Chapter 4: Thermal Physics

At the end of the lesson, students should be able to:

- Define temperature, temperature measurement and heat
- Explain heat capacity and specific heat capacity
- Know latent heat of fusion and Vaporisation
- Know thermal energy and heat of combustion
- Explain conduction, convection and radiation

4.1 Introduction

Thermal or heat energy is the internal energy of an object due to the kinetic energy of its atoms and/or molecules. The atoms and/or molecules of a hotter object have greater kinetic energy than those of a colder one, in the form of vibrational, rotational, or, in the case of a gas, translational motion.

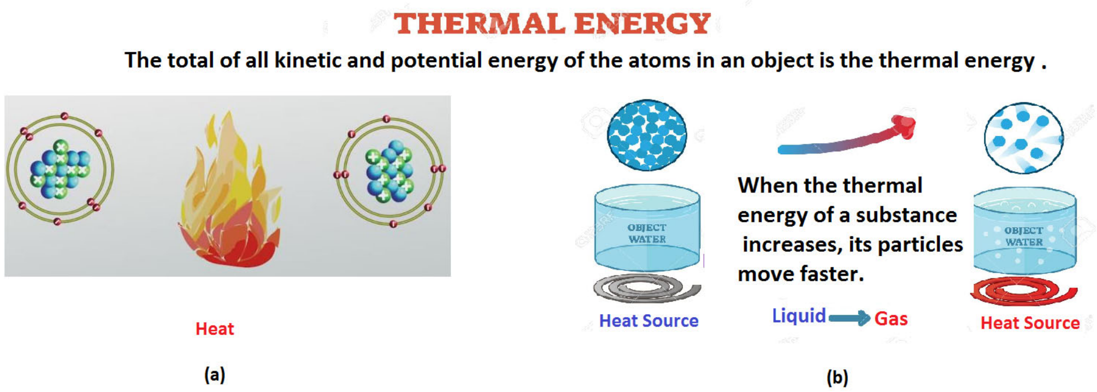

Figure 4.1: Thermal Energy

To study thermal energy, we must know temperature and heat.

https://www.youtube.com/watch?v=LL54E5CzQ-A

(a) Temperature and its measurements

The temperature tells us how hot or cold a matter is. It can be defined as the average kinetic energy of the molecules of the matter. Heat can flow from a high temperature body to a low temperature body by conduction, convection or radiation.

Heat will not flow between two substances at the same temperature.

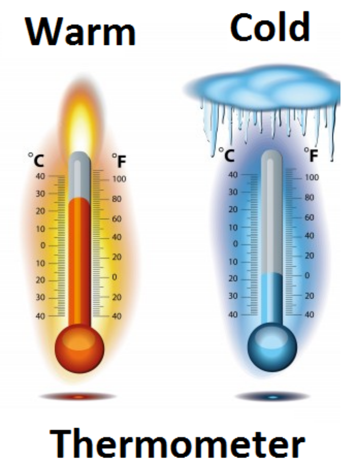

Figure 4.2: Measurement of Temperature

There are three main temperature scales used in the world - Celsius, Fahrenheit, and Kelvin. These are compared in the following table.

Situation	^{0} C	K	^{0} F
Water boils	100	373	212
Water freezes	0	273	32
Absolute zero	-273	0	-459

Table 4.1: Temperature scale comparisons

The relationship between centigrade and Kelvin is:

$$K \;=\; {}^0C + 273$$

The relationship between centigrade and Fahrenheit is:

$$^oC = \frac{(^oF - 32)\ X\ 5}{9}$$

e.g.

$$98.6\ ^oF \;=\; \frac{(\,98.6 - 32\,)\ X\ 5}{9} = 37\ ^oC$$

Example 4.1

Nitrogen boils at -196^0 C. What is this temperature on the absolute scale?

K = -196 + 273

Therefore, temperature in Kelvin is = 77^o K.

Example 4.2

The surface temperature of the sun is about 6000°K. What is the Celsius equivalent of this temperature?

$6000 = {}^{0}C + 273$

Therefore, temperature is $5727^{0}C$.

