Density

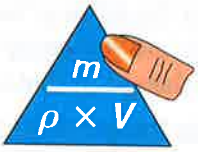
Time for some maths I'm afraid. But at least it comes with a fun experiment, so it's not all bad...

Density is Mass per Unit Volume

Density is a measure of the 'compactness' (for want of a better word) of a substance. It relates the mass of a substance to how much space it takes up.

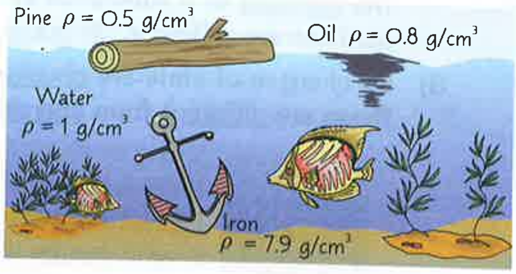
The symbol for density is a Greek letter rho (ρ) — it looks like a p but it isn't.

$$\text{Density} = \frac{\text{mass}}{\text{volume}}$$



The units of density are g/cm³ or kg/m³.

1) The density of an object depends on what it's made of. Density doesn't vary with size or shape.
2) The average density of an object determines whether it floats or sinks — a solid object will float on a fluid if it has a lower average density than the fluid (p.102).

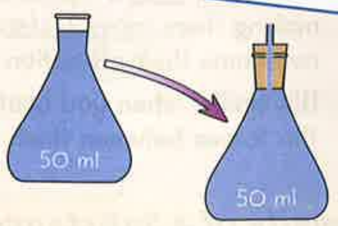


You Can Find the Density of Solids and Liquids

1) To find the density of a substance, measure its mass and volume and use the formula above.
2) The easiest way to find the density of a liquid is to use a measuring cylinder.
3) Use a mass balance (p.104) to measure the mass of the empty measuring cylinder.
4) Pour in the liquid you're investigating. Measure the mass of the cylinder again — the difference in mass is equal to the mass of the liquid.
5) Finding the volume of the liquid is easy — just read it from the cylinder's scale. 1 ml = 1 cm³.
6) If you want to measure the volume of a prism, find the area of its base and then multiply it by its height. For a cube this is dead easy — it's just length × width × height.
7) If your object isn't a regular shape, you can find its volume using the fact that an object submerged in water will displace a volume of water equal to its own volume. One way of doing this is to use a density bottle:

PRACTICAL

1) Measure the mass (m_1) of the object using a mass balance.
2) Fill the bottle with a liquid of a known density (e.g. water).
3) Place the stopper into the bottle and dry the outside.
4) Measure the mass of the bottle (m_2).
5) Empty the bottle and place the object into the density bottle. Repeat steps 2 and 3. Measure the mass of the bottle (m_3).
6) Calculate the volume of displaced water:
   - The mass of the displaced water = $m_2 - (m_3 - m_1)$
   - You know the density of water, so you can use $V = m \div \rho$ to find the volume displaced. This equals the volume of the object.
7) Calculate the density of the object using $\rho = m \div V$ with the mass you measured in step 1 (m_1) and the volume you calculated in step 6.



Liquid is pushed up the tube in the stopper, so the volume inside the bottle is constant.

You can also use a eureka can and a measuring cylinder if you don't have access to density bottles.

I'm feeling a bit dense after that lot...

Remember — density is all about how tightly packed the particles in a substance are. Nice and simple really.

Q1 An object has a mass of 0.45 kg and a volume of 75 cm³. Calculate its density in kg/m³. [3 marks]

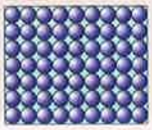
Q2 A cube has edges of length 1.5 cm and an average density of 3500 kg/m³. What is its mass? [3 marks]

Kinetic Theory and States of Matter

According to kinetic theory, everything's made of tiny little balls. The table, this book, your Gran...

