Physics

Big idea (age 11-16)
PMA: Matter

What's the big idea?

The world is made of matter. Matter is a more formal word for 'stuff'. Anything that can be stored in a container, or weighed, is matter. Scientific ideas can help to explain why a given material behaves as it does, and may help scientists to develop new materials with specific properties.

Key concepts

The big idea is developed through a series of key concepts at age 11-16, which have been organised into teaching topics as follows.

11-14:

Topic PMA1
Heating and cooling

Key concepts:
- 1.1 Temperature
- 1.2 Heating and cooling
- 1.3 Thermal conduction
- 1.4 Thermal store of energy

Topic PMA2
Floating and sinking

Key concepts:
- 2.1 Floating, sinking and density
- 2.2 Pressure in fluids
- 2.3 Convection

14-16:

Topic PMA3
Energy of moving particles

Key concepts:
- 3.1 Transfer of energy by conduction
- 3.2 Specific heat capacity
- 3.3 Specific latent heat

Topic PMA4
Particle explanations

Key concepts:
- 4.1 Density
- 4.2 Pressure

Topic PMA5
Nuclear physics

Key concepts:
- 5.1 Atomic nuclei
- 5.2 Radioactive decay
- 5.3 Ionizing radiation
- 5.4 Radioactive half-life

The numbering gives some guidance about teaching order based on research into effective sequencing of key concepts. However, the teaching order can be tailored for different classes as appropriate.

This document last updated: January 2022

Guidance notes

The BEST resources for chemistry include a big idea: *CPS Particles and structure*. This big idea includes the BEST key concept: *CPS1.1 Particle model for the solid, liquid and gas states* and the BEST topic: *CPS4 Energy and changes of state*. For the BEST topic: *PMA1 Heating and cooling* it has been assumed that the ideas in the BEST key concept: *CPS1.1 Particle model for the solid, liquid and gas states* have already been covered.

In the BEST key concept: *PMA1.1 Temperature*, temperature is described as a measure of how quickly the particles in a substance or a material are moving. This is correct for particles in a particular substance or material when its temperature is changed, but not necessarily true when comparing the particles in different substances that are at different temperatures. It is more accurate to describe temperature as a measure of the average energy that particles in a in a substance or material have because of their kinetic properties. The former definition has been used because it gives a clear and simple model for thinking about heating and temperature and does not contradict the more accurate definition that is usually taught in post-16 physics courses.

Learning progression

The science story associated with the big idea develops from age 5 to age 16, and could be summarised as follows:

Science story at age 5-11

Materials

There are many different materials (or kinds of matter) in the world. Examples include wood, paper, glass, plastics, steel, water, air, brick, skin, hair. Some are found naturally; others have to be made. Each material has its own distinctive properties. Useful words for describing the properties of a material include: rough/smooth; light/heavy (relative to its size); hard/soft; shiny/dull; rigid/flexible; springy/pliable. Other important properties of materials are: magnetic/non-magnetic; electrical conductor/insulator; thermal conductor/insulator; transparent/translucent/opaque (to visible light).

Some everyday objects are made of a single material; others have several parts made of different materials. For an object made of a single material, some of its properties are properties of the material; others are due its size and shape.

States of matter

Most everyday materials (kinds of matter) exist in one of three states at room temperature:

- Matter that is in the solid state keeps its shape unless it is bent or squeezed or stretched by an applied force (or forces). The size of the force needed to do this varies widely from one material to another.
- Matter that is in the liquid state flows, and fills the bottom of any container it is placed in.
- Matter that is in the gas state expands or flows spontaneously to fill the whole of its container.

A material made of tiny grains (such as sand, table salt, flour) behaves rather like a liquid, but the individual grains are solid.

A sample of matter in the gas state has weight. If gas is added to a container, the weight increases. Matter in the gas state can be compressed relatively easily by squeezing; matter in the solid and liquid states cannot.

If a sample of a solid material is cut into several pieces, or changed in shape by squeezing or rolling it, the amount of matter stays the same, as does the total weight. If a sample of a liquid is poured into a container of a different shape, the amount of matter stays the same, as does its volume and weight.