(b) Heat

Heat can be thought of as the internal kinetic energy of the atoms and molecules that make up a substance. Heat can perform work. Being a form of energy, it is measured in the standard unit of Joule, but it is also commonly measured in the following units:

- **calorie:** this is the heat energy needed to raise 1 gm of water 1 °C. 1 calorie is equal to 4.186 Joules.
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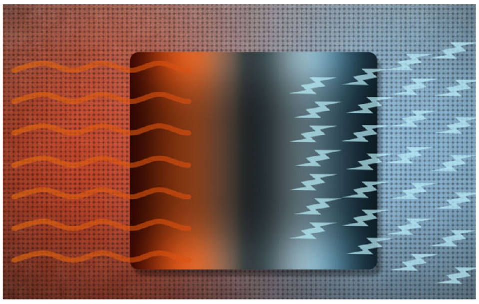
- **BTU:** this is a British Thermal Unit (BTU). 1 BTU = 252 calories = 1054.87Joules.

(a) Heat Energy



(b) Converting Heat to Electricity

Figure 4.3: Heat is Energy

4.2 Heat Capacity and Specific Heat Capacity

The **heat capacity** of a substance is a measure of how well the substance can store heat. Whenever we supply heat to a material, it will cause an increase in the material's temperature. The heat capacity is defined, as the amount of heat required per unit increase in temperature, so that

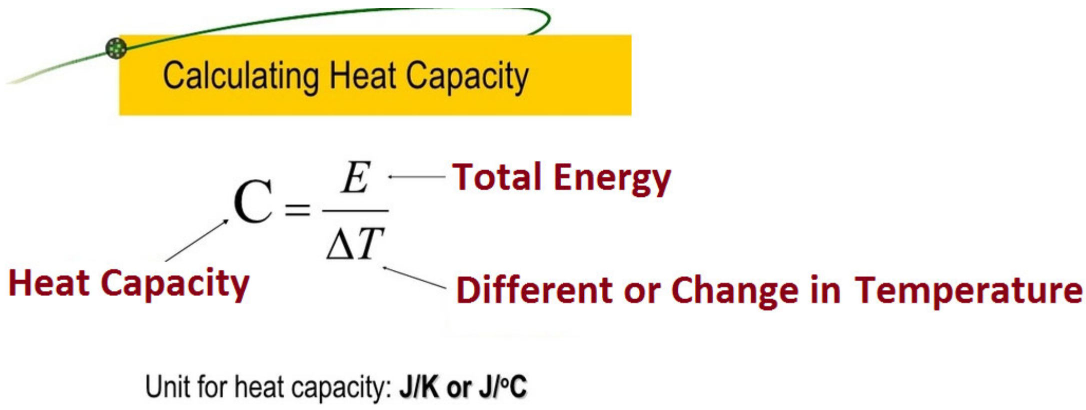


Figure 4.4: Calculating Heat Capacity

Thus, materials with large heat capacities, like water, hold heat well. Their temperature will not rise much for a given amount of heat; whereas, materials with small heat capacities like copper, do not hold heat well. Their temperature will rise significantly when heat is added.

On the other hand, the **Specific Heat Capacity** is the amount of heat per unit mass required to raise the temperature by one degree Celsius. The relationship between heat and temperature change is usually expressed in the form shown below where c is the specific heat capacity.

