A LEVEL PHYSICS YEAR 1
PREPARATORY READING BOOK
3.4.2: MATERIALS

Volume

Three

NAME	
PHYSICS CLASS	
MODULE TEACHER	
ALPS GRADE	

A-LEVEL PHYSICS

TOPIC 4

PREP READING 3

THIS MUST BE BROUGHT TO ALL PHYSICS LESSONS.

Contents

Vectors and their treatment are introduced followed by development of the student's knowledge and understanding of forces, energy and momentum.

The section continues with a study of materials considered in terms of their bulk properties and tensile strength.

IMPORTANT NOTE
This booklet, along with the student workbook, must be brought to all Physics lessons with the appropriate teacher.

This booklet may be used as a learning resource in lessons; you are not fully equipped to learn if this is not used in lesson.

This booklet may also be used as a revision resource for intervention, internal assessments and external assessments.
Please keep this in your student file.

As part of this course you are expected to **read through this preparatory reading book** and **complete the independent study tasks**.

This work will not be assessed but will be monitored by your class teacher.

This must be completed by the deadline set by your class teacher.

Definition List

Definitions you must learn for this module are…

Brittle, snaps without stretching or bending when subject to stress.

Density of a substance, mass per unit volume of the substance.

Ductile, stretches easily without breaking.

Elastic limit, point beyond which a wire is permanently stretched.

Elasticity, property of a solid that enables it to regain its shape after it has been deformed or distorted.

Hooke's Law, the extension of a spring is proportional to the force needed to extend it.

Limit of proportionality, the limit beyond which, when a wire or a spring is stretched, its extension is no longer proportional to the force that stretches it.

Plastic deformation, deformation of a solid beyond its elastic limit.

Stiffness constant, the force per unit extension needed to extend a wire or a spring.

Strain, extension per unit length of a solid when deformed.

Stress, force per unit area of cross-section in a solid perpendicular to the cross-section.

Ultimate tensile stress, tensile stress needed to break a solid material.

Yield point, point at which the stress in a wire suddenly drops when the wire is subjected to increasing strain.

Young Modulus, stress/strain (assuming the limit of proportionality has not been exceeded).

IMPORTANT NOTE

These definitions must be memorised by students.

You will be tested on your knowledge of these definitions.

The Language of Measurement

The following subject specific vocabulary provides definitions of key terms used in the A-level Science specifications.

Accuracy
A measurement result is considered accurate if it is judged to be close to the true value.

Calibration
Marking a scale on a measuring instrument.
This involves establishing the relationship between indications of a measuring instrument and standard or reference quantity values, which must be applied.
For example, placing a thermometer in melting ice to see whether it reads 0 °C, to check if it has been calibrated correctly.

Data
Information, either qualitative or quantitative, that has been collected.

Errors
See also uncertainties.

Measurement error
The difference between a measured value and the true value.
anomalies
These are values in a set of results which are judged not to be part of the variation caused by random uncertainty.

Random error
These cause readings to be spread about the true value, due to results varying in an unpredictable way from one measurement to the next.
Random errors are present when any measurement is made, and cannot be corrected. The effect of random errors can be reduced by making more measurements and calculating a new mean.

Systematic error
These cause readings to differ from the true value by a consistent amount each time a measurement is made.
Sources of systematic error can include the environment, methods of observation or instruments used.
Systematic errors cannot be dealt with by simple repeats. If a systematic error is suspected, the data collection should be repeated using a different technique or a different set of equipment, and the results compared.

Zero error
Any indication that a measuring system gives a false reading when the true value of a measured quantity is zero, e.g. the needle on an ammeter failing to return to zero when no current flows.
A zero error may result in a systematic uncertainty.

Evidence
Data which has been shown to be valid.

Fair test
A fair test is one in which only the independent variable has been allowed to affect the dependent variable.

Hypothesis
A proposal intended to explain certain facts or observations.

Interval
The quantity between readings, e.g. a set of 11 readings equally spaced over a distance of 1 metre would give an interval of 10 centimetres.

Precision
Precise measurements are ones in which there is very little spread about the mean value. Precision depends only on the extent of random errors – it gives no indication of how close results are to the true value.

Prediction
A prediction is a statement suggesting what will happen in the future, based on observation, experience or a hypothesis.

Range
The maximum and minimum values of the independent or dependent variables; important in ensuring that any pattern is detected.
For example, a range of distances may be quoted as either:
'From 10 cm to 50 cm'
or
'From 50 cm to 10 cm'

Repeatable
A measurement is repeatable if the original experimenter repeats the investigation using same method and equipment and obtains the same results.

Reproducible
A measurement is reproducible if the investigation is repeated by another person, or by using different equipment or techniques, and the same results are obtained.

Resolution
This is the smallest change in the quantity being measured (input) of a measuring instrument that gives a perceptible change in the reading.

Sketch graph
A line graph, not necessarily on a grid, that shows the general shape of the relationship between two variables. It will not have any points plotted and although the axes should be labelled they may not be scaled.

True value
This is the value that would be obtained in an ideal measurement.

Uncertainty
The interval within which the true value can be expected to lie, with a given level of confidence or probability, e.g. "the temperature is 20 °C ± 2 °C, at a level of confidence of 95%.

Validity
Suitability of the investigative procedure to answer the question being asked. For example, an investigation to find out if the rate of a chemical reaction depended upon the concentration of one of the reactants would not be a valid procedure if the temperature of the reactants was not controlled.

Valid conclusion
A conclusion supported by valid data, obtained from an appropriate experimental design and based on sound reasoning.

Variables
These are physical, chemical or biological quantities or characteristics.

Categoric variables
Categoric variables have values that are labels. E.g. names of plants or types of material.

Continuous variables
Continuous variables can have values (called a quantity) that can be given a magnitude either by counting (as in the case of the number of shrimp) or by measurement (e.g. light intensity, flow rate etc.).

Control variables
A control variable is one which may, in addition to the independent variable, affect the outcome of the investigation and therefore must be kept constant or at least monitored.

Dependent variables
The dependent variable is the variable of which the value is measured for each change in the independent variable.

Independent variables
The independent variable is the variable for which values are changed or selected by the investigator.

IMPORTANT NOTE
These definitions must be memorised by students.

You will be tested on your knowledge of these definitions.

TOPIC: 3.4.2.1 Bulk Properties of Solids

SPEC CHECK

Specification	Completed?
Density, $\rho = \frac{m}{V}$	
Hooke's law, elastic limit, $F = k\Delta L$, k as stiffness and spring constant.	
Tensile strain and tensile stress.	
Elastic strain energy, breaking stress.	
Energy stored = ½ $F\Delta L$ = area under force−extension graph	
Description of plastic behaviour, fracture and brittle behaviour linked to force–extension graphs.	
Quantitative and qualitative application of energy conservation to examples involving elastic strain energy and energy to deform.	
Spring energy transformed to kinetic and gravitational potential energy.	
Interpretation of simple stress–strain curves.	
Appreciation of energy conservation issues in the context of ethical transport design.	
Students can compare the use of analogue and digital meters.	
Estimate the volume of an object leading to an estimate of its density.	

