11 Thermal physics

11.1 Internal energy and temperature

Learning objectives:

- What do we mean by internal energy?
- What is the lowest possible temperature?
- What is a gas thermometer?

Specification reference: 3.5A.3

Figure 1 *Heat transfer in winter*

When you are outdoors in winter, you need to wrap up well otherwise heat transfer from your body to the surroundings takes place and you lose energy. In summer, if you are in a very hot room, you gain energy from the room due to heat transfer.

Energy transfer between two objects takes place if:

- one object exerts a force on the other one and makes it move. In other words, one object does work on the other one.
- one object is hotter than the other so heat transfer takes place by means of conduction, convection or radiation. In other words, heat transfer is energy transfer due to a temperature difference.

Internal energy

The brake pads of a moving vehicle become hot if the brakes are applied for long enough. The work done by the frictional force between the brake pads and the wheel heats the brake pads which gain energy from the kinetic energy of the vehicle. The temperature of the brake pads increases as a result and the internal energy of each brake pad increases.

As explained below, the internal energy of an object is the energy of its molecules due to their individual movements and positions. The internal energy of an object due to its temperature is sometimes referred to as **thermal energy.** However, some of the internal energy of an object might be due to other causes. For example, an iron bar that is magnetised has more internal energy than if it is unmagnetised because of the magnetic interaction between its atoms.

The internal energy of an object changes as a result of:

- heat transfer or energy transfer by radiation to or from the object, or
- work done on or by the object, including work done by electricity.

If the internal energy of an object is constant, either:

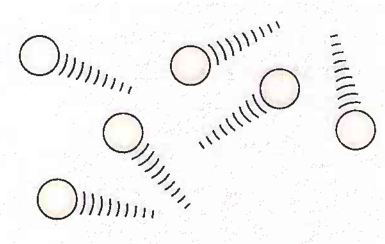
- there is no heat transfer or energy transfer due to radiation and no work is done, or
- heat transfer, energy transfer due to radiation and work done 'balance' each other out.

For example, the internal energy of a lamp filament increases when the lamp is switched on because work is done by the electricity supply pushing electrons through the filament. The filament becomes hot as a result. When it reaches its operating temperature, heat transfer to the surroundings takes place and it radiates light. Work done by the electricity supply pushing electrons through the filament is balanced by heat transfer and light radiated from the filament.

About molecules

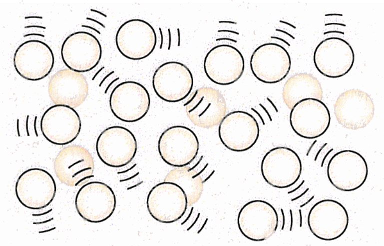
A molecule is the smallest particle of a pure substance that is characteristic of the substance. For example, a water molecule consists of two hydrogen atoms joined to an oxygen atom.

An atom is the smallest particle of an element that is characteristic of the element. For example, a hydrogen atom consists of a proton and an electron.

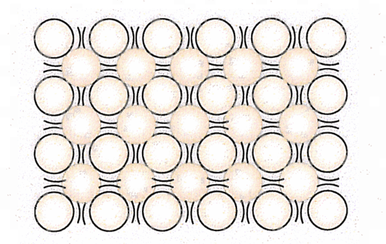


In a gas, the particles are far apart. There are almost no forces of attraction between them. The particles move about at high speed. Because the particles are so far apart, a gas occupies a very much larger volume than the same mass of liquid.

The molecules collide with the container. These collisions are responsible for the pressure which a gas exerts on its container.



In a liquid the particles are free to move around. A liquid therefore flows easily and has no fixed shape. There are still forces of attraction between the particles.
When a liquid is heated, some of the particles gain enough energy to break away from the other particles. The particles which escape from the body of the liquid become a gas.



A solid is made up of particles arranged in a regular 3-dimensional structure. There are strong forces of attraction between the particles. Although the particles can vibrate, they cannot move out of their positions in the structure.

When a solid is heated, the particles gain energy and vibrate more and more vigorously. Eventually they may break away from the solid structure and become free to move around. When this happens, the solid has turned into liquid: it has melted.

Figure 2 *Particles in a solid, a liquid and a gas*

- In a solid, the atoms and molecules are held to each other by forces due to the electrical charges of the protons and electrons in the atoms. The molecules in a solid vibrate randomly about fixed positions. The higher the temperature of the solid, the more the molecules vibrate. The energy supplied to raise the temperature of a solid increases the kinetic energy of the molecules. If the temperature is raised sufficiently, the solid melts. This happens because its molecules vibrate so much that they break free from each other and the substance loses its shape. The energy supplied to melt a solid raises the potential energy of the molecules because they break free from each other.
- In a liquid, the molecules move about at random in contact with each other. The forces between the molecules are not strong enough to hold the molecules in fixed positions. The higher the temperature of a liquid, the faster its molecules move. The energy supplied to a liquid to raise its temperature increases the kinetic energy of the liquid molecules. Heating the liquid further causes it to vaporise. The molecules have sufficient kinetic energy to break free and move away from each other.
- In a gas or vapour, the molecules also move about randomly but much further apart on average than in a liquid. Heating a gas or a vapour makes the molecules speed up and so gain kinetic energy.

The internal energy of an object is the sum of the random distribution of the kinetic and potential energies of its molecules.

Increasing the internal energy of a substance increases the kinetic and/or potential energy associated with the random motion and positions of its molecules.

Temperature and temperature scales

The temperature of an object is a measure of the degree of hotness of the object. The hotter an object is, the more internal energy it has. Place your hand in cold water and it loses internal energy due to heat transfer. Place it in warm water and it gains internal energy due to heat transfer. If the water is at the same temperature as your hand, no overall heat transfer takes place. Your hand is then in **thermal equilibrium** with the water. No overall heat transfer takes place between two objects at the same temperature.

