18 Understand and use the terms density, laminar flow, streamline flow, terminal velocity, turbulent flow, upthrust and viscous drag, for example, in transport design or in manufacturing

Density: Density is mass per unit volume: where mass m is in kg, volume V is in m^3 and density ρ is in kg m^{-3}.

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

Pressure: It is the force per unit area: Pressure in fluids is calculated by:

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

Pressure increases as you go deeper under a fluid due to the weight of the fluid above you.

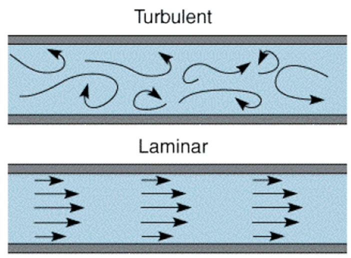
$$P = h\rho g$$

Upthrust: When an object is submerged in a fluid, it feels an upward force caused by the fluid pressure. This upward force is called upthrust. According to Archimedes principle, upthrust is equal to the weight of the fluid displaced by the object. Therefore, If the upthrust on a fully submerged object is less than its weight, the object will sink. An object will float if it can displace its own weight of fluid without becoming fully submerged.

$$upthrust = weight\ of\ fluid = mg = v\rho g$$

Moving fluids – laminar and turbulent flow Streamlines represent the velocity of a fluid at each point within it. They can be drawn as arrowed lines that show the paths taken by small regions of the fluid.

Laminar flow (or **streamline flow**) occurs when adjacent layers of fluid do not cross into each other. They usually occurs at lower speeds and around more streamlined objects. The layers do not mix, so your drawings should not show streamlines crossing over. The layers are roughly parallel. The speed and direction at any point remain constant over time. There are no sudden changes in speed or direction along the streamlines either, so do not draw sharply angled changes in direction when the lines flow around the objects. **Turbulent flow** occurs when the streamlines are not continuous. The flow is chaotic and subject to sudden changes in speed and direction. There is a lot of large-scale mixing of layers, so eddies and vortices are frequently seen.



Laminar flow is an important consideration in fluid motion. The uplift on an aeroplane's wings is dependent on laminar flow, and passengers experience a rocky ride when turbulent conditions are encountered. Similarly, the drag forces on a motor car are affected by turbulence, and wind tunnels are used to observe the nature of the airflow over prototype designs.

The efficiency of fluid transfer through tubes is greatly reduced if turbulence occurs, so the rate of flow of oil and gas must be controlled so that the critical speed is not exceeded. In the food industry, the flow of sweet casings such as toffee and chocolate over nuts or other fillings should be laminar so that sir bubbles are not trapped as a result of turbulence.

Viscous drag: When solids and fluids move relative to each other, the layer of fluid next to the solid exerts a frictional force on it. Successive layers of fluid experience frictional forces between each other as well. The frictional forces cause **viscous drag**, which is one of the causes of air resistance. *More will be covered in 20.*

19 Recall, and use primary or secondary data to show that the rate of flow of a fluid is related to its viscosity

Viscosity: The viscosity of a fluid relates to its stickiness and thus to its viscous drag. It can be described in terms of the resistance between adjacent layers in laminar flow.

The **coefficient of viscosity**, η, usually just called viscosity, is used to compare different fluids. Fluids with lower viscosity will have a greater rate of flow and cause less viscous drag.
The unit of viscosity is kg m^{-1} s^{-1} or N s m^{-2}.

Experiment: To investigate how fluid rate depends on its viscosity.
(Diagram from Hodder Pg – 54)
Using the apparatus in the figure, fill the funnel with liquid to a level just above the upper mark. For example, water. Open the clip to allow the liquid to flow through the tube in the beaker. Start timing passes the upper mark and stop as it passes the lower one. Repeat for various samples, e.g.: chocholate and then note down the time taken.

Observation: Samples that took longer time is more viscous. And therefore, their (chocolate) fluid rate is lower comparing to other (water).

Precaution: For runny liquids like water or sugar solution of a low concentration, a capillary tube with a diameter of 1mm should be used so that very short times (and large percentage uncertainties) are avoided. For syrup, etc, tubes with bores of 5mm or wider can be used.

