Edexcel IAL Physics A-level

Topic 1.4: Materials

Notes

1.4 - Materials

1.4.23 - Density

The **density (ρ)** of a material is its mass per unit volume, and it's a measure of how compact a substance is. You can calculate density using the following equation:

$$\rho = \frac{m}{V}$$

Where m is the mass of the object and V is its volume.

1.4.24 - Upthrust

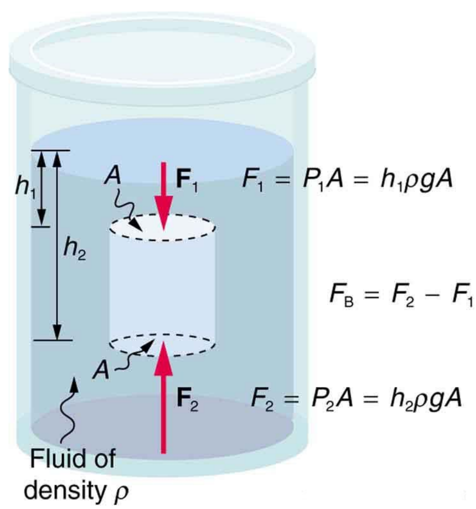
Objects in fluids may experience a force called **upthrust** due to different pressures being exerted on the surface of the object.

In order to fully understand the origin of upthrust, you should be aware of the following equation used to calculate pressure (p):
*(**Note**: you are **not expected** to be aware of or use this equation, it is just being used to illustrate the origins of upthrust).*

$$\Delta p = \rho g \Delta h$$

Where **ρ** is the density of the fluid, **g** is the gravitational field strength and **h** is the depth of the object in the fluid.

Consider a cylinder which is submerged in water. The bottom of the cylinder is deeper down in the fluid, therefore **h is larger than it is for the top of the cylinder.** This means that the **pressure at the bottom of the cylinder will also be larger**. As the two faces of the cylinder have an equal area, and **P = F/A**, the force experienced by the bottom of the cylinder is larger than the top of the cube and it is pushed upwards. The force pushing the cylinder upwards is **upthrust**.



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Archimedes' principle states that the **upthrust** experienced by an object is equal to the weight of the fluid it displaces.

$$Upthrust \ = \ weight\ of\ fluid\ displaced$$

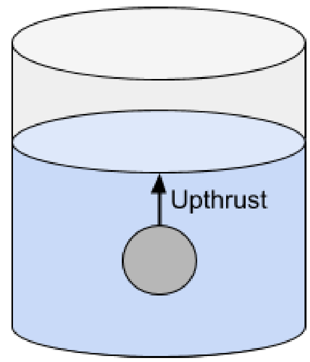
The **weight** of the displaced fluid can be calculated by finding the product of the density of the fluid, the volume of the displaced fluid and gravitational field strength:

$$Upthrust \ = weight\ of\ fluid\ displaced \ = \ \rho\, V\, g$$

Where **ρ** is the density, **V** is the volume of displaced fluid and **g** is the gravitational field strength.

If an object is **fully submerged**, then the volume of the displaced fluid is just equal to the volume of the object.
Below are two example questions where you have to use the formulas given above:

A steel pendulum bob is submerged in a beaker of water. The pendulum bob has a volume of 5 cm^3, the density of steel is 8.05×10^{-3} kg/cm^3 and the density of water is 1000 kg/m^3. Calculate the mass of the pendulum bob and the upthrust it experiences.



