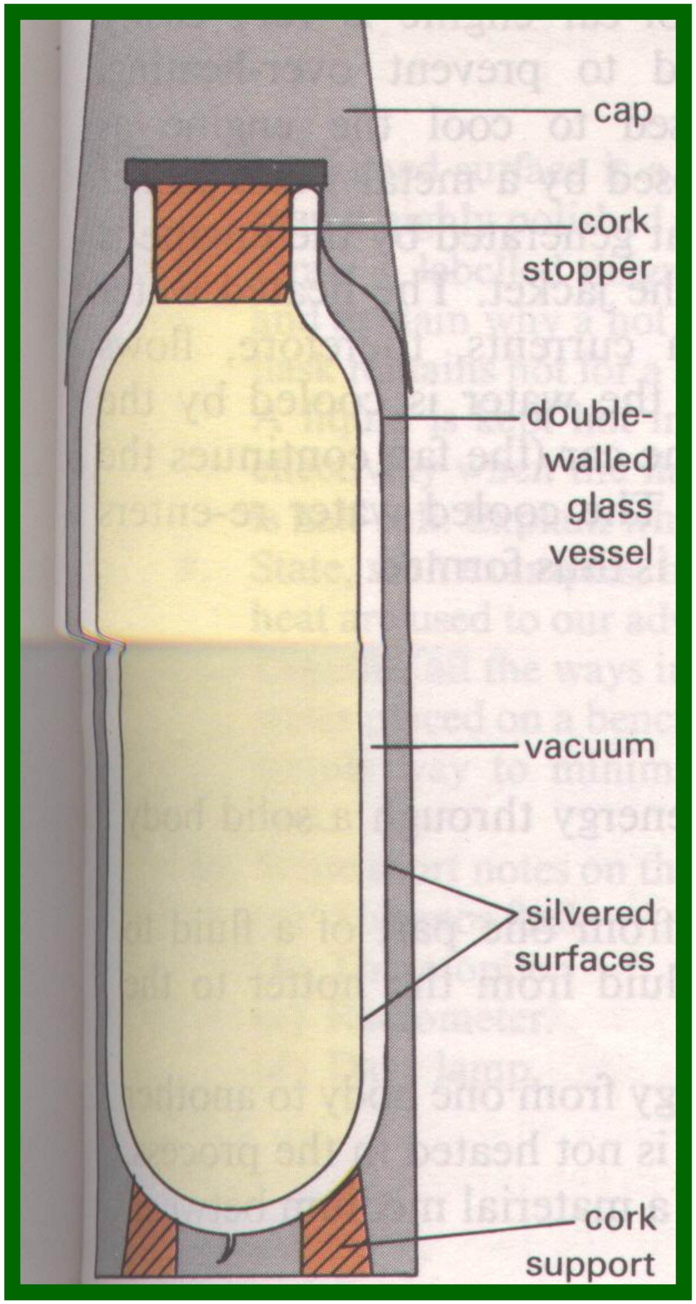
Vacuum Flask

- A vacuum Flask is used to keep hot water hot or keep ice-cream cold.
- It does this by reducing or stopping conduction, convection and radiation.