Student Checklist

Have I…….	Yes or No?
Read through the notes of this section?	
Highlighted/underlined the key concepts of this section?	
Made my own notes based on the notes of this section?	
Brought the notes to be used in lesson?	

Hooke's Law

Prior Knowledge Link
This is a topic found in a previous GCSE module **– Forces.**

If we take a metal wire or a spring and hang it from the ceiling it will have a natural, unstretched length of *l* metres. If we then attach masses to the bottom of the wire is will begin to increase in length (stretch). The amount of length it has increased by we will call the extension and represent by *e*.

If the extension increases proportionally to the force applied it follows Hooke's Law:

The force needed to stretch a spring is directly proportional to the extension of the spring from its natural length.

So, it takes twice as much force to extend a spring twice as far and half the force to extend it half as far. We can write this in equation form: $F \propto e$ or $\boxed{F = ke}$

Here *k* is the constant that shows us how much extension in length we would get for a given force.

Physics Tip

In Hooke's Law, the metal wire is light – this means you can ignore the force acting downwards due to the weight of the wire.

Physics Tip

Remember that the extension should be given in metres.

Physics Tip

If two factors are directly proportional, it means that if one increases, the other increases by the same proportion.

Physics Tip

Remember that Hooke's Law applied for compression as well as tension.

Physics Tip

You will be given the formula for Hooke's Law in your data and formulae booklet so you do not need to know it by heart.

Examination Tip

It is a common examination question to define Hooke's Law…

Force proportional to extension (1 mark).

up to the limit of proportionality (accept elastic limit) (1 mark)

The Spring Constant

Prior Knowledge Link
This is a topic found in a previous GCSE module **– Forces.**

The spring constant gives us an idea of the stiffness (or stretchiness) of the material.

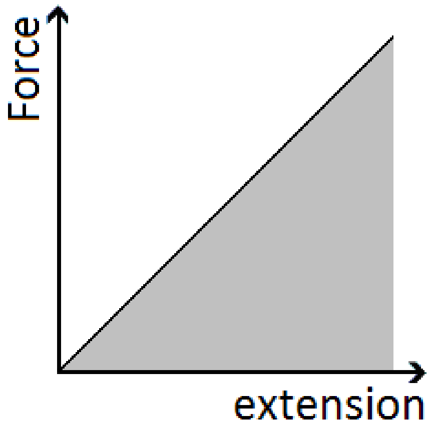
If we rearrange Hooke's Law we get: $k = \frac{F}{e}$

If we record the length of a spring, add masses to the bottom and measure its extension we can plot a graph of force against extension.

The gradient of this graph will be equal to the spring constant.

A small force causes a large extension the spring constant will be *small – very stretchy*

A large force causes a small extension the spring constant will be *large – not stretchy*



The gradient of the straight line produced is the spring constant.

Spring Constant is measured in Newtons per metre, N/m

Physics Tip

An object's stiffness constant is the force needed to extend it by 1m. It depends on the material that its made from, as well as its length and shape.

Physics Tip

A tensile force stretches something and a compressive force squashes it.

Physics Tip

The two features which show that the material under test obeys Hooke's Law are that it produces a straight line through the origin.

Physics Tip

The limit of proportionality can also be described as the point beyond which the force-extension graph is no longer linear (straight).

Springs in Series

The combined spring constant of spring *A* and spring *B* connected in series is given by:

$\frac{1}{k_T} = \frac{1}{k_A} + \frac{1}{k_B}$ If *A* and *B* are identical this becomes:

$\frac{1}{k_T} = \frac{1}{k} + \frac{1}{k}$ → $\frac{1}{k_T} = \frac{2}{k}$ → $k_T = \frac{k}{2}$

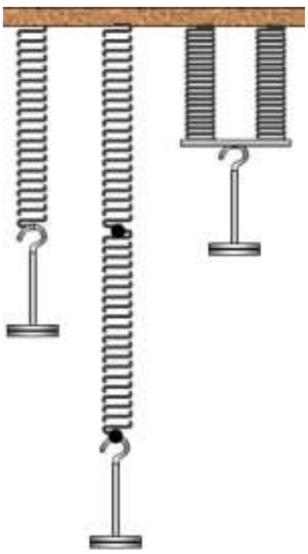
Since this gives us a smaller value for the spring constant, applying the same force produces a larger extension. *It is stretchier*

Springs in Parallel

The combined spring constant of spring *A* and spring *B* connected in parallel is:

$k_T = k_A + k_B$ so if *A* and *B* are identical this becomes: $k_T = k + k$ → $k_T = 2k$

Since this gives us a larger value for the spring constant applying the same force produces a smaller extension. *It is less stretchy*



Physics Tip

Do not be put it off if you are asked a question involves two or more springs.

The formula still applies for each spring.

Energy Stored (Elastic Strain Energy)

Prior Knowledge Link
This is a topic found in previous GCSE modules **– Forces and Energy.**

We can calculate the energy stored in a stretched material by considering the work done on it.

We defined work done as the force x distance moved in the direction of the force or $W = Fs$

Work done is equal to the energy transferred, in this case transferred to the material, so: $E = Fs$

The distance moved is the extension of the material, *e*, making the equation: $E = Fe$

The force is not constant; it increases from zero to a maximum of *F*.

The average force is given by: $\frac{(F-0)}{2}$

If we bring these terms together we get the equation $E = \frac{(F-0)}{2}e$ which simplifies to:

$$E = \tfrac{1}{2}Fe$$

This is also equal to the area under the graph of force against extension.

We can write a second version of this equation by substituting our top equation of $F = ke$ into the one above.

$$E = \tfrac{1}{2}Fe \rightarrow E = \tfrac{1}{2}(ke)e \rightarrow E = \tfrac{1}{2}ke^2$$

Physics Tip

In real life, some kinetic energy is always transferred to heat as well as elastic strain energy – but you can usually ignore those losses in energy conservation calculations.

Deforming Solids

Forces can be used to change the speed, direction and shape of an object.
This section of Physics looks at using forces to change of shape of a solid object, either temporarily or permanently.

If a pair of forces are used to *squash* a material, we say that they are *compressive* forces.

If a pair of forces is used to *stretch* a material, we say that they are *tensile* forces.

Tensile Stress, σ

Tensile stress is defined as the force applied per unit cross-sectional area (which is the same as pressure).
This is represented by the equations:

$$stress = \frac{F}{A} \qquad \boxed{\sigma = \frac{F}{A}}$$

The largest tensile stress that can be applied to a material before it breaks is called the ultimate tensile stress (UTS).

Nylon has an UTS of 85 MPa whilst Stainless steel has a value of 600 MPa and Kevlar a massive 3100 MPa

Stress is measured in Newtons per metre squared, N/m^2 or N m^{-2}

Stress can also be measured in Pascals, Pa

A tensile stress will cause a tensile strain.
Stress causes Strain

> **Examination Tip**
>
> It is a common examination question to define tensile strain…
>
> tensile stress is the force exerted per/over cross-sectional area (1 mark)

Tensile Strain, ε

Tensile strain is a measure of how the extension of a material compares to the original, unstretched length.