Calculate the bob's mass by using the formula for density, rearranged so that mass is the subject. (Be sure to take note of the units for volume and density).

$$m = \rho V$$

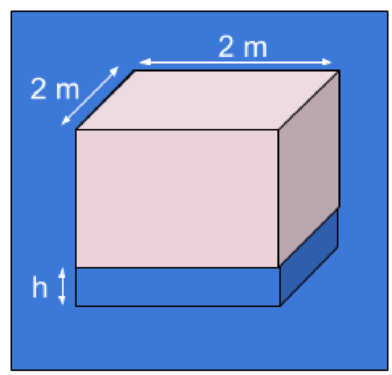
$$m = 8.05 \times 10^{-3} \times 5 \qquad = \mathbf{0.04025\ kg}$$

You can find the value of the upthrust by using Archimedes' principle. (Making sure to convert the volume into m^3).

$$Upthrust = \rho V g$$

$$Upthrust = 1000 \times 5 \times 10^{-6} \times 9.8 \qquad = \mathbf{0.049\ N}$$

A cube is floating (partially-submerged) in a tub of water. The mass of the cube is 1000 kg, the length of its sides are 2 m, and the density of water is 1000 kg/m^3.
Calculate the height (h) to which the water reaches on the cube (as shown on the diagram).



Firstly, find the weight of the cube using the formula below.

$$Weight = mg$$

$$Weight = 1000 \times 9.8 \qquad = \mathbf{9800\ N}$$

As the cube is floating on the surface of the water, its weight must be equal to the upthrust of the water, so you can set them equal to each other.

$$Weight = upthrust$$

Using Archimedes' principle you can write:

$$Weight = \rho V g$$

You can simplify the volume of the displaced fluid by writing:

$$V = 2 \times 2 \times h \qquad = 4h$$

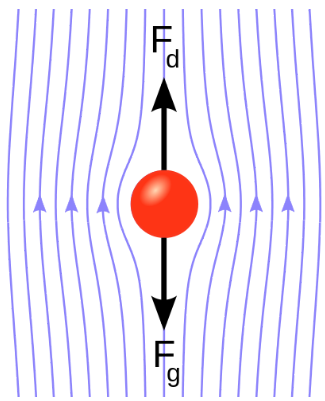
Where the first "2" represents the width, while the second represents the breath of the cube.

Finally, you can substitute the equation for volume that we just derived into the equation we got by using Archimedes' principle. Using this you can substitute in known values and rearrange to find h.

$$Weight = \rho \times 4h \times g$$
$$9800 = 1000 \times 4h \times 9.8$$
$$1000 = 4000h$$
$$h = 1/4 \quad = \mathbf{0.25\ m}$$

1.4.25 - Stokes' law

The resistive force experienced by an object moving in a fluid is known as **viscous drag force**. This force is labelled as $\mathbf{F_d}$ on the diagram below.



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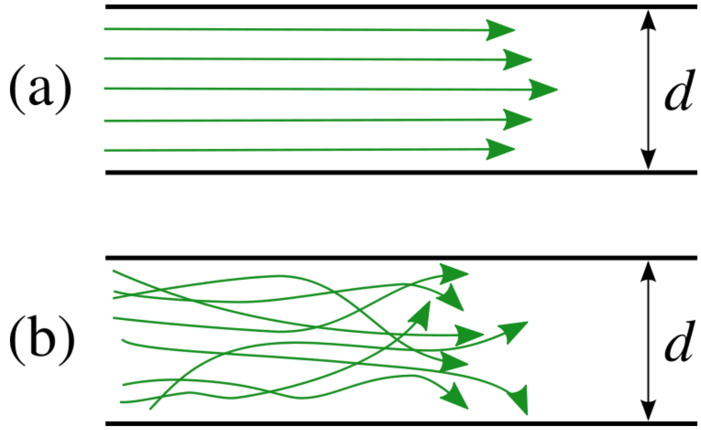
The viscous drag force exerted on an object can be calculated using **Stokes' law** if the following conditions apply:

- The object is **small + spherical**
- The object moves at a **low speed** with **laminar flow**.

Laminar flow (a in the diagram below) is where the particles in a fluid move by following **smooth** paths with **little to no mixing** between adjacent layers of the fluid.
On the other hand, **turbulent flow** (b in the diagram below) is where particles in the fluid **mix** between layers and form **separate currents**, because of this, turbulent flow is often described as chaotic.