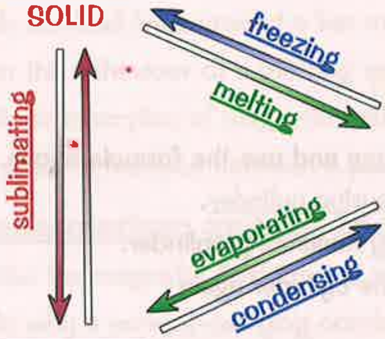
Kinetic Theory is a Way of Explaining Matter

1) In kinetic theory, you can think of the particles that make up matter as tiny balls. You can explain the ways that matter behaves in terms of how these tiny balls move, and the forces between them.
2) Three states of matter are solid (e.g. ice), liquid (e.g. water) and gas (e.g. water vapour). The particles of a substance in each state are the same — only the arrangement and energy of the particles are different. If you reverse a change of state, the particles go back to how they were before.
3) So changes of state are physical changes (only the form of a substance changes). These are different from chemical reactions, where new substances are created by the reaction.



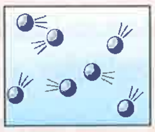
SOLID

Strong forces of attraction hold the particles close together in a fixed, regular arrangement. The particles don't have much energy in their kinetic energy stores so they can only vibrate about their fixed positions.



LIQUID

The forces of attraction between the particles are weaker. The particles are close together, but can move past each other and form irregular arrangements. They have more energy in their kinetic energy stores than the particles in a solid — they move in random directions at low speeds.



GAS

There are almost no forces of attraction between the particles. Particles have more energy in their kinetic energy stores than those in liquids and are free to move — they travel in random directions at high speeds.

When a change of state occurs, the spacing between particles changes, so the internal energy (see next page) of the substance also changes. As the particles get closer together, their internal energy decreases.

4) The energy in a substance's thermal energy store is held by its particles in their kinetic energy stores — this is what the thermal energy store actually is.
5) When you heat a liquid, the extra energy is transferred into the particles' kinetic energy stores, making them move faster. Eventually, when enough of the particles have enough energy to overcome their attraction to each other, big bubbles of gas form in the liquid — this is boiling.
6) It's similar when you heat a solid. The extra energy makes the particles vibrate faster until eventually the forces between them are partly overcome and the particles start to move around — this is melting.

Density of a Substance Varies with State but Mass Doesn't

1) Provided you're working with a closed system (i.e. no particles can escape, and no new particles can get in) the mass of a substance isn't affected when it changes state. This makes sense — the mass of a substance is the mass of its particles, and the particles aren't changing, they're just being rearranged.
2) However, when a substance changes state its volume does change. The particles in most substances are closer together when they're a solid than a liquid (ice and water are an exception), and are closer together when they're a liquid than a gas (see the diagrams above).
3) Since density = mass ÷ volume (p.93), then density must change too. Generally, substances are most dense when they're solids and least dense when they're gases.

Physics — it's really about state of mind...

Remember, the mass of a substance just comes from the particles, not the spaces between them. So as something expands or contracts, its volume changes but its mass stays the same.

Q1 Explain how the density of a typical substance changes as it changes from solid to liquid to gas. [3 marks]

Specific Heat Capacity

The temperature of something isn't quite the same thing as the energy stored in the substance's thermal energy store. That's where specific heat capacity comes in...

Specific Heat Capacity Relates Temperature and Energy

Internal energy is actually the sum of the energy in the kinetic and potential stores of the particles. You can usually ignore energy in potential stores though.

1) Heating a substance increases the energy in its thermal energy store (or the kinetic energy stores of its particles, see p.24). You may sometimes see this referred to as the internal energy of a substance.
2) So in kinetic theory, temperature is a way of measuring the average internal energy of a substance.
3) However, it takes more energy to increase the temperature of some materials than others. E.g. you need 4200 J to warm 1 kg of water by 1 °C, but only 139 J to warm 1 kg of mercury by 1 °C.
4) Materials that need to gain lots of energy to warm up also release loads of energy when they cool down again. They store a lot of energy for a given change in temperature.
5) The change in the energy stored in a substance when you heat it is related to the change in its temperature by its specific heat capacity. The specific heat capacity of a substance is the change in energy in the substance's thermal store needed to raise the temperature of 1 kg of that substance by 1 °C. E.g. water has a specific heat capacity of 4200 J/kg°C (that's pretty high).
6) You need to know how to use the equation relating energy, mass, specific heat capacity and temperature.

$$\Delta Q = m \times c \times \Delta\theta$$

Change in thermal energy (J)

Mass (kg)

Specific heat capacity (J/kg°C)

Temperature change (°C)

Δ just means 'change in'.