20 Recognise and use the expression for Stokes' Law, F = 6πηrv and upthrust = weight of fluid displaced

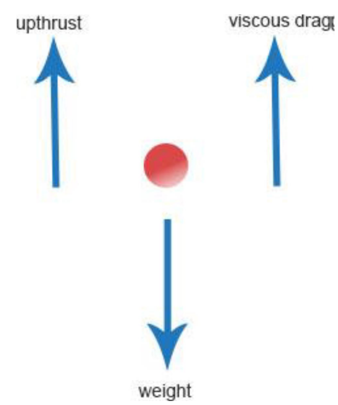
Stoke's law gives a formula for viscous drag for a small sphere at low speeds in laminar flow. The viscous drag force, *F*, is given by:

$$F = 6\pi\eta r v$$

where r is the radius of the sphere, in metres, η is the viscosity, in N s m-2, and v is the velocity, in ms-1.

Terminal velocity

In a falling object in liquid, three forces act on it – weight,
upthrust and drag as in the figure. Drag force changes with
speed. When upthrust and drag force balances the weight, the
velocity becomes constant which we call **terminal velocity**. In
equation:



$$upthrust + viscous\ drag = weight$$

Expressing in terms of Stoke's law gives:

$$\frac{4}{3}\pi r^3\, \rho_{fluid}\, g + 6\pi\eta r v = \frac{4}{3}\pi r^3\, \rho_{steel}\, g$$

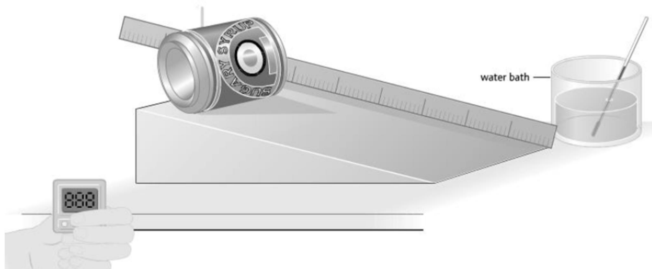
Rearranging further gives:

$$v = \frac{2r^2 g(\rho_{steel} - \rho_{fluid})}{9\eta}$$

21 Investigate, using primary or secondary data, and recall that the viscosities of most fluids change with temperature.

Explain the importance of this for industrial applications An even greater variation in viscosity of liquid chocolate is caused by changes in its temperature. If a sweet manufacture wants to account for variations in a recipe (which might come from something as minor as change in supplier of cocoa beans), they can adjust the flow rate by altering the temperature. Viscosity is directly related to fluid temperature. In general, liquids have a lower coefficient of viscosity at higher temperature. For gases, viscosity increases with temperature.

Experiment: To investigate the change of viscosity with temperature The change in viscosity of a liquid with temperature can be observed in a school laboratory using re-sealable tin or bottle half full of a test fluid.

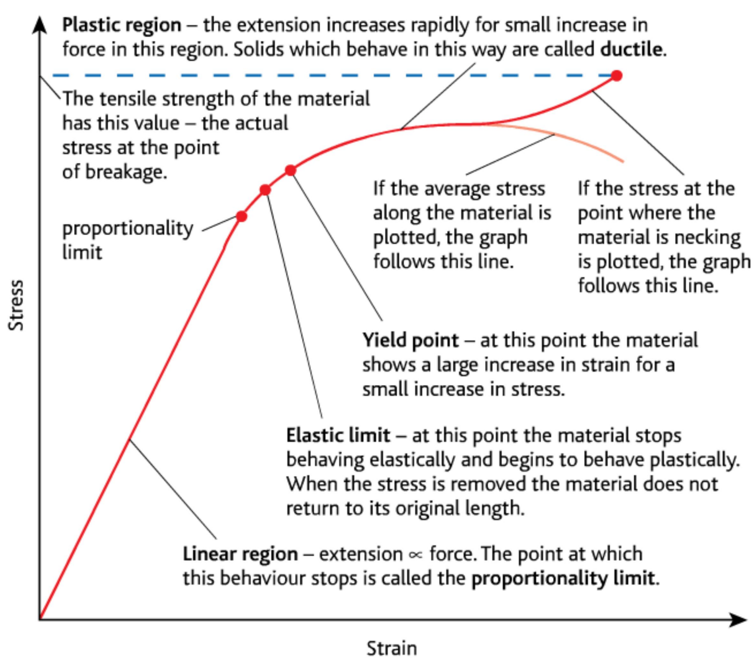


The temperature of the liquid is varied using a water bath. The viscosity of the liquid will affect the rate at which the tin or bottle rolls down a fixed ramp.