This is represented by the equations:

$$strain = \frac{e}{l} \qquad \boxed{\varepsilon = \frac{e}{l}}$$

Steel wire will undergo a strain of 0.01 before it breaks. This means it will stretch by 1% of its original length then break.

Spider silk has a breaking strain of between 0.15 and 0.30, stretching by 30% before breaking

Strain has no units, it is a ratio of two lengths

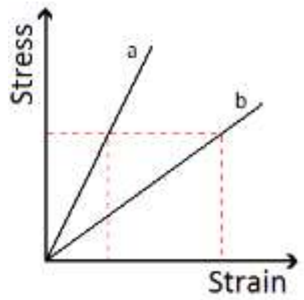
> **Physics Tip**
>
> You might see strain given as a percentage instead. Just multiply the ratio by 100 to get your strain as a percentage.

> **Examination Tip**
>
> It is a common examination question to define tensile stress…
>
> tensile strain is the extension per/over original length (1 mark)

Stress-Strain Graphs

A stress-strain graph is very useful for comparing different materials.

Here we can see how the strain of two materials, **a** and **b**, changes when a stress is applied.



If we look at the dotted lines, we can see that the same amount of stress causes a bigger strain in **b** than in **a**. This means that **b** will increase in length more than **a** (compared to their original lengths).

> **Physics Tip**
>
> If an object has an uneven cross-section, the strain and stress will be different in different parts of the object – but it will always be somewhere on the stress-strain graph.

Elastic Strain Energy

We can build on the idea of energy stored from the previous lesson now that we know what stress and strain are.
We can work out the amount of elastic strain energy that is stored *per unit volume* of the material.

It is given by the equation: $E = \frac{1}{2} stress \times strain$

There are two routes we can take to arrive at this result:

Equations

If we start with the equation for the total energy stored in the material: $E = \frac{1}{2} Fe$

The volume of the material is given by: $V = Al$

Now divide the total energy stored by the volume: $E = \frac{\frac{1}{2} Fe}{Al}$ which can be written as: $E = \frac{1}{2} \frac{F}{A} \frac{e}{l}$

If we compare the equation to the equations, we know for stress and strain we see that: $E = \frac{1}{2} stress \times strain$

> **Physics Tip**
>
> You may be asked to explain how E = 1/2FΔL can be derived from graphs.

Graphs

The area under a stress-strain graph gives us the elastic strain energy per unit volume (m^3). The area is given by:

$A = \frac{1}{2} base \times height$ → $A = \frac{1}{2} strain \times stress$ or $A = \frac{1}{2} stress \times strain$ → $E = \frac{1}{2} stress \times strain$

> **Physics Tip**
>
> When calculating the area under the curve, the examiners will accept a range of answers for questions as it is tricky to get the area under a curve exactly right.

Material Properties

You can describe different materials with the following terms.

Density, ρ

Density is the *mass per unit volume of a material*, a measure of how much mass each cubic metre of volume contains.

Prior Knowledge Link
This is a topic found in a previous GCSE module **- Particles.**

Density if given by the equation: $$\rho = \frac{m}{V}$$

Where ρ is density, m is mass in kilograms and V is volume in metres cubed.

Density is measured in kilograms per metre cubed, kg/m^3 or $kg\ m^{-3}$

Physics Tip

Remember that $1\ g\ cm^{-3} = 1000\ kg\ m^{-3}$

Physics Tip

Density is given by the symbol rho not 'p'.

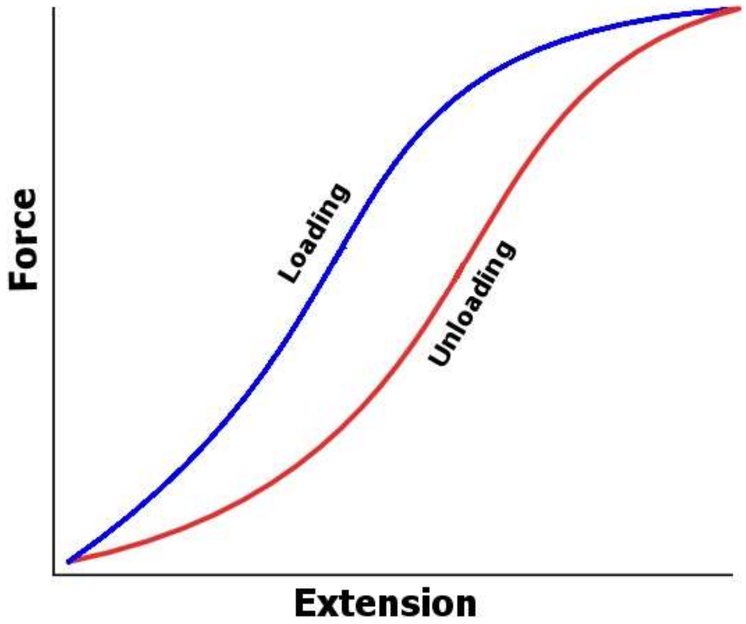
Elasticity

Materials extend in length when a stress is applied to them (masses hung from them). A material can be described as elastic if it returns to its original length when the stress is removed. Here is a force-extension graph for elastic materials.

Physics Tip

When measuring extension – the object under test should be supported at the top.

Weights should then be added one at a time to the other end of the object.



Physics Tip

Loading just means increasing the force on the material and unloading means reducing the force on the material.

Physics Tip

You do not need to know why the curves are not exactly the same- just that they start and end in the same places for elastic stretches.

Physics Tip

If you have unknown masses, rather than known weights, the object can be suspended by a newton meter - this will let you calculate the additional force being applied each time a mass is added.

Limit of Proportionality, P

Up to this point the material obeys Hooke's Law; extension is proportional to the force applied.

Elastic Limit, E

The elastic limit is the final point where the material will return to its original length if we remove the stress which is causing the extension (take the masses off). There is no change to the shape or size of the material.

We say that the material acts plastically beyond its elastic limit.

Yield Point, Y

Beyond the elastic limit a point is reached where small increases in stress cause a massive increase in extension (strain). The material will not return to its original length and behaves like a plastic.

Plasticity

Materials extend in length when a stress is applied to them (masses hung from them). A material can be described as plastic if it does not return to its original length when the stress is removed. There is a permanent change to its shape

Physics Tip

It is not just plastic materials that can deform plastically – most material have plastic deformation if enough force is applied.

Examination Tip

It is a common examination question to re-draw the shape of a force-extension graph during unloading...

Line from ending of loading (1 mark)

Parallel to straight section of original (1 mark)

Ending at horizontal axis (1 mark)

Examination Tip

It is a common examination question to explain why plastic deformation occurs…

Plastic deformation has produced permanent extension/re-alignment of bonds in material hence intercept non-zero (1 mark).

Gradient is same because after extension identical forces between bonds (1 mark).

Breaking Stress – Ultimate Tensile Strength, UTS
This is the maximum amount of stress that can be applied to the material without making it break.
It is sometimes referred to as **the strength of the material**.

Breaking Point, B
This is (surprisingly?) the point where the material breaks.

Stiffness
If different materials were made into wires of equal dimensions, the stiffer materials bend the least.