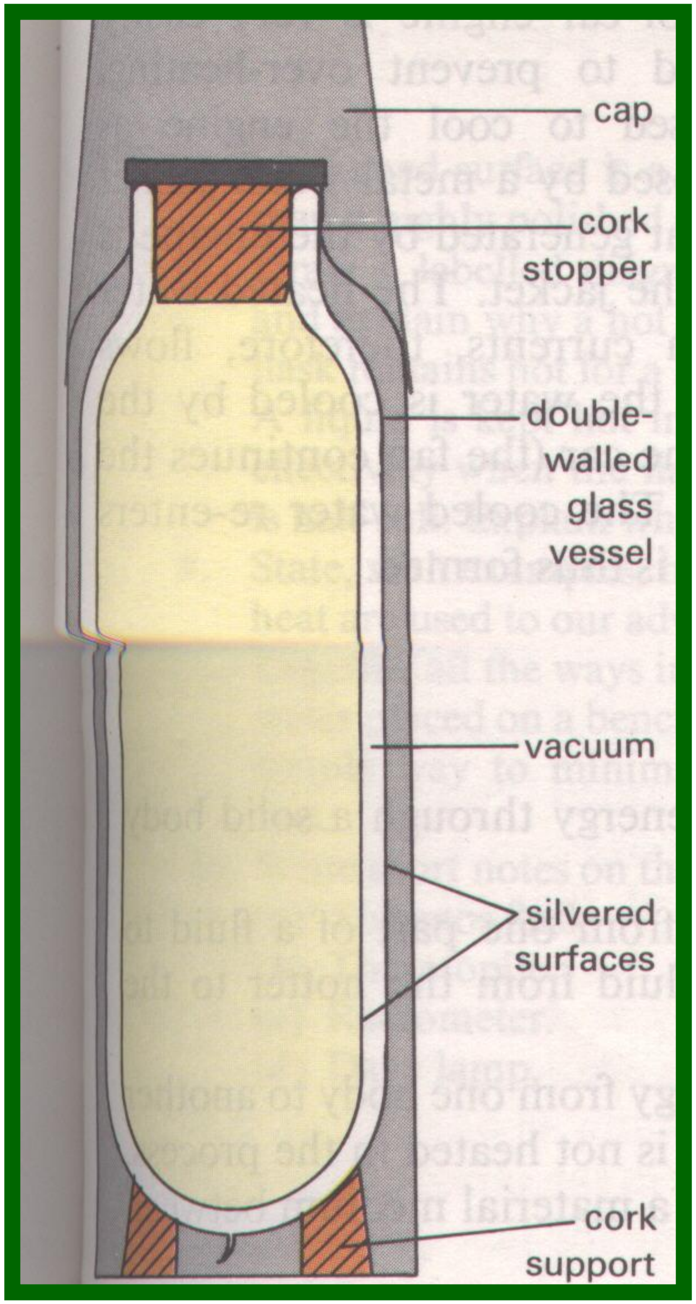
Vacuum Flask

- It is a double-walled glass bottle. The space between the two walls is a vacuum. This can stop energy transfer out by conduction and convection.
- It cannot stops radiation, as radiation can takes place in the vacuum.