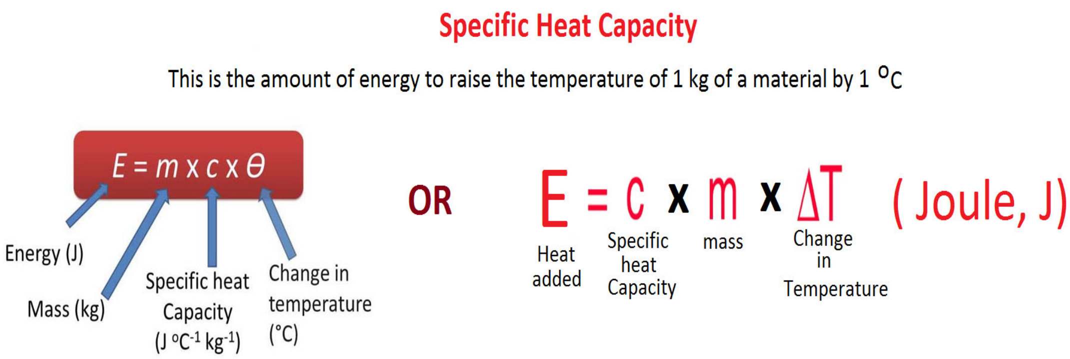


Figure 4.5: Specific Heat Capacity

The specific heat of water is 1 calorie/gram °C = 4.186 joule/gram °C which is higher than any other common substance. As a result, water plays a very important role in temperature regulation. The specific heat per gram for water is much higher than that for a metal, as described in the water-metal example.

https://www.youtube.com/watch?v=hwxmNLo1cho

Example 4.3

(a) How much heat is required to raise the temperature of 250 mL of water from 20^o C to 35^o C? [The specific heat of water is 1 calorie/gram °C = 4.186 joule/gram °C]

(b) How much heat is lost by the water as it cools down to 20^o C?

(a) Q = 4.186 x 250 x (35 -20) = 15697.5 J

Note: 250 mL = 250 cc = 250 gm as the density of water is 1 gm/cc.

(b) Same amount as it gained i.e. 15697.5 J

Example 4.4

How much heat does 25 g of aluminum give off as it cools from 100^o C to 20^o C? For aluminum, c = 880 J/kg. ^{o} C.

25 g = 25 $\times 10^{-3}$ kg.

Heat given off = 880 x 25 x 10^{-3} x 80 = 1760 J

Example 4.5

A certain amount of heat is added to a mass of aluminum (c= 0.21 cal/g.^{o} C), and its temperature is raised 57^o C. Suppose that the same amount of heat is added to the same mass of copper(c= 0.093 cal/g.^{o} C). How much does the temperature of the copper rise?

Heat added to Al = 0.21 x m x 57

Heat added to Cu = 0.093 x m x ΔT

As the heat added to both are same, we have

0.21 x m x 57 = 0.093 x m x ΔT

Therefore, ΔT = 0.21 x 57 /0.093 = 128.71^0 C

4.3 Latent heat of fusion and Vaporization

The best way to understand Latent heat of fusion and vaporisation is by analysing how ice (solid) is transformed to water (liquid) and how water is being transformed to steam (or gas) when heat is continuously applied to ice and then water till the water is being evaporated off. There are 2 changes of phases from ice to steam (or solid to gas) at 2 constant temperatures.

When you take out ice, which is at 0 °C, and put them in a container with a thermometer at room temperature, you would notice that the ice begins to melt at 0 °C. That is, ice changed from solid state to liquid state at the same temperature. Obviously, heat has been absorbed by the ice though the temperature remains constant. This process of changing from solid state to liquid state of a material is known as Latent Heat of Fusion.

When all the ice has melted, put the container with the thermometer on a stove and heat it up. As the temperature of the just melted water rises from 0 °C to boiling point of water, you would noticed that the thermometer increases from 0 °C to 100 °C.

When the water begins to boil, the temperature remained at 100 °C. The steam being produced is also at 100 °C. During this process, you are continuing to add heat energy to the water, but no matter how much heat you added to the boiling water, the water and steam temperature is constant at 100 °C. This process of changing from liquid state to gaseous state of a material is known as Latent Heat of Evaporation.

The amount of heat that is added per unit mass for a phase change to occur in a given material is a constant. This amount of heat is called the heat of fusion for the phase change from solid to liquid, and heat of vaporization for change from liquid to gas.

The Latent Heat equations for phase changes for a given mass, m, are:

Heat applied $\mathbf{Q = m \times L_f}$ where L_f is the Specific Latent Heat of Fusion

Heat applied $\mathbf{Q = m \times L_v}$ where L_v is the Specific Latent Heat of Vaporization

The unit of Latent Heat is Joules per kilogram (J/kg).

The Latent Heat of Fusion for water at 0 °C is approximately 334000 J/kg (334 kJ/kg) and the Latent Heat of Vaporization at 100 °C is about 2260000 J/kg (2260 kJ/Kg).