You can Find the Specific Heat Capacity of Water

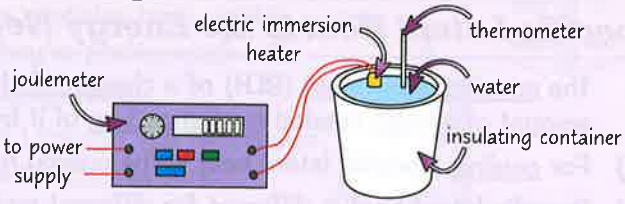
PRACTICAL

You can use the experiment below to find the specific heat capacity of water — or any liquid for that matter. (There's another experiment on page 96 that investigates how water behaves when it changes state.)

If you can, you should use a thermally insulated container for both of these experiments to reduce energy wasted to the surroundings (p.27).

You can use this set up with solid blocks to find the SHC of solids.

1) Use a mass balance to measure the mass of the insulating container.
2) Fill the container with water and measure the mass again. The difference in mass is the mass of the water in the container.
3) Set up the experiment as shown — make sure the joulemeter reads zero and place a lid on the container if you have one.



4) Measure the temperature of the water, then turn on the power.
5) Keep an eye on the thermometer. When the temperature has increased by e.g. ten degrees, stop the experiment and record the energy on the joulemeter, and the increase in temperature.
6) You can then calculate the specific heat capacity of the water by rearranging the equation above, and plugging in your measurements.
7) Repeat the whole experiment at least three times, then calculate an average of the specific heat capacity (p.7).

You could also use a voltmeter and ammeter instead of a joulemeter, time how long the heater was on for, then calculate the energy supplied (p.77).

I wish I had a high specific fact capacity...

Make sure you practise using that equation — it's a bit of a tricky one.

Q1 If a metal has a specific heat capacity of 420 J/kg°C, calculate how much the temperature of a 0.20 kg block of the metal will increase by if 1680 J of energy are supplied to it. [2 marks]

Q2 Describe an experiment you could do to find the specific heat capacity of water. [4 marks]

Specific Latent Heat

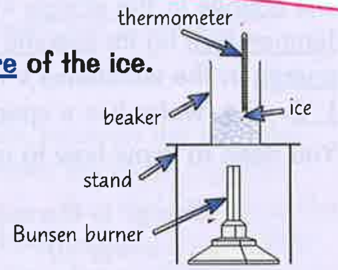
If you heat up a pan of water on the stove, the water never gets any hotter than 100 °C. You can carry on heating it up, but the temperature won't rise. How come, you say? It's all to do with latent heat...

You Need to Put In Energy to Break Bonds Between Particles

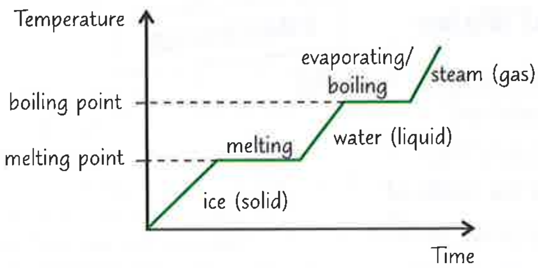
1) Remember, when you heat a solid or liquid, you're transferring energy to the kinetic energy stores of the particles in the substance, making the particles vibrate or move faster (p.24).
2) When a substance is melting or boiling, you're still putting in energy, but the energy's used for breaking bonds between particles rather than raising the temperature.
3) When a substance is condensing or freezing, bonds are forming between particles, which releases energy. This means the temperature doesn't go down until all the substance has turned into a liquid (condensing) or a solid (freezing).
4) You can see this by doing this simple experiment:

PRACTICAL

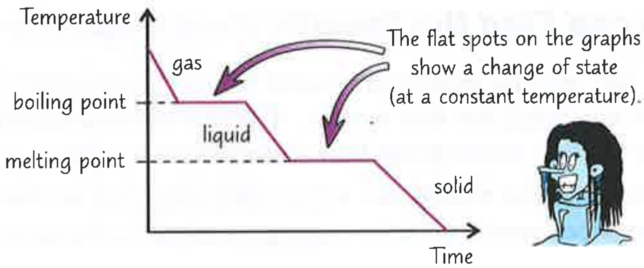
1) Fill a beaker with crushed ice.
2) Place a thermometer into the beaker and record the temperature of the ice.
3) Using the Bunsen burner, gradually heat the beaker full of ice.
4) Every twenty seconds, record the temperature and the current state of the ice (e.g. partially melted, completely melted).
5) Continue this process until the water begins to boil.
6) Plot a graph of temperature against time for your experiment.