Stiff materials have low flexibility

Ductility

A ductile material can be easily and permanently stretched. Copper is a good example, it can easily be drawn out into thin wires.

This can be seen in graph **d** below.

Brittleness

A brittle material will extend obeying Hooke's Law when a stress is applied to it. It will suddenly fracture with no warning sign of plastic deformation. Glass, pottery and chocolate are examples of brittle materials.

Examination Tip

It is a common examination question to define what a brittle material is…

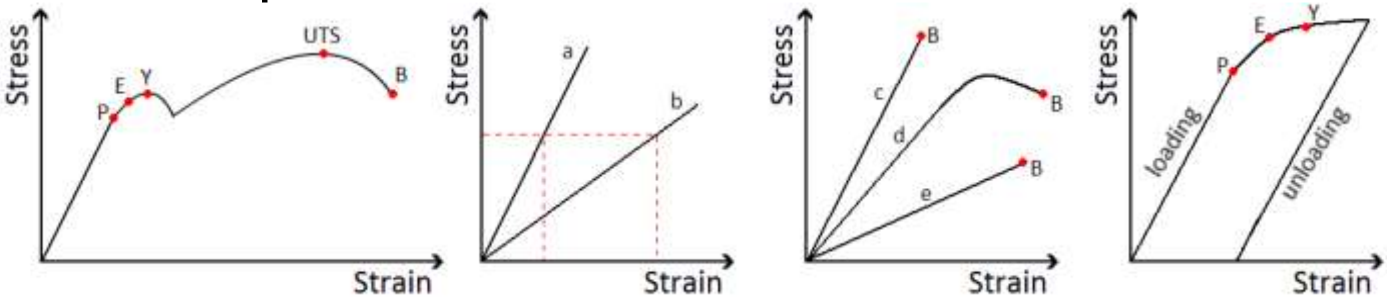
shown on a stress-strain graph by little or no of plastic behaviour OR by linear behaviour/straight line to breaking stress (1 mark)

OR

material has high Young modulus OR material is stiff (1 mark)

shown on graph by large gradient/steep line (compared to other materials) (1 mark)

Stress-Strain Graphs



In the first graph, we see a material that stretches, shows plastic behaviour and eventually breaks.

In the second graph, we can see that material **a** is stiffer than material **b** because the same stress causes a greater strain in **b**.

In the third graph, we see materials **c** and **e** are brittle because they break without showing plastic behaviour.

The fourth graph shows how a material can be permanently deformed, the wire does not return to its original length when the stress is removed (the masses have been removed).

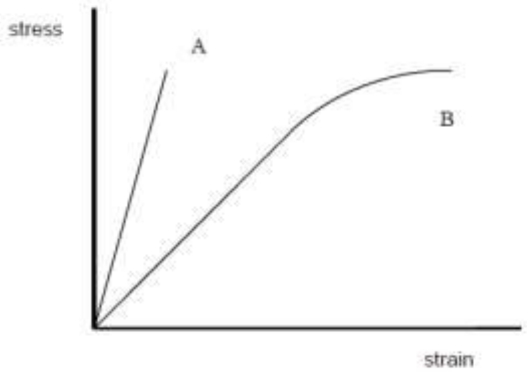
Physics Tip

Plastic deformation is useful if you do not want a material to return to its original shape.

Like drawing copper into wires or gold into foil.

Examination Tip

It is a common examination question to ask how to sketch possible stress-strain graphs for wires such as wire A which is found to have a higher Young modulus than wire B and it fractures before any permanent deformation takes place. Wire B stretches well beyond its elastic limit before fracturing.



Straight line labelled 'A' with greater gradient than other line and starting close to origin (1 mark)

Line labelled 'B' with significant curve and decreasing gradient which may then undulate (1 mark).

TOPIC: 3.4.2.2 The Young Modulus
SPEC CHECK

Specification	Completed?
Young modulus = $\frac{\text{tensile stress}}{\text{tensile strain}} = \frac{FL}{A \Delta L}$	`
Use of stress–strain graphs to find the Young modulus.	

Student Checklist

Have I.......	**Yes or No?**
Read through the notes of this section?	
Highlighted/underlined the key concepts of this section?	
Made my own notes based on the notes of this section?	
Brought the notes to be used in lesson?	

The Young Modulus, E

Key Topic Warning
This topic is very common for questions on previous A-Level Papers.

The Young Modulus can be thought of as the stiffness constant of a material, a measure of how much strain will result from a stress being applied to the material. It can be used to compare the stiffness of different materials even though their dimensions are not the same.

The Young Modulus only applies up to the limit of proportionality of a material.

$YoungModulus = \frac{stress}{strain}$ or in equation terms we have $E = \frac{\sigma}{\varepsilon}$

We have equations for stress $\sigma = \frac{F}{A}$ and strain $\varepsilon = \frac{e}{l}$ which makes the equation look like this: $E = \frac{\left(\frac{F}{A}\right)}{\left(\frac{e}{l}\right)}$

An easier way of writing this is $E = \left(\frac{F}{A}\right) \times \left(\frac{l}{e}\right)$ which becomes:

$$E = \frac{Fl}{Ae}$$

The Young Modulus is measured in Newtons per metre squares, N/m^2 or N m^{-2}

Stress-Strain Graphs

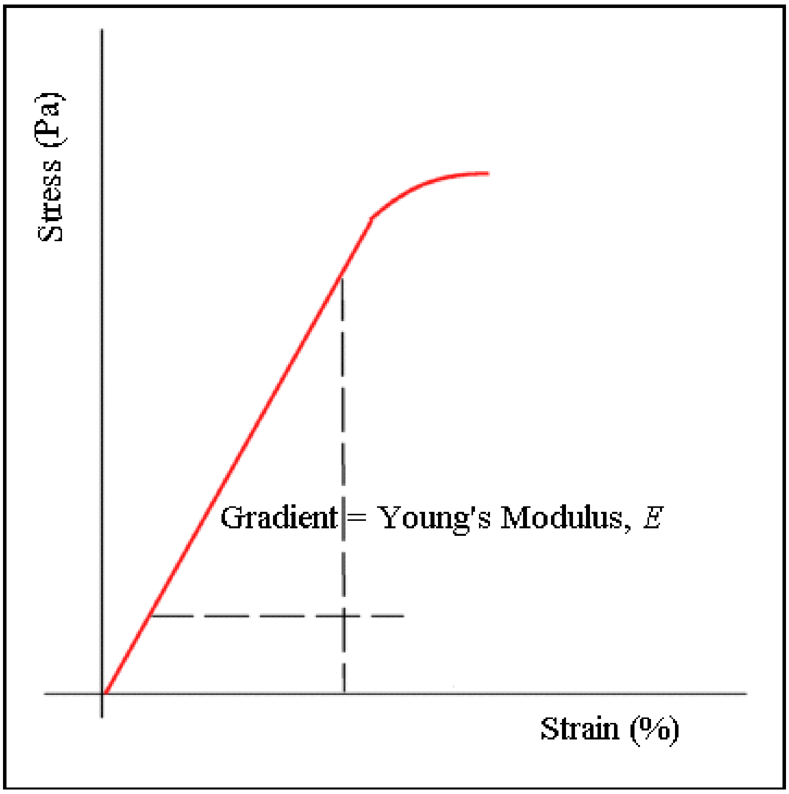
The Young Modulus of a material can be found from its stress-strain graph.