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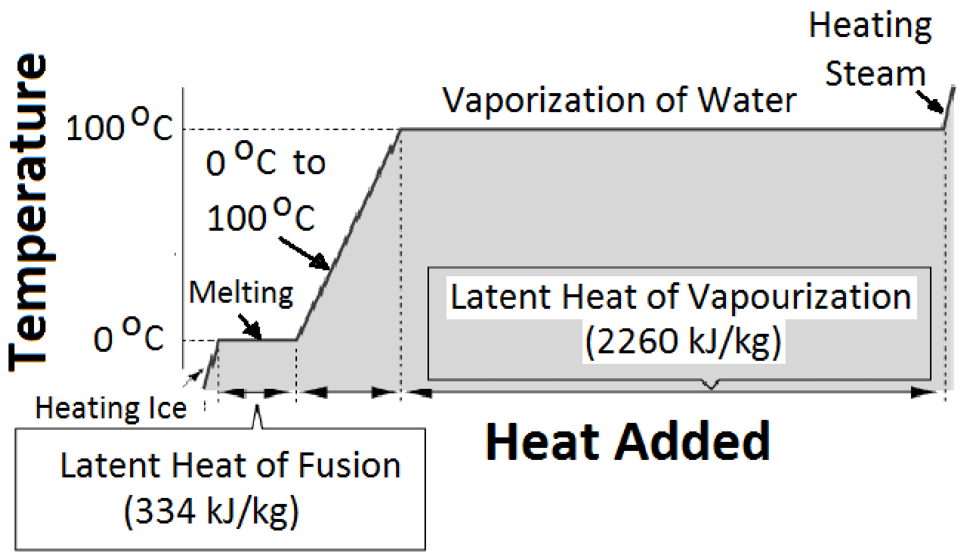


Figure 4.6: Latent Heat of Fusion and Vaporization of Water

Latent Heat of Fusion and Vaporization apply to all materials that changed from solid to liquid and liquid to gases states.

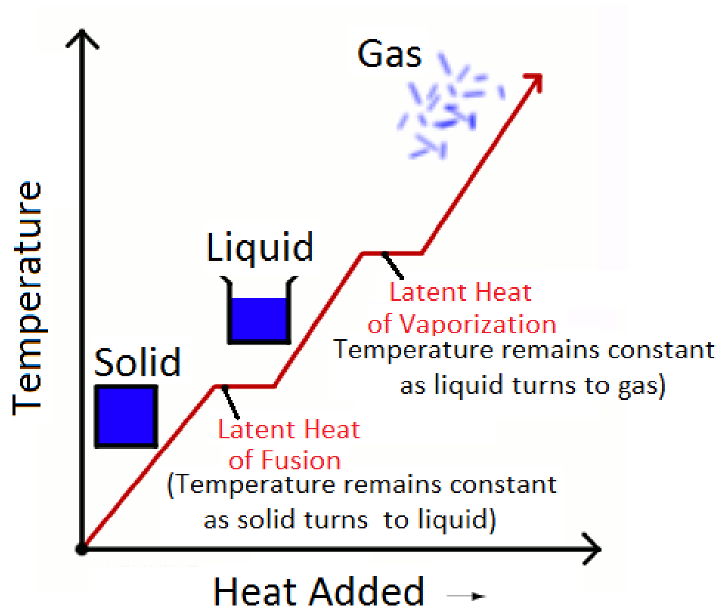


Figure 4.7: Latent Heat of Fusion and Vaporization of any material

4.4 Thermal Energy and Heat of Combustion

(a) Thermal Energy

Thermal energy is the internal energy of an object due to the kinetic energy of its atoms and/or molecules. The atoms and/or molecules of a hotter object have greater kinetic energy than those of a colder one, in the form of vibrational, rotational, or, in the case of a gas, translational motion. In general, the higher the temperature of a substance, the higher is the thermal energy.

Thermal energy can be transferred. For example, thermal energy from a hot stove is transferred to a metal pot and causes the water molecules to move faster increasing the temperature of the water.

The 3 common types of thermal energy **transfer** are conduction, convection and radiation. Conduction involves **direct** contact of atoms; convection involves the movement of warm particles and radiation involves the movement of electromagnetic waves.