22 Obtain and draw force-extension, force-compression, and tensile/compressive stress-strain graphs. Identify the limit of proportionality, elastic limit and yield point

Read 23, 24 first.

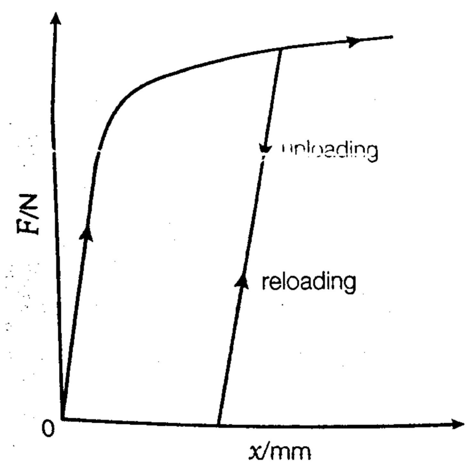
Stress-strain graphs This figure shows a stress-strain graph a copper wire.



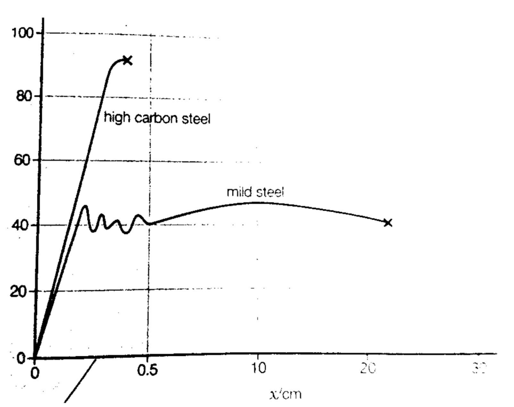
Obtain graphs for, for example, copper wire, nylon and rubber