Stokes' law states that the viscous drag force (F) experienced by a **small**, **spherical** object moving **slowly** with **laminar flow** can be calculated as shown below:

$$F = 6\pi\eta rv$$

Where **η** is the viscosity of the fluid, **r** is the radius of the object and **v** is the terminal velocity of the object.

Viscosity is a measure of how resistant a fluid is to deformation (e.g. caused by an object moving through it). A fluid's viscosity is determined by the internal frictional forces that occur between adjacent layers of the fluid.

It is important to note that viscosity is **temperature dependent**:

- In (most) **liquids** -
  As temperature **increases**, the viscosity of a liquid **decreases**.
- In **gases** -
  As temperature **increases**, the viscosity of a gas **increases**.

The reason that viscosity varies differently with temperature in liquids as opposed to gases, arises from the fact that the frictional forces between layers are formed by different means in them.

1.4.26 - Hooke's law

Hooke's law states that extension is **directly proportional** to the force applied, given that the environmental conditions (e.g temperature) are kept **constant**.

Hooke's law can be described using the equation:

$$\Delta F = k\Delta x$$

Where **k** is the stiffness of the object, and **Δx** is the extension.

1.4.27 - Young modulus

Stress - Force applied per unit cross-sectional area.

$$Stress = \frac{F}{A}$$

Strain - This is caused by stress, and is defined as the change in length over the original length.

$$Strain = \frac{\Delta L}{L}$$

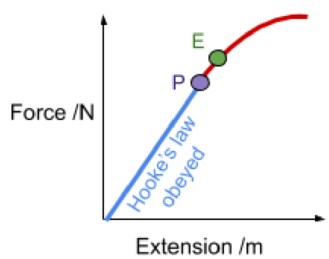
The **Young modulus** is a value which describes the stiffness of a material.
It is known that up to the **limit of proportionality** (explained below), for a material which obeys Hooke's law, stress is proportional to strain, therefore the value of stress over strain is constant, this value is the Young modulus.

$$Young\ Modulus = \frac{Stress}{Strain}$$

1.4.28 - Force-extension and force-compression graphs

Force-extension graphs show how the extension of an object varies with the force applied to it.

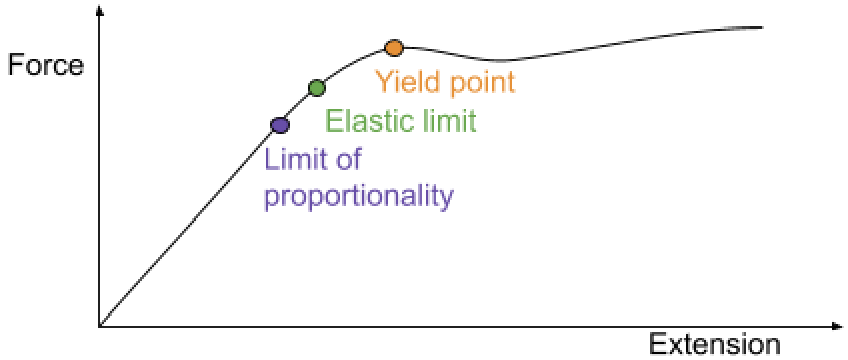
Hooke's law can be demonstrated by a force-extension graph which is a **straight line through the origin** as this shows that force and extension are **directly proportional**.



The **limit of proportionality (P)** is the point after which Hooke's law is no longer obeyed.

The **elastic limit (E)** is just after the limit of proportionality and if you increase the force applied beyond this, the material will deform plastically (be permanently stretched).

The **yield point** is the point at which the material begins to stretch **without** an increase in load.