A temperature scale is defined in terms of **fixed points** which are standard degrees of hotness which can be accurately reproduced.

- The **Celsius scale** of temperature, in °C, is defined in terms of:
  1. ice point, 0 °C, which is the temperature of pure melting ice,
  2. steam point, 100 °C, which is the temperature of steam at standard atmospheric pressure.
- The **absolute scale** of temperature, in kelvins (K) is defined in terms of:
  1. **absolute zero**, 0 K, which is the lowest possible temperature,
  2. the triple point of water, 273.16 K, which is the temperature at which ice, water and water vapour coexist in thermodynamic equilibrium.

Because ice point on the absolute scale is 273.15 K and steam point is 100 K higher, then

temperature in °C = absolute temperature in kelvins − 273.15

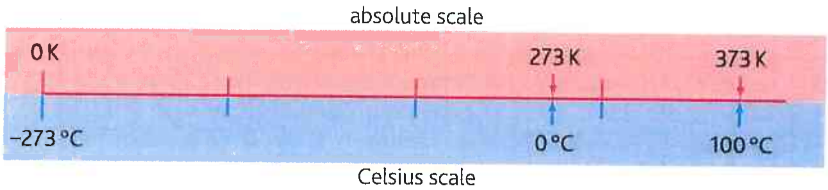


Figure 3 *Temperature scales*

AQA Examiner's tip

Add 273 to change from °C to kelvins. The kelvin scale depends on a fundamental feature of nature, namely the lowest possible temperature. In comparison, the Celsius scale depends on the properties of a substance, water, chosen for convenience rather than for any fundamental reason.

About absolute zero

The absolute scale of temperature, also referred to as the kelvin scale, is based on absolute zero, the lowest possible temperature. No object can have a temperature below absolute zero. **An object at absolute zero has minimum internal energy**, regardless of the substances the object consists of.

The pressure of a fixed mass of an ideal gas in a sealed container of fixed volume decreases as the gas temperature is reduced (see Topic 12.1). If the pressure measured at ice point and at steam point is plotted on a graph as shown in Figure 4, the line between the two points always cuts the temperature axis at −273 °C, regardless of which gas is used or how much gas is used.

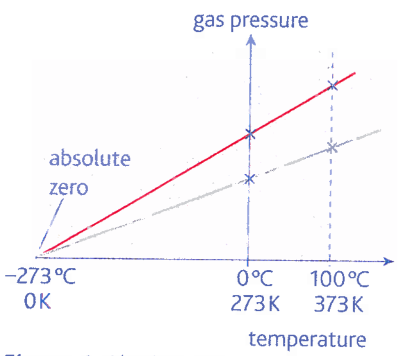


Figure 4 *Absolute zero*

How science works

The coldest places in the world

You don't need to travel to the South Pole to find the coldest places in the world. Go to the nearest University physics department that has a low temperature research laboratory. Substances have very strange properties at very low temperatures. For example, metals cooled to a few degrees within absolute zero become superconductors which means they have zero electrical resistance. Superfluids that can empty themselves out of containers have been discovered. Temperatures within a few microkelvins of absolute zero have been reached in these laboratories.

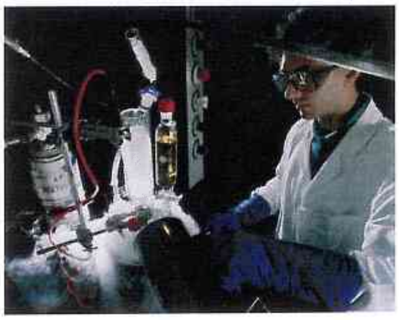


Figure 5 *A low temperature research laboratory*

A thermometer test

Use a travelling microscope to measure the interval between adjacent graduations on the scale of an accurate liquid-in glass thermometer. You may be surprised to find that the interval distance is not the same near the middle of the scale as it is near the ends of the scale. This is because the expansion of the liquid is not directly proportional to the change of temperature.

All thermometers are calibrated in terms of the temperature measured by a gas thermometer. This is a thermometer consisting of a dry gas in a sealed container. The pressure of the gas is proportional to the absolute temperature of the gas. By measuring the gas pressure, p_{Tr}, at the triple point of water (273.16 K by definition) and at an unknown temperature T/K, the unknown temperature in kelvins can be calculated using

$\frac{T}{273.16} = \frac{p}{p_{Tr}}$, where p is the gas pressure at the unknown temperature.

Although the above formula is not on your A level specification, the above notes are provided to give you a clear understanding of how accuracy is ensured when we use a thermometer.

Summary questions

1 **a** Explain why an electric motor becomes warm when it is used.

b A battery is connected to an electric motor which is used to raise a weight at a steady speed. When in operation, the electric motor is at a constant temperature which is above the temperature of its surroundings. Describe the energy transfers that take place.

2 **a** State what is meant by internal energy.

b Describe a situation in which the internal energy of an object is constant even though work is done on the object.

3 **a** State one difference between the motion of the molecules in a solid and the molecules in a liquid.

b Describe how the motion of the molecules in a solid changes when the solid is heated.

4 **a** State each of the following temperatures to the nearest degree on the absolute scale:

- i the temperature of pure melting ice,
- ii 20 °C,
- iii −196 °C

b The pressure of a constant-volume gas thermometer was 100 kPa at a temperature of 273 K.

- i Calculate the temperature, in kelvins, of the gas when its pressure was 120 kPa.
- ii Calculate the pressure of the gas at 100 °C.