Change of state

Many materials change from being solid to being liquid when their temperature is increased, and from liquid to solid when their temperature falls. Many liquids become gases when their temperature is increased, and change from gas to liquid when their temperature falls.

Words used to describe the changes of state are: melt (solid → liquid); freeze, or solidify (liquid → solid); evaporate or boil (liquid → gas); condense (gas → liquid).

For example, water in the solid state (ice) changes into liquid water when its temperature reaches 0°C. Its temperature does not change while it melts. Water in the liquid state changes into ice (water in the solid state) when its temperature falls to 0°C. Again, its temperature does not change while it freezes. The temperature at which the change of state from solid to liquid (or vice versa) occurs is called the melting point. Similarly, water in the liquid state changes into steam (water in the gas state) when its temperature reaches 100°C. Its temperature does not change while it boils. Water in the gas state (steam) changes into liquid water when its temperature falls to 100°C. Its temperature does not change while it condenses. The temperature at which the change of state from liquid to gas (or vice versa) occurs is called the boiling point. Other materials behave in a similar way. The melting point and boiling point vary from one material to another.

Water steadily evaporates at any temperature; evaporation gets faster as it gets hotter. Only when it starts to boil do bubbles of steam start forming within the liquid.

Solid, liquid and gas are called states of matter. A material does not have a 'natural' state; its state depends on its temperature.

When solid matter changes to the liquid state, there is usually a small increase in volume. Water is unusual in decreasing in volume when it melts. When liquid matter changes to the gas state, there is a very large increase in volume.

Science story at age 11-14

A particulate model of matter

A particulate model can explain basic properties of substances in the solid, liquid and gas states. The model can also account for changes of state.

In this model:

- All matter is made of very tiny particles – very, very much smaller than anything that can be seen under a microscope.
- There is no other matter except these particles (in particular, no matter between them).
- The properties of matter are the properties of large collections of particles – single particles do not have the same properties as the bulk matter.
- The particles of any given substance are all the same.
- There are attractive forces between particles. These differ in strength from one substance to another.

- In the solid state, the particles are close together, arranged in a regular pattern, and unable to move away from their neighbours.
- In the liquid state, the particles are also close together, but are less regularly arranged and can slide past each other.
- In the gas state, the particles are further apart, and can move freely.
- The particles are always moving: in the solid state, they are vibrating; in the liquid state, they are vibrating and jostling around; in the gas state, they are moving freely in random directions.
- The hotter something is, the faster its particles are vibrating or moving.
- A substance in the gas state exerts pressure because of the collisions between its particles and walls of the container.

Temperature and energy

The temperature of an object is a measure of how hot it is. It can be measured using a thermometer (in degrees Celsius, ^{o}C). To raise the temperature of an object, energy has to be transferred to it (gained by it). To lower the temperature of an object, energy has to be transferred from it (lost by it).

The amount of energy stored in a hot object depends on its temperature – the hotter the object, the more energy is stored. Also, if two objects made of the same material are at the same temperature, the bigger (more massive) object stores more energy.

If two objects at different temperatures are in contact, energy will move spontaneously from the object at the higher temperature to the object at the lower temperature. The ‘other object’ might simply be the surrounding air. The rate at which energy moves depends on the temperature difference and the nature and thickness of the material(s) between the two objects. Materials which significantly reduce the rate of energy transfer are called thermal insulators.

If several objects and materials are left for some time in contact with one another, all of them will reach the same temperature (thermal equilibrium).

To keep an object at a steady temperature above that of its surroundings, energy has to be supplied to it at the same rate as it is losing energy to its surroundings. Similarly, to keep an object at a steady temperature below that of its surroundings, energy must be removed from it at the same rate as it is gaining energy from its surroundings.

Thermal transfer of energy

If different parts of a metal object are at different temperatures, energy moves spontaneously (and quite rapidly) from the region at higher temperature to the region at lower temperature. This process is called thermal conduction. Non-metals are, in general, less good thermal conductors. Some, such as materials that contain trapped air pockets, are good thermal insulators.