Force-extension graphs

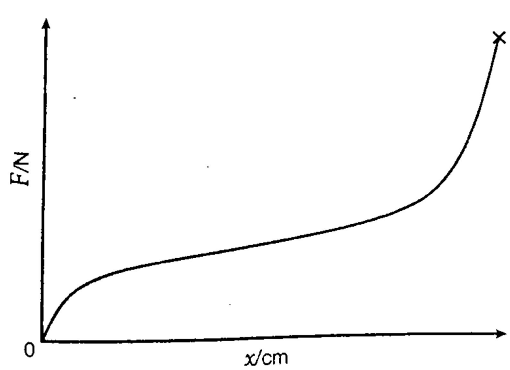
Copper wire



Steel wires

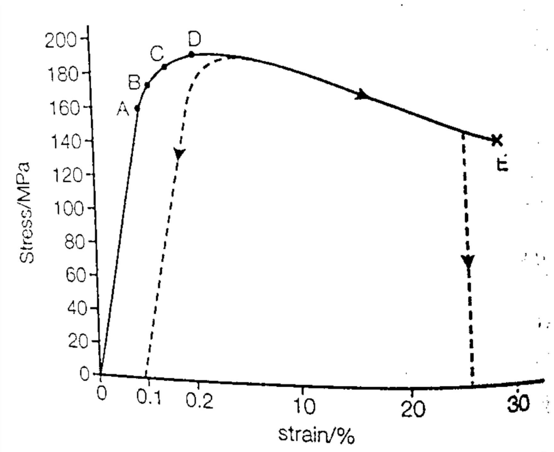


Natural rubber

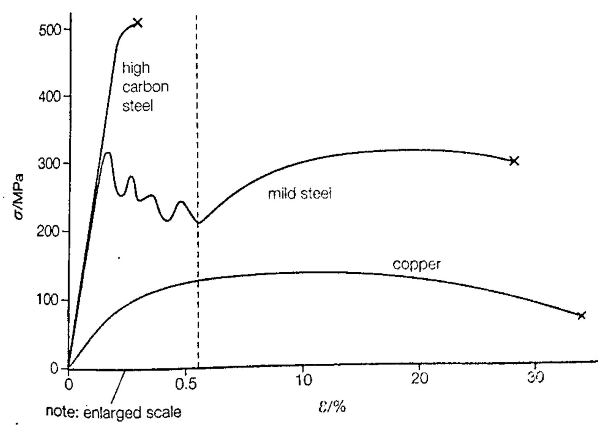


Stress-strain graphs

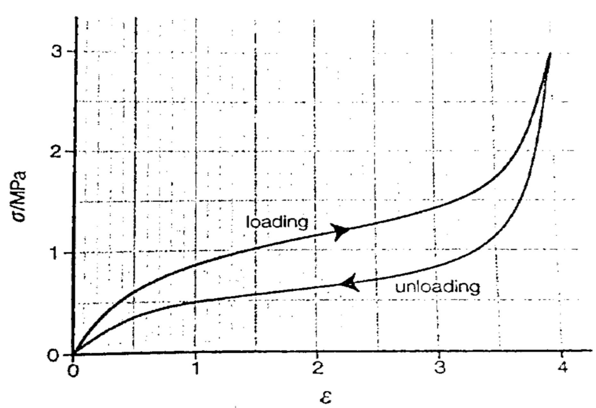
Copper wire



Steel wires

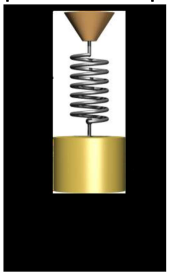


Rubber

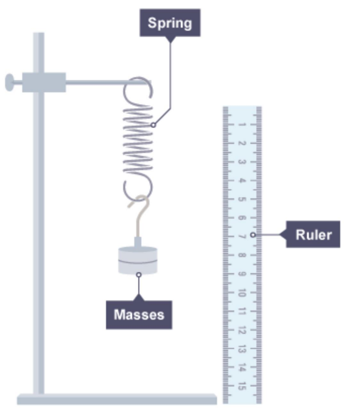


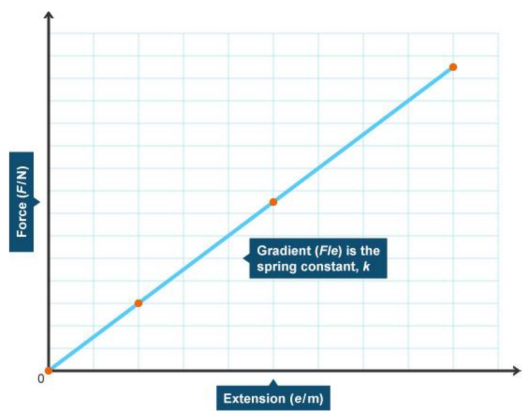
23 Investigate and use Hooke's law, F = kΔx, and know that it applies only to some materials

Hooke's law states that, up to given load, the extension of a spring is directly proportional to
the force applied to the spring.
F = - kΔx; where k is the constant for a particular spring called constant of proportionality or spring constant. It represents the stiffness of the spring.
The negative sign shows that the force exerted by the spring in the opposite direction to the extension.
The spring constant k is different for different materials – the larger the k the stiffer the spring.



Experiment: To investigate Hooke's law
The apparatus for the experiment and a sketch of the resulting load-extension graph are shown below.





The straight line formed confirms that the Hooke's law is obeyed.

Elastic limit: The limit beyond which the extension increases rapidly than expected and the spring remains permanently deformed when the load is removed is called the elastic limit. Upto the limit, the spring regain its original shape whenever the load is removed.

24 Explain the meaning and use of, and calculate, tensile/compressive stress, tensile/compressive strain, strength, breaking stress, stiffness and Young Modulus.