Since $gradient = \frac{\Delta y}{\Delta x}$, this becomes $gradient = \frac{stress}{strain}$ for our graph.

Our top equation stated that $YoungModulus = \frac{stress}{strain}$ so we see that the gradient of a stress-strain graph gives us the Young Modulus.

This only applied to the straight-line section of the graph, where gradient (and Young Modulus) are constant.

The area under the graph is the strain energy per unit volume stored in the wire.



Note; The gradient only represents the Youngs Modulus when it is a straight line.

The stress-strain graph is a straight line provided that Hooke's Law is obeyed, so you can also calculate the energy per unit volume as…

Energy per unit volume = ½ x Stress x Strain

Physics Tip

When using the gradient to work out the Young Modulus, you can only use it up to the limit of proportionality.

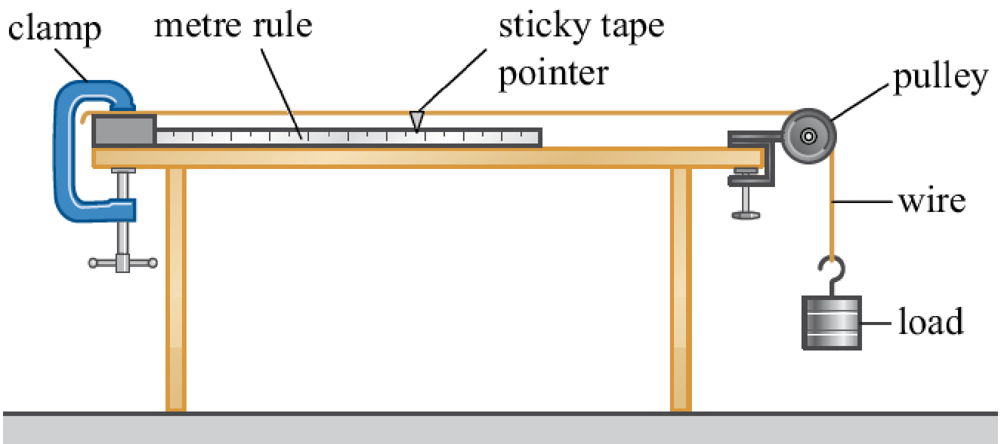
After then, the stress and strain are no longer proportional.

Physics Tip

Do not forget to convert any lengths to m and areas to m^2 when working out the Young Modulus.

Measuring the Young Modulus -Required Practical

Here is a simple experimental set up for finding the Young Modulus of a material.



The test wire should be thin, and as long as possible. The longer and thinner the wire, the more it extends for the same force – this reduces the uncertainty in your measurements.

You need to find the cross sectional area of the wire. Use a micrometer to measure the diameter of the wire in several places and take an average of your measurements. By assuming that the cross-section is circular, use the formula for the area of the circle.

Clamp the wire to the bench so you can hang weights off one end of it. Start with the smallest weight necessary to straighten the wire. Do not include the weight in your final calculations.

Measure the distance between the fixed end of the wire and the marker – this is your unstretched length.

Increase the weight, the wire stretches and the marker moves.

Increase the weight in steps e.g. 100g intervals – recording the marker reading each time. The extension is the difference between this reading and thee unstretched length.

Use the results from the experiment to calculate the stress and strain of the wire.

Plot a stress-strain curve and calculat the Young Modulus.

Physics Tip

If you are doing this experiment wear safety goggles in case the wire snaps.

You should also do a full risk assessment before starting work.

Physics Tip

You should do a pilot experiment in which you plot a force-extension graph for an identical piece of test wire to find its limit of proportionality. That way you can make sure you get nowhere near it in this experiment.

Physics Tip

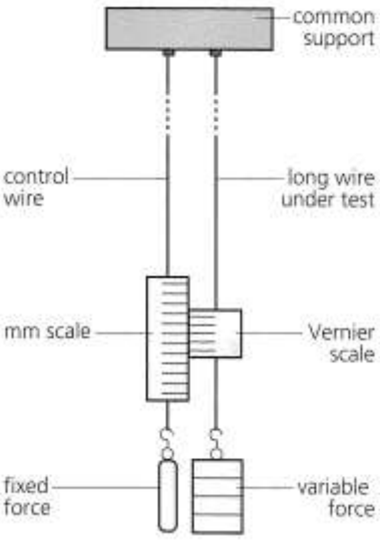
Extensions can be very small, so you can use a travelling microscope to measure them more precisely than with a ruler.

Physics Tip

The cross-sectional area is worked out by Area = ∏ (diameter / 2)^2.

Here is a more precise way of finding the Young Modulus but involves taking the same measurements of extension and force applied.

It is called Searle's apparatus.



Physics Tip

You can also measure the Young modulus in the lab using Searle's apparatus.

This is a bit more accurate, but it is harder to do and the equipment is more complicated.

Examination Tip

It is a common examination question to ask how to 'Outline how the student can use these results and other measurements to determine the Young modulus of the wire.'

Measure original length and diameter (1 mark)

Determine gradient of linear section to obtain F/extension (1 mark)

E = $F/e \times length/\ \pi/(d/2)^2$ (1 mark)

Examination Tip

It is a common examination question to ask how you could 'obtain the data necessary to accurately determine the Young modulus of the metals...'

- Diagram (not necessarily labelled) showing a workable arrangement of suitable apparatus
- measure diameter of wires
- use a micrometer (for the diameter)
- apply range of loads or masses
- measure original length
- measure or calculate extension
- (metre) rule (or equivalent) for the original length or extended length or extension
- Calculation of the weight of the mass \ use 'weights' in newtons
- Measure diameter in several places
- At least 7 different loads*
- Repeat measurements for the same wire (or measure whilst unloading)
- Use of a travelling microscope or Searle's apparatus \ pointer touching scale \ set square (for parallax reduction) \ Vernier scale (not Vernier calipers)
- Monitor diameter change during experiment.

UPGRADE YOUR PHYSICS

The following section include information beyond the A-Level Physics.
This information would further your understanding and provide a bridge to University Level Physics.

A model of a rigid body is an idealized example of an object that does not deform under the actions of external forces. It is very useful when analyzing mechanical systems—and many physical objects are indeed rigid to a great extent. The extent to which an object can be *perceived* as rigid depends on the physical properties of the material from which it is made. For example, a ping-pong ball made of plastic is brittle, and a tennis ball made of rubber is elastic when acted upon by squashing forces. However, under other circumstances, both a ping-pong ball and a tennis ball may bounce well as rigid bodies. Similarly, someone who designs prosthetic limbs may be able to approximate the mechanics of human limbs by modeling them as rigid bodies; however, the actual combination of bones and tissues is an elastic medium.