At room temperature, thermal insulators feel warmer to the touch than conductors (such as metals, glass, stone and ceramics), because they do not allow energy to be transferred as quickly from our body (which is at 37^{o}C – well above room temperature).

If the temperature of one region of a fluid is raised, the fluid expands and becomes less dense. It then rises within the fluid, carrying the energy stored in it, and cooler denser fluid takes its place. This process of energy transfer from place to place within a fluid is called convection.

A hot object can also lose energy by emitting radiation. The hotter an object is, and the larger its surface is, the more radiation it emits every second. When this radiation is absorbed by another object, it causes the other object's temperature to rise. Objects with matt and black surfaces both radiate and absorb the types of radiation responsible for heating more rapidly than shiny and lighter coloured ones.

Density

The density of a substance is a measure of how heavy it is for its size. The density of a substance is defined as: mass of a sample divided by its volume. Density is a characteristic property of a substance.

A compact solid object (i.e. one that is not boat-shaped or hollow) floats in a liquid if its density is lower than that of the liquid.

If an object is wholly or partly immersed in a fluid, its apparent weight (as measured by a spring balance) is less than in air. The fluid exerts an upthrust on the object, so the net downward force acting on it is smaller (zero, if it floats). The upthrust is equal to the weight of fluid that the object displaces. An object made of a material less dense than the liquid displaces its own weight of liquid when only partly immersed, so it floats. An object made of a material that is more dense than the liquid will float if its shape means that it will displace its own weight of liquid before it becomes completely immersed (e.g. if it is cup- or boat-shaped, or hollow).

Most solids and liquids (and all gases) expand continuously as their temperature is raised. The behaviour of water is anomalous; when a block of ice melts, the volume of the liquid water is less than the volume of the ice. The water continues to contract as its temperature rises from 0^oC to 4^oC, and then begins to expand steadily. The expansion with temperature is small for solids and liquids, but bigger for gases. As a result of expansion, the density of a sample of gas gets less as its temperature increases.

Pressure in fluids

An object immersed in a fluid experiences forces acting on its surfaces caused by the pressure of the fluid. At any given point in a fluid, pressure acts equally in all directions. Its size is equal to the force acting normal to a surface, divided by the surface area (pressure = force divided by area).

The pressure at a point in a fluid is proportional to its depth, as it is caused by the gravitational force on the fluid above that point.

The pressure of the Earth's atmosphere is called atmospheric pressure. Usually atmospheric pressure causes equal forces to act in all directions on objects, so its presence is not apparent. But if a vacuum, or partial vacuum, is created by removing air, the force due to atmospheric pressure can cause movement (e.g. liquid moving up a drinking straw) or other effects (such as rubber suckers being pressed tightly on to surfaces).

Because pressure is proportional to depth in a fluid, the force exerted by a fluid is larger on the lower surface of an immersed object than on the upper surface. This difference causes the observed upthrust. It also explains why the apparent weight of a fully or partly immersed object is less than its weight out of the fluid.

All of these ideas apply to objects immersed in a gas (such as air) though the size of the upthrust is much smaller than for a liquid.

Science story at age 14-16

Energy of moving particles

In non-metals, thermal conduction occurs as particles with larger vibrations interact with adjacent particles causing them to vibrate more vigorously in turn. Thermal conduction in metals is rapid because in addition to this process, outer electrons from metal atoms that move freely in-between metal ions can be accelerated by heating and move quickly through the metal to cause non-adjacent particles (ions) to vibrate more vigorously. In some non-metals, such as diamond, the bonds holding the particles together are so rigid that thermal conduction through the structure is faster than it is in a metal.

Heating a system will change the energy stored within the system and raise its temperature or produce changes of state.

Specific heat capacity of a material is the amount of energy required to raise the temperature of one kilogram of the material by 1^{o}C (or one Kelvin).

The amount of energy required to increase the temperature of a material is calculated by multiplying the mass of the material by both its specific heat capacity and the increase in its temperature.