Your graph should look like this:



You get a similar one for condensing and freezing:



Don't get confused with specific heat capacity, which relates to a temperature rise of 1 °C.

Specific Latent Heat is the Energy Needed to Change State

1) The specific latent heat (SLH) of a change of state of a substance is the amount of energy needed to change 1 kg of it from one state to another without changing its temperature.
2) For cooling, specific latent heat is the energy released by a change in state.
3) Specific latent heat is different for different materials, and for changing between different states.
4) The specific latent heat for changing between a solid and a liquid (melting or freezing) is called the specific latent heat of fusion. The specific latent heat for changing between a liquid and a gas (evaporating, boiling or condensing) is called the specific latent heat of vaporisation.
5) You can work out the energy needed (or released) when a substance of mass m changes state using this formula:

Thermal Energy (Q) = Mass (m) × Specific Latent Heat (L)

Thermal energy is given in joules (J), mass is in kg and SLH is in J/kg.

Breaking Bonds — Blofeld never quite manages it...

Fun fact: this stuff explains how sweating cools you down — the energy that builds up in your body when you exercise is used to change liquid sweat into gas, rather than increasing your temperature. Nice...

Q1 Sketch a graph showing how the temperature of a sample of water will change over time as it's heated from –5 °C to 105 °C. [3 marks]

Particle Motion in Gases

Gas particles fly around, bump into things and exert forces on them. This is happening to you right now — the air around you is exerting pressure on you (unless you're somehow reading this in space).

Colliding Gas Particles Create Pressure

1) According to kinetic theory, all matter is made up of very small, constantly moving particles.
2) Particles in a gas hardly take up any space. Most of the gas is empty space.
3) As the gas particles move about at high speeds, they bang into each other and whatever else happens to get in the way. When they collide with something, they exert a force (and so a pressure — p.101) on it.
4) In a sealed container, the outward gas pressure is the total force exerted by all of the particles in the gas on a unit area of the container walls.

A sealed container is an example of a closed system — no matter can get in or out.

Gas Pressure Varies with Volume and Temperature

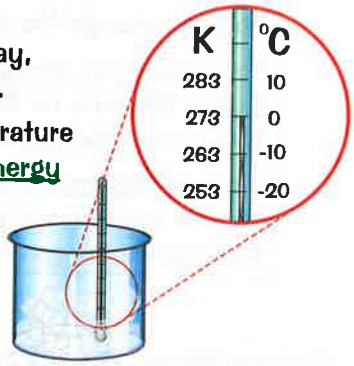
1) The speed of gas particles depends on the temperature of the gas. The higher the temperature, the faster the particles move and the more often they collide with the container. The force exerted by each particle during a collision also increases as the temperature increases.
2) So increasing the temperature of a fixed volume of gas increases its pressure.
3) Alternatively, if temperature is constant, increasing the volume of a gas means the particles get more spread out and hit the walls of the container less often. The gas pressure decreases.
4) Pressure and volume are inversely proportional — when volume goes up, pressure goes down (and vice versa). For a gas of fixed mass at a constant temperature, the relationship is:

$$P_1V_1 = P_2V_2$$

where P_1 is the pressure at a volume V_1 and P_2 is the pressure at a volume V_2. Pressure is in Pa (or N/m^2) and volume is in m^3.

Absolute Zero is as Cold as Stuff Can Get — 0 kelvin

1) If you increase the temperature of something, you give its particles more energy — they move about more quickly or vibrate more. In the same way, if you cool a substance down, you're reducing the energy of the particles.
2) In theory, the coldest that anything can ever get is -273 °C — this temperature is known as absolute zero. At absolute zero, the particles have as little energy in their kinetic stores as it's possible to get — they're pretty much still.
3) Absolute zero is the start of the Kelvin scale of temperature.
4) A temperature change of 1 °C is also a change of 1 kelvin. The two scales are pretty similar — the only difference is where the zero occurs.
5) To convert from degrees Celsius to kelvins, just add 273. And to convert from kelvins to degrees Celsius, just subtract 273.