For the remainder of this chapter, we move from consideration of forces that affect the motion of an object to those that affect an object's shape. A change in shape due to the application of a force is known as a deformation. Even very small forces are known to cause some deformation. Deformation is experienced by objects or physical media under the action of external forces—for example, this may be squashing, squeezing, ripping, twisting, shearing, or pulling the objects apart. In the language of physics, two terms describe the forces on objects undergoing deformation: *stress* and *strain*.

Stress is a quantity that describes the magnitude of forces that cause deformation. Stress is generally defined as *force per unit area*. When forces pull on an object and cause its elongation, like the stretching of an elastic band, we call such stress a **tensile stress**. When forces cause a compression of an object, we call it a **compressive stress**. When an object is being squeezed from all sides, like a submarine in the depths of an ocean, we call this kind of stress a **bulk stress** (or **volume stress**). In other situations, the acting forces may be neither tensile nor compressive, and still produce a noticeable deformation. For example, suppose you hold a book tightly between the palms of your hands, then with one hand you press-and-pull on the front cover away from you, while with the other hand you press-and-pull on the back cover toward you. In such a case, when deforming forces act tangentially to the object's surface, we call them 'shear' forces and the stress they cause is called **shear stress**.

The SI unit of stress is the pascal (Pa). When one newton of force presses on a unit surface area of one meter squared, the resulting stress is one pascal:

$$\text{one pascal} = 1.0\,\text{Pa} = \frac{1.0\,\text{N}}{1.0\,\text{m}^2}.$$

In the British system of units, the unit of stress is 'psi,' which stands for 'pound per square inch' $\left(\text{lb/in}^2\right)$. Another unit that is often used for bulk stress is the atm (atmosphere). Conversion factors are

$$1\,\text{psi} = 6895\,\text{Pa} \;\text{ and }\; 1\,\text{Pa} = 1.450 \times 10^{-4}\,\text{psi}$$
$$1\,\text{atm} = 1.013 \times 10^{5}\,\text{Pa} = 14.7\,\text{psi}.$$

An object or medium under stress becomes deformed. The quantity that describes this deformation is called **strain**. Strain is given as a fractional change in either length (under tensile stress) or volume (under bulk stress) or geometry (under shear stress). Therefore, strain is a dimensionless number. Strain under a tensile stress is called **tensile strain**, strain under bulk stress is called **bulk strain** (or **volume strain**), and that caused by shear stress is called **shear strain**.

The greater the stress, the greater the strain; however, the relation between strain and stress does not need to be linear. Only when stress is sufficiently low is the deformation it causes in direct proportion to the stress value. The proportionality constant in this relation is called the **elastic modulus**. In the linear limit of low stress values, the general relation between stress and strain is

$$\text{stress} = (\text{elastic modulus}) \times \text{strain}. \qquad (12.33)$$

As we can see from dimensional analysis of this relation, the elastic modulus has the same physical unit as stress be strain is dimensionless.

We can also see from Equation 12.33 that when an object is characterized by a large value of elastic modulu effect of stress is small. On the other hand, a small elastic modulus means that stress produces large strain and noti deformation. For example, a stress on a rubber band produces larger strain (deformation) than the same stress on a band of the same dimensions because the elastic modulus for rubber is two orders of magnitude smaller than the modulus for steel.

The elastic modulus for tensile stress is called **Young's modulus**; that for the bulk stress is called the **bulk modulu** that for shear stress is called the **shear modulus**. Note that the relation between stress and strain is an *observed* re measured in the laboratory. Elastic moduli for various materials are measured under various physical conditions as varying temperature, and collected in engineering data tables for reference (Table 12.1). These tables are va references for industry and for anyone involved in engineering or construction. In the next section, we discuss strain relations beyond the linear limit represented by Equation 12.33, in the full range of stress values up to a fracture po the remainder of this section, we study the linear limit expressed by Equation 12.33.

Material	Young's modulus $\times 10^{10}$ Pa	Bulk modulus $\times 10^{10}$ Pa	Shear modulus $\times 10^{10}$ Pa
Aluminum	7.0	7.5	2.5
Bone (tension)	1.6	0.8	8.0
Bone (compression)	0.9		
Brass	9.0	6.0	3.5
Brick	1.5		
Concrete	2.0		
Copper	11.0	14.0	4.4
Crown glass	6.0	5.0	2.5
Granite	4.5	4.5	2.0
Hair (human)	1.0		
Hardwood	1.5		1.0
Iron	21.0	16.0	7.7
Lead	1.6	4.1	0.6
Marble	6.0	7.0	2.0
Nickel	21.0	17.0	7.8
Polystyrene	3.0		
Silk	6.0		
Spider thread	3.0		
Steel	20.0	16.0	7.5
Acetone		0.07	
Ethanol		0.09	
Glycerin		0.45	
Mercury		2.5	
Water		0.22	

Table 12.1 Approximate Elastic Moduli for Selected Materials

Tensile or Compressive Stress, Strain, and Young's Modulus

Tension or compression occurs when two antiparallel forces of equal magnitude act on an object along only one of its dimensions, in such a way that the object does not move. One way to envision such a situation is illustrated in Figure 12.18. A rod segment is either stretched or squeezed by a pair of forces acting along its length and perpendicular to its cross-section. The net effect of such forces is that the rod changes its length from the original length L_0 that it had before the forces appeared, to a new length L that it has under the action of the forces. This change in length $\Delta L = L - L_0$ may be either elongation (when L is larger than the original length L_0) or contraction (when L is smaller than the original length L_0). Tensile stress and strain occur when the forces are stretching an object, causing its elongation, and the length change ΔL is positive. Compressive stress and strain occur when the forces are contracting an object, causing its shortening, and the length change ΔL is negative.

In either of these situations, we define stress as the ratio of the deforming force $F_\perp$ to the cross-sectional area A of the object being deformed. The symbol $F_\perp$ that we reserve for the deforming force means that this force acts perpendicularly to the cross-section of the object. Forces that act parallel to the cross-section do not change the length of an object. The definition of the tensile stress is

$$\text{tensile stress} = \frac{F_\perp}{A}. \quad (12.34)$$

Tensile strain is the measure of the deformation of an object under tensile stress and is defined as the fractional change of the object's length when the object experiences tensile stress

$$\text{tensile strain} = \frac{\Delta L}{L_0}. \quad (12.35)$$

Compressive stress and strain are defined by the same formulas, Equation 12.34 and Equation 12.35, respectively. The only difference from the tensile situation is that for compressive stress and strain, we take absolute values of the right-hand sides in Equation 12.34 and Equation 12.35.

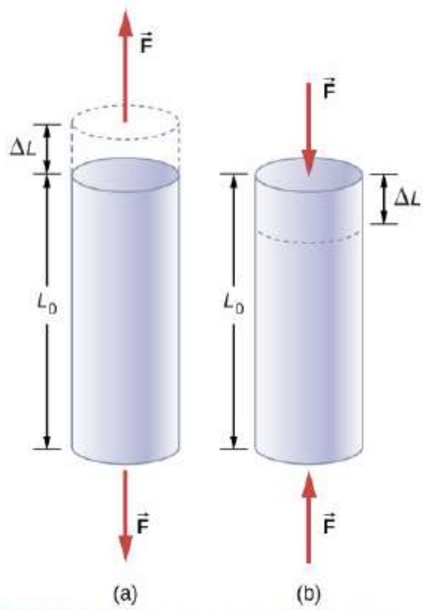


Figure 12.18 When an object is in either tension or compression, the net force on it is zero, but the object deforms by changing its original length L_0. (a) Tension: The rod is elongated by ΔL. (b) Compression: The rod is contracted by ΔL. In both cases, the deforming force acts along the length of the rod and perpendicular to its cross-section. In the linear range of low stress, the cross-sectional area of the rod does not change.