Specific latent heat of fusion is the amount of energy required to melt one kilogram of a material whilst it is at its melting point. Specific latent heat of fusion is the amount of energy required to vaporise one kilogram of a material whilst it is at its boiling point.

The amount of energy required to melt or vaporise a material is calculated by multiplying the specific latent heat of the material by its mass.

Particle explanations of density and pressure

Density is a measure of the mass of material in one cubic metre or in one cubic centimetre. It is dependent on both the mass of the constituent particles and their spatial arrangement. It is calculated by dividing mass by the volume of an object or a material. The volume of an object can be measured using a ruler or Vernier calliper and then calculated, or the object can be submerged with the volume of water that it displaces measured.

When substances melt, freeze, evaporate, condense or sublimate, mass is conserved and these physical changes are all reversible.

Increasing the temperature of a gas will increase the average speed of its particles. If it is in a container that has a fixed volume, the particles will hit each other both at a higher speed and more frequently. This will increase both the pressure of the gas and the force that the gas exerts on the walls of the container.

Squeezing a gas into a smaller volume will increase the number of particles in each cubic centimetre of the gas. The particles will hit each other more frequently. This will increase the pressure of the gas. If the gas is in a container, more particles will hit each square centimetre of its walls each second. This will increase the force of the gas on each square centimetre of the walls of the container.

Atomic nuclei and isotopes

An atom comprises of a positively charged nucleus surrounded by negatively charged electrons.

An atom's nucleus contains most of its mass in the form of protons, that are positively charged, and neutrons that have no charge. Protons and neutrons each have a mass of about 1 atomic mass unit, which is almost 2000 times the mass of an electron.

The radius of an atom is in the order of 10 000 times that of its nucleus and most of an atom is empty space.

Atoms are too small to see with a microscope. The images produced by electron microscopes show computer generated representations of atoms.

Atoms of each element have a fixed number of protons in their nuclei. Electrons are attracted to a nucleus (and vice-versa) because the electric charge of an electron is equal in size and opposite to the electric charge of a proton. The number of electrons in an atom is the same as the number of protons in its nucleus, and the total charge of protons and electrons in an atom adds to zero.

The number of neutrons in atoms of an element can sometimes vary. Isotopes of an element contain the same number of protons and electrons as each other, but differ in the number of neutrons in their nuclei.

An atom can be represented as ${}^{A}_{Z}X$, where: X is the symbol of the element; $_Z$ is the atomic number, equal to the number of protons (and equal to the number of electrons); and ^{A} is the mass number, equal to the total number of protons *and* neutrons in a nucleus of the atom. The mass number is also called the nucleon number.

In a nuclear equation, sub-atomic particles can be represented in a very similar way as ${}^{A}_{Z}X$, where: X is the atomic symbol of a nucleus *or* the symbol of a particle; $_Z$ is the charge number, equal to the charge relative to that of a proton (-1 for an electron); and ^{A} is the mass number that is equal to the total number of protons *and* neutrons.

Radioactive decay

A stable nucleus does not change over time. Smaller atoms that are stable have approximately the same number of protons as neutrons; larger stable atoms have more neutrons than protons.

(In a nucleus, protons repel each other with an electrostatic force and attract each other, and neutrons, with the *strong nuclear force*. Neutrons attract both neutrons and protons with the *strong nuclear force*. Neutrons help hold protons together in a nucleus; and by moving protons further apart, reduce the electrostatic forces pushing protons apart. On their own, neutrons quickly decay into protons and electrons.)

An unstable nucleus may spontaneously change into a more stable nucleus by emitting radiation in the form of a particle or a gamma photon. This is a random event that is not affected by a chemical reaction. A substance that contains atoms with unstable nuclei is radioactive. Some isotopes of an element may be stable and others may be radioactive isotopes.

Activity is the rate at which a source of unstable nuclei decays. It is measured as the number of decays each second, in becquerel (Bq).

Alpha-decay

Alpha-particles (α) are often emitted by unstable nuclei that are very large.