Obtain the Young modulus for a material

The extension of a material depends on the stiffness, k, and the applied force. But it is also the case that for a given force a longer sample will experience a greater extension, and a thicker sample will extend less. If different materials are to be compared fairly, the effect of the sample's thickness and length must be taken into account. In order to to do this, graphs of force against extension are replaced with graphs of **stress** against **strain**. A **tensile force** is the force used in a material to stretch it apart. **A compressive force** is when the material is being compressed. **Stress:** The applied force per unit area is called stress, σ.

$$tensile/compressive\ stress = \frac{tensile/compressive\ force}{cross - sectional\ area}$$

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

Stress has units N m^{-2} or Pa

Strain: The extension per unit length is called strain.

$$tensile/compressive\ strain = \frac{extension}{orginal\ length}$$

$$\varepsilon = \frac{\Delta x}{x}$$

Strain has no unit.

Strength: The strength of a materials is the stress at which the material breaks.

Breaking stress: The maximum stress a material can stand before it breaks is called the breaking stress or ultimate tensile stress.

Young modulus: The ratio of stress to strain is a constant. This constant is called Young modulus, E.

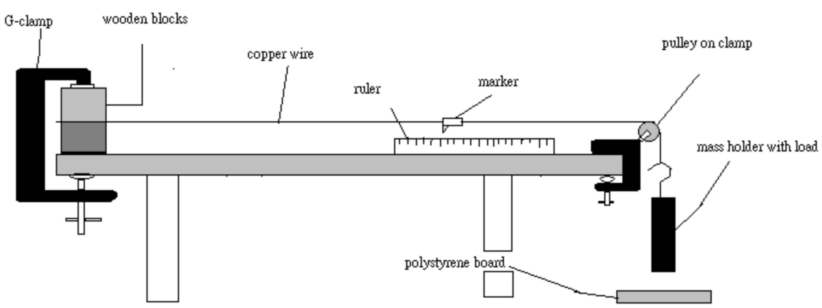
$$Young\ modulus = \frac{stress}{strain} = \frac{applied\ force/cross - sectional\ area}{extension/original\ length}$$

$$E = \frac{\sigma}{\epsilon} = \frac{Fx}{A\Delta x}$$

The units of the Young modulus are N m^{-2}, or Pa. For many materials, MPa (10^6 Pa) is a more convenient unit as the Pa is very small.

Experiment: To measure the Young modulus

The apparatus used to measure the Young modulus is shown in the diagram below. Increase the force applied to a long, thin wire by adding masses of known weight. Measure the diameter of the wire with a micrometer screw gauge, remembering to measure at different positions and in different planes, and find a mean value. Measure the original length, from the clamp to the marker, with a metre rule, and then measure the increase in length (the extension) using a fixed scale as the force is changed. Plot a graph of force against extension, and find the gradient, F/Δx. This is multiplied by the original length/cross-sectional area to find the Young modulus.



Uncertainties in measurements To measure the Young modulus all that is necessary in principle is to measure the extension of a sample for a given force and then to calculate the To find E, a graphical method is usually used. Since:

E = tensile strain = $\frac{\sigma}{\varepsilon}$

then,

$$\sigma = E\varepsilon$$

tensile stress and tensile strain, from E can be calculated. In practice such a method is unlikely to lead to very reliable results. It follows that a graph of tensile stress plotted against tensile strain will have slope E . To plot the graph you will need to make a number of measurements. The table below suggests possible uncertainties in these measurements when using simple equipment.

Measurement	Possible uncertainty in measurement	Note
Force/N	±2% (if using slotted masses)	Slotted masses may have very variable uncertainties in their mass. If carefully selected, they are unlikely to have an uncertainty of more than ±2g. The mass used will need to be converted to weight using an appropriate value of g – the approximation of g to 10 N kg^{-1} would lead to an uncertainty of more than +1%.
Diameter of wire/m	±2% (using micrometer)	A micrometer should be capable of measuring a wire 1mm in diameter to within ±0.02mm if used carefully. This is an uncertainty of ±2%, which will also be the uncertainty of the radius (d/2).
Cross-sectional area/m^2	±4% (depends on $radius^2$)	Since the cross-sectional area of the wire depends on its $radius^2$, the uncertainty of the cross-sectional area will be twice the uncertainty of the radius. (Where two quantities are multiplied together or one is divided by the other their uncertainties are added to find the uncertainty of the result. Where two quantities area added or subtracted their uncertainties are averaged to find the uncertainty of the result.)
Original length of wire/m	±1.5% (using metre rule)	If a piece of wire 2m long is used, its length can be measured to within around 3mm using a metre rule – an uncertainty of 1.5%.
Extension of wire/m	10%	The extension of the wire depends on many factors like its length, cross-sectional area and the material it is made of. If extensions of the order of 5mm are measured to within 0.5mm, the uncertainty is ±10%.
Tensile stress = F/A	±6%	This is the sum of the uncertainties of F and A.
Tensile stress = Δx/x	±11.5%	This is the sum of uncertainties for Δx and x.