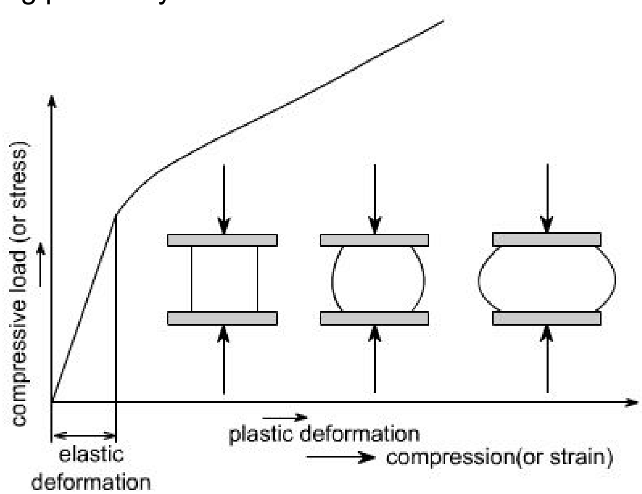


Elastic deformation is where a material returns to its original shape once the force applied is removed. This is because **all** the work done is stored as **elastic strain energy**.

Plastic deformation is where a material's shape is changed permanently. This is because work is done to move atoms apart, so energy is **not only** stored as elastic strain energy but is also **dissipated as heat**.

Force-compressions graphs show how the compression of an object varies with the force applied to it.

Solids usually behave similarly when tensile and compressive forces are applied, therefore force-extension and force-compression graphs often look very **similar**. The main difference being that beyond the elastic limit, compressed solids will buckle (suddenly change shape) and break instead of extending plastically.



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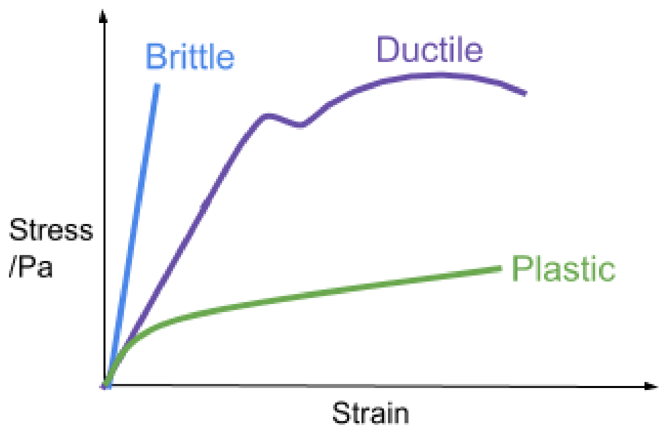
1.4.30 - Stress-strain graphs

Stress-strain graphs are similar to force-extension graphs, however they describe the behaviour of a material rather than the behaviour of a specific object.

Their shape can also show whether a material is:

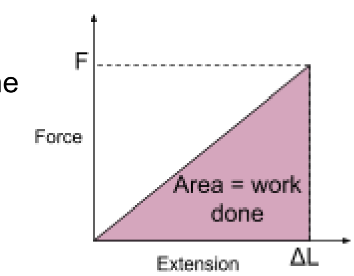
- **Ductile** - can undergo a large amount of plastic deformation before fracturing
- **Brittle** - where a material will extend very little, and therefore is likely to fracture (break apart) at a low strain
- **Plastic** - where a material will experience a large amount of extension as the load is increased.



The **breaking stress** of a material is the value of stress at which the material will break apart, this value will depend on the conditions of the material e.g its temperature.

1.4.32 - Elastic strain energy

When work is done on a material to stretch or compress it, this energy is stored as **elastic strain energy**. This value cannot be calculated using the formula $W = F\Delta s$ because the force is **variable**, however you can find it by calculating the area under a force-extension graph or by using the formula below:



$$\Delta E_{el} = \frac{1}{2}F\Delta x$$

Where **F** is the force applied and **x** is the extension.

Once a material is stretched beyond its elastic limit, a force-extension graph showing loading and unloading will not return to the origin, however the loading and unloading lines will be parallel because the material's stiffness is constant, as shown below. The area between the loading and unloading line is the work done to permanently deform the material.