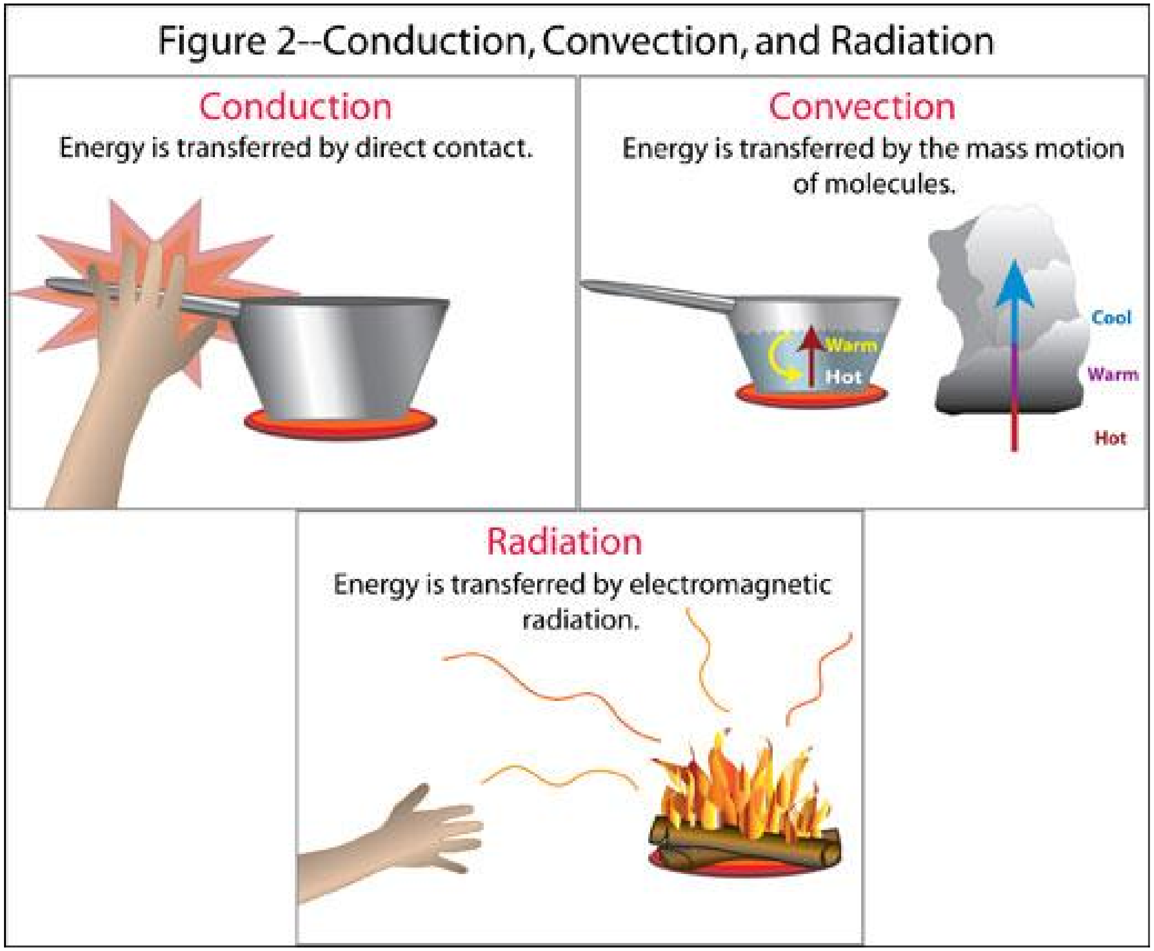


Vacuum Flask

- **The shiny bright silvering surface on glass wall reduces heat loss by radiation.**
- **cork stopper which is made of poor conductors reduces heat loss by conduction and convection**

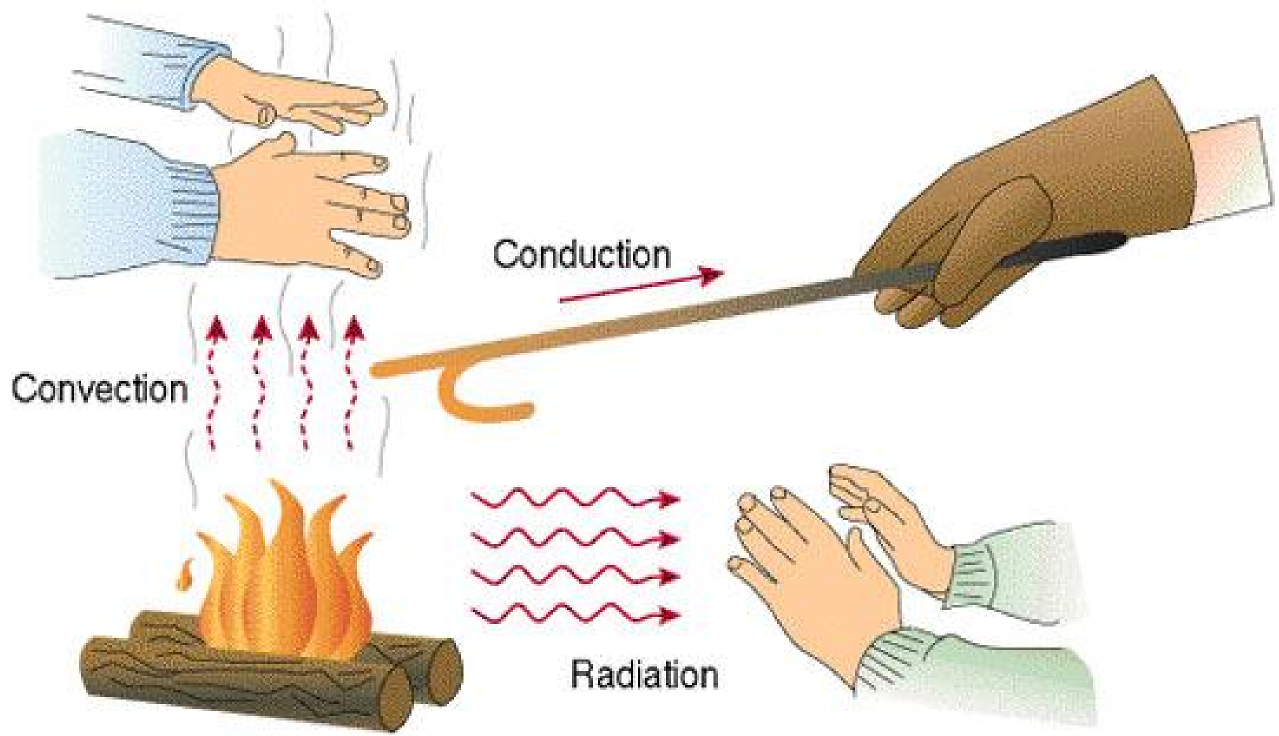


Basic modes of heat transfer



There are THREE ways heat can move

- Conduction
- Convection
- Radiation



Examples for Convection, Conduction, and Radiation

A pot sitting on a hot burner.

conduction

How the inside of a greenhouse works.

convection

Touching a metal spoon that is sitting in a pot of boiling water

conduction

Using a heating blanket to get warm

conduction

A person placing their cold hands over a warm fire

radiation

A person placing their hand over a hot burner

radiation

Lying out in the sun to get a tan

radiation

Putting your wet shoes on a floor vent to dry them faster

convection

Picking up a hot cup of coffee

conduction

Macaroni rising and falling in a pot of boiling water

convection

- What does conduction look like in the kitchen?
  - Boiling water on the stove: the water is making contact with the hot stove

- What does this look like in the kitchen?
  - Inside the oven, the warm air is moving around. Thatôs why you keep the door closed.
  - Would a cookie ñbakeò if you put it on the stove?
    - No, the bottom would just burn.
- What does this look like in the kitchen?
  - Take a pot off the stove and hold your hand over the element. Can you feel the waves of heat warming your hand?!