Young's modulus Y is the elastic modulus when deformation is caused by either tensile or compressive stress, and is defined by Equation 12.33. Dividing this equation by tensile strain, we obtain the expression for Young's modulus:

$$Y = \frac{\text{tensile stress}}{\text{tensile strain}} = \frac{F_\perp / A}{\Delta L / L_0} = \frac{F_\perp}{A}\frac{L_0}{\Delta L}. \quad (12.36)$$

Objects can often experience both compressive stress and tensile stress simultaneously Figure 12.20. One example is a long shelf loaded with heavy books that sags between the end supports under the weight of the books. The top surface of the shelf is in compressive stress and the bottom surface of the shelf is in tensile stress. Similarly, long and heavy beams sag under their own weight. In modern building construction, such bending strains can be almost eliminated with the use of I-beams Figure 12.21.

Figure 12.20 (a) An object bending downward experiences tensile stress (stretching) in the upper section and compressive stress (compressing) in the lower section. (b) Elite weightlifters often bend iron bars temporarily during lifting, as in the 2012 Olympics competition. (credit b: modification of work by Oleksandr Kocherzhenko)

Figure 12.21 Steel I-beams are used in construction to reduce bending strains. (credit: modification of work by "US Army Corps of Engineers Europe District"/Flickr)

Bulk Stress, Strain, and Modulus

When you dive into water, you feel a force pressing on every part of your body from all directions. What you are experiencing then is bulk stress, or in other words, **pressure**. Bulk stress always tends to decrease the volume enclosed by the surface of a submerged object. The forces of this "squeezing" are always perpendicular to the submerged surface Figure 12.22. The effect of these forces is to decrease the volume of the submerged object by an amount ΔV compared with the volume V_0 of the object in the absence of bulk stress. This kind of deformation is called bulk strain and is described by a change in volume relative to the original volume:

$$\text{bulk strain} = \frac{\Delta V}{V_0}. \qquad (12.37)$$

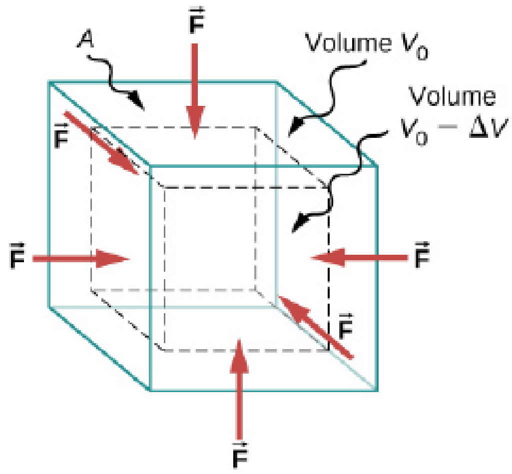


Figure 12.22 An object under increasing bulk stress always undergoes a decrease in its volume. Equal forces perpendicular to the surface act from all directions. The effect of these forces is to decrease the volume by the amount ΔV compared to the original volume, V_0.

The bulk strain results from the bulk stress, which is a force $F_\perp$ normal to a surface that presses on the unit surface area *A* of a submerged object. This kind of physical quantity, or pressure *p*, is defined as

$$\text{pressure} = p \equiv \frac{F_\perp}{A}. \qquad (12.38)$$

We will study pressure in fluids in greater detail in **Fluid Mechanics**. An important characteristic of pressure is that it is a scalar quantity and does not have any particular direction; that is, pressure acts equally in all possible directions. When you submerge your hand in water, you sense the same amount of pressure acting on the top surface of your hand as on the bottom surface, or on the side surface, or on the surface of the skin between your fingers. What you are perceiving in this case is an increase in pressure Δp over what you are used to feeling when your hand is not submerged in water. What you feel when your hand is not submerged in the water is the **normal pressure** p_0 of one atmosphere, which serves as a reference point. The bulk stress is this increase in pressure, or $\Delta p,$ over the normal level, p_0.

When the bulk stress increases, the bulk strain increases in response, in accordance with **Equation 12.33**. The proportionality constant in this relation is called the bulk modulus, *B*, or

$$B = \frac{\text{bulk stress}}{\text{bulk strain}} = -\frac{\Delta p}{\Delta V / V_0} = -\Delta p \frac{V_0}{\Delta V}. \qquad (12.39)$$

The minus sign that appears in **Equation 12.39** is for consistency, to ensure that *B* is a positive quantity. Note that the minus sign $(-)$ is necessary because an increase Δp in pressure (a positive quantity) always causes a decrease ΔV in volume, and decrease in volume is a negative quantity. The reciprocal of the bulk modulus is called **compressibility** $k,$ or

$$k = \frac{1}{B} = -\frac{\Delta V / V_0}{\Delta p}. \qquad (12.40)$$

The term 'compressibility' is used in relation to fluids (gases and liquids). Compressibility describes the change in the volume of a fluid per unit increase in pressure. Fluids characterized by a large compressibility are relatively easy to compress. For example, the compressibility of water is $4.64 \times 10^{-5}/\text{atm}$ and the compressibility of acetone is $1.45 \times 10^{-4}/\text{atm}.$ This means that under a 1.0-atm increase in pressure, the relative decrease in volume is approximately three times as large for acetone as it is for water.

Shear Stress, Strain, and Modulus

The concepts of shear stress and strain concern only solid objects or materials. Buildings and tectonic plates are examples of objects that may be subjected to shear stresses. In general, these concepts do not apply to fluids.

Shear deformation occurs when two antiparallel forces of equal magnitude are applied tangentially to opposite surfaces of a solid object, causing no deformation in the transverse direction to the line of force, as in the typical example of shear stress illustrated in Figure 12.24. Shear deformation is characterized by a gradual shift Δx of layers in the direction tangent to the acting forces. This gradation in Δx occurs in the transverse direction along some distance L_0. Shear strain is defined by the ratio of the largest displacement Δx to the transverse distance L_0

$$\text{shear strain} = \frac{\Delta x}{L_0}. \quad (12.41)$$

Shear strain is caused by shear stress. Shear stress is due to forces that act *parallel* to the surface. We use the symbol $F_{\parallel}$ for such forces. The magnitude $F_{\parallel}$ per surface area *A* where shearing force is applied is the measure of shear stress

$$\text{shear stress} = \frac{F_{\parallel}}{A}. \quad (12.42)$$

The shear modulus is the proportionality constant in Equation 12.33 and is defined by the ratio of stress to strain. Shear modulus is commonly denoted by *S*:

$$S = \frac{\text{shear stress}}{\text{shear strain}} = \frac{F_{\parallel}\ /A}{\Delta x / L_0} = \frac{F_{\parallel}}{A}\frac{L_0}{\Delta x}. \quad (12.43)$$