The change in **thermal energy** due to temperature changes is:

$$\Delta \text{Thermal Energy} = mc\,\Delta \text{temperature} \quad \text{(J)}$$

Where m is the mass in gram, c is the specific capacity. The unit of thermal energy is Joules (J).

Example 4.6

A 0.2 gram of material with heat capacity of 4.180 J/g is heated up from 25 °C to 100 °C. What is the change in thermal energy?

$$\Delta \text{Thermal Energy} = mc\,\Delta \text{temperature} \quad \text{(J)}$$

Therefore, change in thermal energy = 0.200 × 4,180 × 75.0 = 62.7 kJ.

(b) Heat of Combustion

Heat of combustion is the amount of heat released when one mole of a substance is completely oxidized or burnt. The mass of one mole of a substance equals its relative molecular mass expressed in grams.

One mole of water, H_2O to its molecular mass. Water has 2 grams of hydrogen (or 2 moles of H atoms) + 16 grams of oxygen (or 1 moles of O atom). Thus, one mole of water is 18 g.

One mole of carbon dioxide, CO_2, is equal to its molecular mass. CO_2 has a molecular mass of 12+2x16 = 44. Hence, one mole of CO_2, is 44 g. (Actually 44.0095 g).

Heat of combustion is negative because heat is being released. Its unit is Joules (J)

Example 4.7

Let us look at an example using Ethanol. First, it is set up with 100 grams of water in the water bath. We record the initial temperature as 25 °C.

We then add 1 mole of ethanol to the bomb cell and ignite it. The temperature of the water increases up to 95.91 degrees Celsius.

Change in water temperature is 95.91°C – 25 °C = 70.91 °C

Therefore, the change in temperature is 70.91 °C. The specific heat capacity of water is 4.2 J/ g/C.

Thus the heat of combustion of ethanol = - (100) (70.91) (4.2) =-29728.2 J = -29.7282 kJ.

4.5 Conduction, convection and radiation

Heat can be transferred from a higher temperature to a lower temperature within the same object / material or between 2 different objects / materials. For example, if you heat one end of a copper bar and hold the other end with your hand, very soon, you will feel hot. Heat is being transferred from the heated end to your hand along the copper bar. Copper is a very good conductor of heat and electricity. Similarly, if you put a hot metal bowl of porridge on a plate of cold water, the porridge will be cooled down but the temperature of the water will increase.

For both cases, heat is being transfer. There are three ways that heat may be transferred between substances at different temperatures. They are:

(a) Conduction in solid
(b) Convection of fluid or gases
(c) Radiation through anything that will allow radiation to pass

https://www.youtube.com/watch?v=Eizsm5V8c_c

(a) Conduction in solid

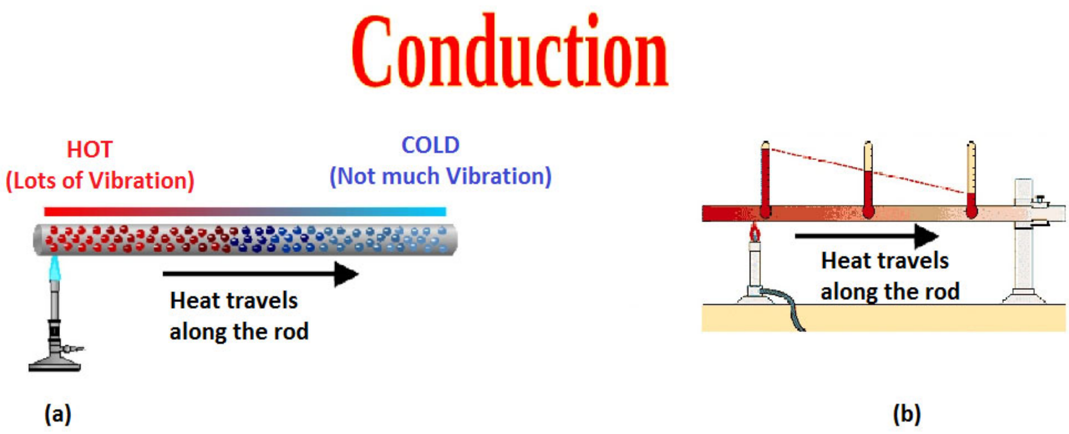


Figure 4.8: Heat Transfer by Conduction

The movement of **heat** when molecules transfer energy between each other by colliding with each other is called "**conduction**". Metals are good conductors of heat.