Basic modes of heat transfer

Conduction is the transfer of heat through solids or stationary fluids.

$$\dot{Q}_{\text{cond}} = -kA\frac{dT}{dx}$$ **Fourier's law of heat conduction**

Convection uses the movement of fluids to transfer heat.

$$\dot{Q}_{\text{conv}} = hA_s(T_s - T_\infty) \quad \text{(W)}$$ **Newton's law of cooling**

Radiation require a medium for transferring heat; this mode uses the electromagnetic radiation emitted by an exchanging heat.

$$\dot{Q}_{\text{emit, max}} = \sigma A_s T_s^4 \quad \text{(W)}$$ **Stefan–Boltzmann law**

$\sigma = 5.670 \times 10^{-8}\ \text{W/m}^2 \cdot \text{K}^4$ Stefanï Boltzmann constant

Conduction and Radiation: Depend on temperature difference

Convection: Needs assistance of mechanical mass transport also and is therefore governed by fluid motion as well

Conduction and Convection: heat flux is directly linearly related to temperature difference

Radiation: Heat flux is related to the difference in the fourth power of the absolute temperatures

Newton's Law

Convection uses the movement of fluids to transfer heat.

q= h A æT **Newton's law of cooling** | Proposed in 1701 |

Where

q = average rate of heat transfer by convection (watt or J/s)

A = heat transfer area (m^2)

æT = Difference between the temperature of the surface and the fluid at some specified location (^0C)

h = an average vale of the proportionality constant called convective heat transfer coefficient (watt/ $m^2\ ^0C$)

h : knowledge of fluid mechanics

h depends on geometry of surface, the velocity, properties of the fluid and also the temperature difference æT

Stefan Boltzmann Law

The heat exchange by radiation was experimentally by Stefan who proposed that the energy radiated by a body is proportional to the fourth power of absolute temperature.

It was confirmed by Boltzmann in 1884 by therefore resulting in the Stefan Boltzmann which may be stated as

$Q = в A T^4$

Stefan–Boltzmann law

Where

q = maximum rate of heat emission by a body at the given temperature (black body emission) (watt)

A = area of the body (m^2)

T = absolute temperature (^0C)

$\sigma = 5.670 \times 10^{-8}$ W/m$^2 \cdot$ K^4 Stefanï Boltzmann constant

Stefan Boltzmann Law

Net rate of heat radiation from a black of area A_1 at absolute temperature T_1 to another black body at a lower temperature T_2 will therefore be given by:

$$q = \sigma A_1 \left(T_1^4 - T_2^4 \right)$$

For the case of real bodies this equation becomes

$$q = \sigma A_1 F_{12} \left(T_1^4 - T_2^4 \right)$$

Where

q = net rate of heat exchange by radiation(watt)

F_{12} = a shape factor depending upon the geometry, emissivities and relative location of the two surfaces

Variation in Heat transfer with reference to time

Steady state	Unsteady (transient) State
óSteady Stateô means the state of the system that does not change with time.	óUnsteady Stateô means the state of the system that does change with time.
The temperature at each point of the system remains constant in the course of time and it is a function of space coordinates. $\frac{dT}{d\tau} = 0$ and T = f(x, y, z) The heat flux at any location remains constant or invariant with respect to time.	When temperature at any point in a system changes with time, process is unsteady state heat transfer $\frac{dT}{d\tau} \neq 0$ and T = f(x, y, z, time) The heat flux at any location does not remain constant
Internal energy does not change in such a process	Internal energy changes in such a process
e.g. Heat transfer to boiling tubes from the hot gases, from hot fluid to cold fluid in a heat exchanger	e.g. Cooling of castings in a foundry or hot steel job on a blacksmithôs anvil

Variation in Heat transfer with reference to time

Periodic or Quasi steady state

The variation in temperature of an unsteady state system undergoes particular cycle, the process is called a periodic or quasi steady state heat transfer process.

The temperature at each point return periodically to the same value.

The rate of heat flow and that of energy storage undergoes periodic variation.

Ex. Heating or cooling of a building wall during 24 hour cycle of the day or that of the walls of an Internal combustion engine.