An alpha-particle comprises of two protons and two neutrons. This is the same as the nucleus of a helium atom, however an alpha particle is emitted from an unstable nucleus at a very high speed (in the order of twenty million metres per second).

The nuclear equation for alpha decay can be represented as: ${}^{N}_{Z}X \rightarrow {}^{N-4}_{Z-2}Y + {}^{4}_{2}\alpha$

Beta-decay

Beta-particles (β) are often emitted by unstable nuclei that have too many neutrons. During beta-decay a neutron changes into a proton and a beta-particle.

A beta-particle is a single electron. It differs from electrons in an atom in that it is emitted from an unstable nucleus at an extremely high speed (in the order of two hundred million metres per second).

The nuclear equation for beta decay can be represented as: ${}^{N}_{Z}X \rightarrow {}_{Z+1}^{N}Y + {}^{0}_{-1}\beta$

Gamma emission

A gamma photon (ν) is a very high frequency electromagnetic radiation.

Following an alpha- or beta-decay, protons and neutrons in the remaining (daughter) nucleus may not be in their most stable arrangement. In order for them to move into a more stable arrangement, a gamma photon is emitted to transfer energy away from the nucleus, with no change to the type of particles in the nucleus.

The nuclear equation for gamma emission can be represented as: ${}^{N}_{Z}X \rightarrow {}^{N}_{Z}X + \ \nu$

Ionising radiation

An ion is an atom or group of atoms that has a different number of electrons to protons. With excess electron, an ion has a negative electric charge and with too few electrons it has a positive charge.

A fast-moving alpha- or beta-particle, or a gamma photon, can knock one or more electrons off an atom (or group of atoms) to form an ion. Each is a form of ionising radiation. Alpha-particles are more powerfully ionising than beta-particles and beta-particles are more powerfully ionising than gamma photons.

- Alpha-particles are stopped by a few centimetres of air or by a thin piece of paper, because each one can cause multiple interactions (and ionisations) within a very small distance.
- Beta-particles have fewer interactions than alpha-particles, because their smaller electric charge and faster speed reduce their influence on the electrons around atoms they move

past. In air beta-particles have a range in the order of one metre and are stopped by 3mm of aluminium (the thickness of twelve sheets of kitchen foil).

- Gamma photons have no electrical charge and are only weakly ionising. They can travel several kilometres through air and need the equivalent to a thick piece of a dense metal, such as lead, to stop them.

Ionising radiation does not cause objects or materials to become radioactive.

Irradiation is the process of exposing an object to ionising radiation.

Radioactive contamination is the unwanted presence of radioactive atoms on or in something else. It is caused by the movement of radioactive atoms either by human action or natural process.

Radioactive half-life

Over time the nuclei of a radioactive isotope decay randomly into other more stable nuclei. It is impossible to predict when any specific nucleus will decay, but it is possible to predict the half-life of a radioactive isotope.

The half-life of a radioactive isotope is the time it takes for half of its nuclei to decay into other more stable nuclei. The half-life of a radioactive isotope remains constant over time.

After a second half life, half of the remaining half of the radioactive isotope's nuclei will have decayed into more stable nuclei; after a third half-life, half of the remaining quarter; and so on.

Different radioactive isotopes have different half-lives.

Uses and dangers of radioactivity

Radioactive isotopes that emit ionising radiation exist naturally all around us, for example in some rocks. They may also get into the environment from nuclear weapons testing or from nuclear accidents. Together with ionising radiation (cosmic rays) from the Sun, these contribute to a low level of *background radiation* that we all experience.

Objects or materials may become radioactive if they are contaminated with the unwanted presence of materials containing radioactive atoms.

Ionising radiation can damage living tissue and suitable precautions should be taken to avoid too much exposure.

Ionising radiation can be useful, for example: in medical diagnosis; to destroy cancer cells; or to detect cracks in pipes or aircraft wings.

Nuclear power stations split large and unstable nuclei (nuclear fission) under controlled conditions. The huge amount of heat generated is used to produce electricity.

In the sun, and in other stars, small nuclei are forced together at high speed to form larger nuclei, in a process called nuclear fusion.