Heat conduction can also happen when heat energy pass between two objects that are in direct, physical contact. It is one of the three types of heat transfer, the other two being convection and radiation. Whenever two objects of different temperatures are in contact with each other, heat energy will pass between them.

To understand this, we have to realize that **temperature** is the average kinetic energy of the molecules in a substance. Hotter materials have molecules that are moving faster. Therefore, when a cold object and a hot object are touching, the fast moving hot molecules will hit the colder molecules, spreading the heat from the hot object into the cold object. This will keep happening until they reach the same temperature.

Conduction or heat transfer is given as

$$\frac{Q}{t} = \frac{kA(T_2 - T_1)}{d}$$

Where

Q is heat being transferred in Joules (J)

t is the time in seconds

k is the thermal conductivity of the material the object is made from

A is the surface area in contact

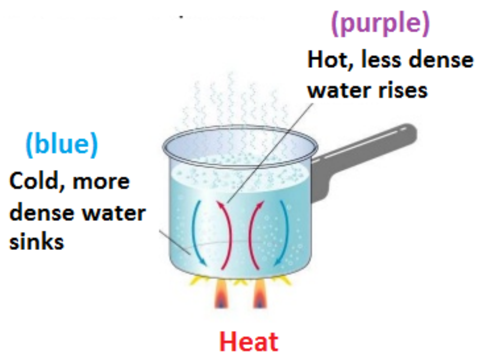
$(T_2 - T_1)$ is the difference in temperature between the two objects in Kelvin or Celsius

d is the thickness of the material

Thus, the rate of heat transfer to an object is equal to the thermal conductivity of the material the object is made from, multiplied by the surface area in contact, multiplied by the difference in temperature between the two objects, divided by the thickness of the material.

(b) Convection of fluid and gases

Convection is the flow of heat through a bulk, macroscopic movement of matter from a hot region to a cool region, as opposed to the microscopic transfer of heat between atoms involved with conduction.



a. When the water at the bottom of the container is heated, it expands.
b. The expanded water is less dense that the surround water and rises to the top.
c. Since the upper region is cooler, it is denser and therefore sinks.
d. The difference in the densities of water in the different regions sets up a convection current.