The largest uncertainty in any measurement of E comes in the measurement of extension. Accurate methods for measuring E thus concentrate on measuring Δx with a great as great a precision as possible. The percentages errors are calculated by finding what fraction of the value the error represents. For example, for the error in the extension of the wire. error in measurement = ±0.5 mm value of measurement = 5 mm

$$\% \text{ error} = \frac{0.5}{5} \times 100\% = 10\%$$

The overall uncertainty in E is likely to be ±6% + ±11.5% i.e. ±17.5%.

Investigations could include, for example, copper and rubber 25 investigate elastic and plastic deformation of a material and distinguish between them

A material undergoing **elastic** deformation will return to its original dimensions when the deforming force is removed. A **plastic** material will remain deformed.

26 explore and explain what is meant by the terms brittle, ductile, hard, malleable, stiff and tough. Use these terms, give examples of materials exhibiting such properties and explain how these properties are used in a variety of applications, for example, safety clothing, foodstuffs

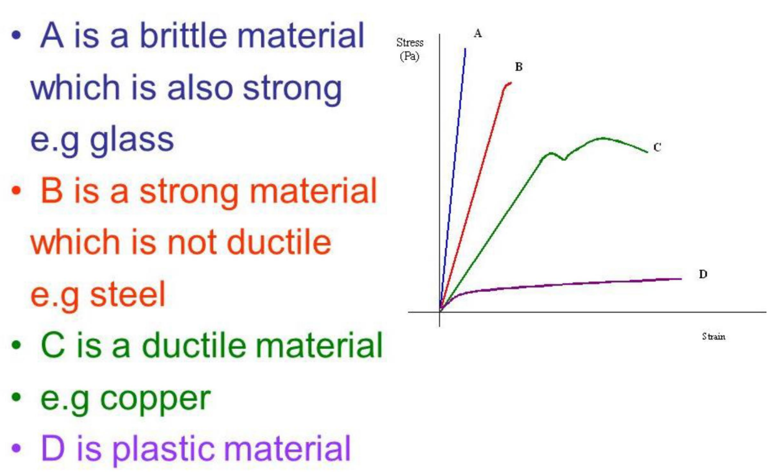
Brittle: Brittle materials break with little or no plastic deformation. e.g: glass, ceramics **Ductile:** Ductile materials show large plastic deformation before failure under tension. These materials can be pulled into wires or threads. e.g.: copper

Hard: Hard materials resist plastic deformation by surface indentation or scratching. e.g.: diamond

Malleable: Malleable materials show a large plastic deformation under compression. These materials can be beaten into sheets. e.g.: gold

Stiff: A stiff material exhibits very small deformation even subjected to large forces. e.g.: steel

Tough: Tough materials can withstand impact forces and absorb a lot of energy before breaking. Larges forces produce a moderate deformation. e.g.: mild steel, copper, rubber tyres.



27 calculate that the elastic strain energy E_{el} is a deformed material sample, using the expression $E_{el} = \frac{1}{2}F\Delta x$, and from the area under its force/extension graph Elastic strain energy

The energy stored in a stretched spring is equal to work done on it as it is stretched. Since the force increases linearly from zero to F as the spring is stretched, the average force used to stretch it is given by.

$$\frac{0+F}{2}=\frac{F}{2}$$

So the work done on the spring = ½ F Δx

Since, F = $-k\Delta x$

Work done = $\frac{1}{2}k\Delta x^2$

This is the work done by the spring. The spring gains energy which is called its potential energy or elastic strain energy.

The area under the force-extension graph gives work done or energy strain.