	Absolute zero	Freezing point of water	Boiling point of water
Celsius scale	–273 °C	0 °C	100 °C
Kelvin scale	0 K	273 K	373 K

There's no degree symbol when you write a temperature in kelvins. Just write K, not °K. OK.

Gas particles need to watch where they're going...

Remember, the more gas particles there are, and the faster they travel, the higher the pressure. Simple...

Q1 Find the value of 25 °C in kelvin. [1 mark]

Q2 Explain how a gas exerts pressure on its container. [2 marks]

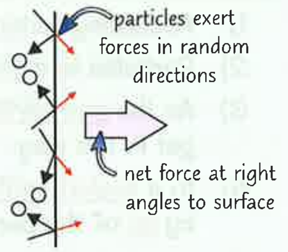
Q3 3.5 m^3 of a gas is at a pressure of 520 Pa. It is compressed to a volume of 1 m^3 at a constant temperature. What is the new pressure of the gas? [3 marks]

Pressure, Temperature and Volume

Don't breathe out yet — there's still more about pressure that you need to know.

A Change in Pressure Can Cause a Change in Volume

1) You know from the previous page that a gas exerts a force on its container due to collisions between the particles and the walls of the container.
2) These collisions happen in random directions, but add together to produce a net (overall) force at right angles to the wall of the container.
3) Unless it's in a vacuum, the outside of a gas container will also be under pressure from whatever's around it — e.g. atmospheric pressure from the air (p.102).



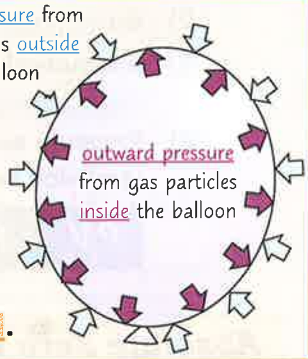
4) For containers without a fixed volume (e.g. a balloon) the volume of the gas is constant (it isn't expanding or contracting) when the pressure of the gas inside pushing outwards is equal to the pressure of the air outside pushing inwards.
5) You can change the volume of a gas in a container that doesn't have a fixed volume by changing either the internal (outward) or external (inward) pressure on the container:

You can change the pressure of a gas inside a container (e.g. a balloon) by heating or cooling.

As the balloon is heated, the gas particles inside it gain energy and move around quicker. This increases the pressure of the gas inside the balloon.

The outward pressure of the gas inside the balloon is now larger than the inward pressure caused by the surroundings. The balloon (and so the volume of the gas) expands until the pressures are equal once more.

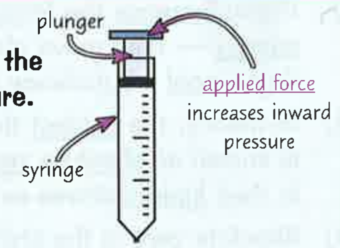
Cooling the gas in the balloon has the opposite effect — the outward pressure is smaller than the inward pressure, so the gas inside the balloon is compressed.



You can change the external pressure on a gas in a number of ways:

For a gas in an air-tight syringe, pushing hard on the plunger increases the inward pressure on the gas, so that it is larger than the outward pressure. This causes the gas inside of the syringe to be compressed.

Atmospheric pressure (p.102) decreases as altitude increases, so as a container of gas rises, the inward pressure decreases. This causes the gas to expand as the altitude increases.



Doing Work on a Gas Can Increase its Temperature

There's more about doing work on p.66.

1) Doing work on a gas can increase its internal energy (p.95), which increases its temperature.
2) You can do work on a gas mechanically, e.g. with a bike pump. (You also do work on a gas when you heat it up.)
3) The gas exerts pressure on the plunger of the pump, and so exerts a force on it. Work has to be done against this force to push down the plunger.
4) This transfers energy to the kinetic energy stores of the gas particles, so increases the internal energy and therefore the temperature.
5) If the pump is connected to e.g. a tyre, some of this energy is transferred from the gas to the thermal energy store of the tyre, and you'll feel the tyre getting warmer as you pump it up.

Hope the pressure's not getting to you...

Get your head around how changing pressure can cause a change in the volume of a gas (and its container).

Q1 Explain why pumping up a bike tyre increases the tyre's temperature. [3 marks]