Figure 4.9: Convection of Liquid

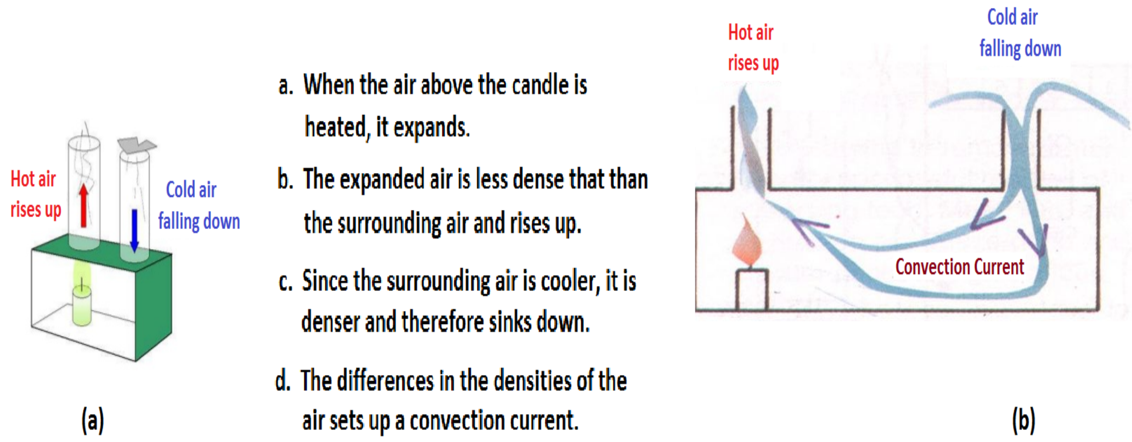


Figure 4.10: Convection of Gases

(c) Radiation

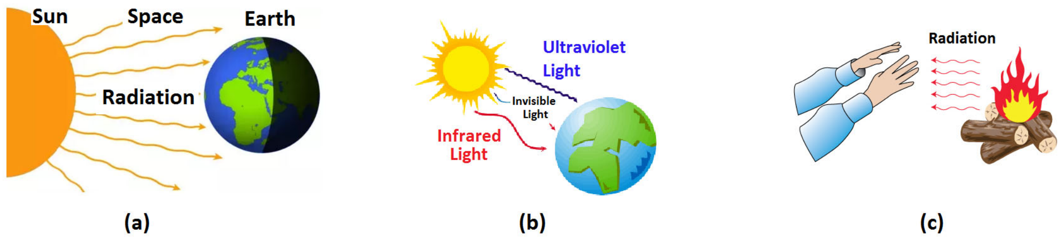


Figure 4.11: Radiation

Both conduction and convection require matter to transfer heat. Radiation is a method of heat transfer that does not rely upon any contact between the heat source and the heated object. That is, radiative heat transfer is the only way to transfer heat from one place to another that does not require a medium.

Radiation happens when heat moves as energy waves, called infrared waves, directly from its source to something else. This is how the heat from the Sun gets to Earth. In fact, all hot things radiate heat to cooler things.

Conduction, convection and radiation can occur at the same time.

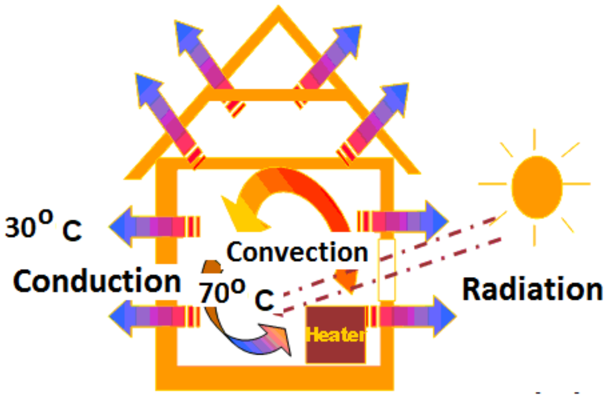


Figure 4.12: Conduction, Convection and Radiation

(d) Thermal Expansion

We have discussed about the changes of temperature and phase when matter is heated. Matter may also change in volume or pressure when heated. When an ideal gas is held at constant pressure, for example, its volume is directly proportional to its temperature.

The volume and pressure relations in the liquid and solid phases are not quite so simple. Liquids and solids are far less compressible than gases, so thermal expansion is less pronounced.

Over small temperature ranges, the linear nature of thermal expansion leads to expansion relationships for length, area, and volume in terms of the linear expansion coefficient.

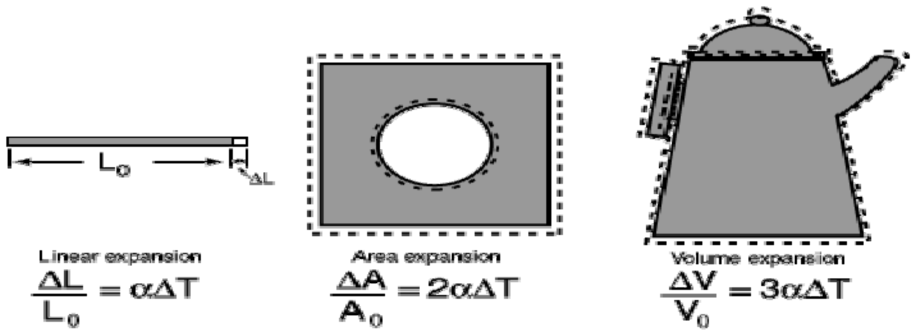


Figure 4.13: Thermal Expansion

Material	**Fractional expansion per degree C x10^{-6}**
Glass, ordinary	9

Glass, pyrex	4
Quartz, fused	0.59
Aluminium	24
Brass	19
Copper	17
Iron	12
Steel	13
Platinum	9
Tungsten	4.3
Gold	14
Silver	18

Table 4.1 Thermal Expansion Coefficients at 20^{0}C