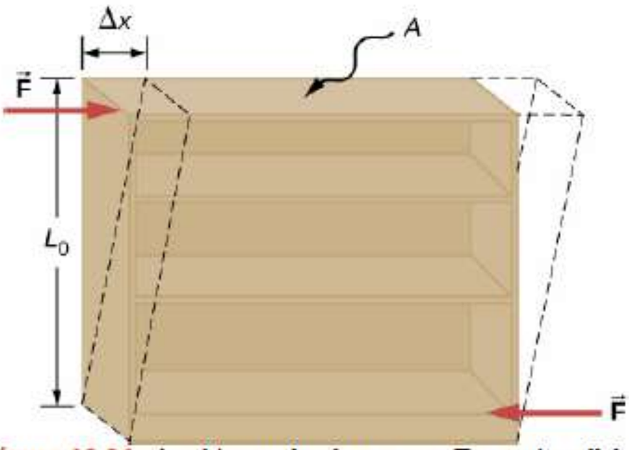


Figure 12.24 An object under shear stress: Two antiparallel forces of equal magnitude are applied tangentially to opposite parallel surfaces of the object. The dashed-line contour depicts the resulting deformation. There is no change in the direction transverse to the acting forces and the transverse length L_0 is unaffected. Shear deformation is characterized by a gradual shift Δx of layers in the direction tangent to the forces.

We referred to the proportionality constant between stress and strain as the elastic modulus. But why do we call it that? What does it mean for an object to be elastic and how do we describe its behavior?

Elasticity is the tendency of solid objects and materials to return to their original shape after the external forces (load) causing a deformation are removed. An object is **elastic** when it comes back to its original size and shape when the load is no longer present. Physical reasons for elastic behavior vary among materials and depend on the microscopic structure of the material. For example, the elasticity of polymers and rubbers is caused by stretching polymer chains under an applied force. In contrast, the elasticity of metals is caused by resizing and reshaping the crystalline cells of the lattices (which are the material structures of metals) under the action of externally applied forces.

The two parameters that determine the elasticity of a material are its *elastic modulus* and its *elastic limit*. A high elastic modulus is typical for materials that are hard to deform; in other words, materials that require a high load to achieve a significant strain. An example is a steel band. A low elastic modulus is typical for materials that are easily deformed under a load; for example, a rubber band. If the stress under a load becomes too high, then when the load is removed, the material no longer comes back to its original shape and size, but relaxes to a different shape and size: The material becomes permanently deformed. The **elastic limit** is the stress value beyond which the material no longer behaves elastically but becomes permanently deformed.

Our perception of an elastic material depends on both its elastic limit and its elastic modulus. For example, all rubbers are characterized by a low elastic modulus and a high elastic limit; hence, it is easy to stretch them and the stretch is noticeably large. Among materials with identical elastic limits, the most elastic is the one with the lowest elastic modulus.

When the load increases from zero, the resulting stress is in direct proportion to strain in the way given by **Equation 12.33**, but only when stress does not exceed some limiting value. For stress values within this linear limit, we can describe elastic behavior in analogy with Hooke's law for a spring. According to Hooke's law, the stretch value of a spring under an applied force is directly proportional to the magnitude of the force. Conversely, the response force from the spring to an applied stretch is directly proportional to the stretch. In the same way, the deformation of a material under a load is directly proportional to the load, and, conversely, the resulting stress is directly proportional to strain. The linearity limit (or the **proportionality limit**) is the largest stress value beyond which stress is no longer proportional to strain. Beyond the linearity limit, the relation between stress and strain is no longer linear. When stress becomes larger than the linearity limit but still within the elasticity limit, behavior is still elastic, but the relation between stress and strain becomes nonlinear.

For stresses beyond the elastic limit, a material exhibits **plastic behavior**. This means the material deforms irreversibly and does not return to its original shape and size, even when the load is removed. When stress is gradually increased beyond the elastic limit, the material undergoes plastic deformation. Rubber-like materials show an increase in stress with the increasing strain, which means they become more difficult to stretch and, eventually, they reach a fracture point where they break. Ductile materials such as metals show a gradual decrease in stress with the increasing strain, which means they become easier to deform as stress-strain values approach the breaking point. Microscopic mechanisms responsible for plasticity of materials are different for different materials.

We can graph the relationship between stress and strain on a **stress-strain diagram**. Each material has its own characteristic strain-stress curve. A typical stress-strain diagram for a ductile metal under a load is shown in **Figure 12.25**. In this figure, strain is a fractional elongation (not drawn to scale). When the load is gradually increased, the linear behavior (red line) that starts at the no-load point (the origin) ends at the linearity limit at point *H*. For further load increases beyond point *H*, the stress-strain relation is nonlinear but still elastic. In the figure, this nonlinear region is seen between points *H* and *E*. Ever larger loads take the stress to the elasticity limit *E*, where elastic behavior ends and plastic deformation begins. Beyond the elasticity limit, when the load is removed, for example at *P*, the material relaxes to a new shape and size along the green line. This is to say that the material becomes permanently deformed and does not come back to its initial shape and size when stress becomes zero.

The material undergoes plastic deformation for loads large enough to cause stress to go beyond the elasticity limit at *E*. The material continues to be plastically deformed until the stress reaches the fracture point (breaking point). Beyond the fracture point, we no longer have one sample of material, so the diagram ends at the fracture point. For the completeness of this qualitative description, it should be said that the linear, elastic, and plasticity limits denote a range of values rather than one sharp point.

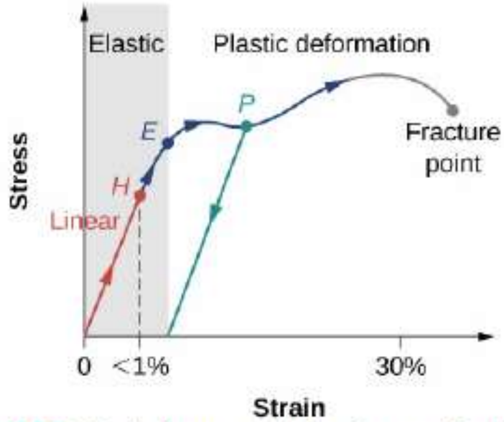


Figure 12.25 Typical stress-strain plot for a metal under a load: The graph ends at the fracture point. The arrows show the direction of changes under an ever-increasing load. Points *H* and *E* are the linearity and elasticity limits, respectively. Between points *H* and *E*, the behavior is nonlinear. The green line originating at *P* illustrates the metal's response when the load is removed. The permanent deformation has a strain value at the point where the green line intercepts the horizontal axis.

The value of stress at the fracture point is called breaking stress (or **ultimate stress**). Materials with similar elastic properties, such as two metals, may have very different breaking stresses. For example, ultimate stress for aluminum is

$2.2 \times 10^8 \text{Pa}$ and for steel it may be as high as $20.0 \times 10^8 \text{Pa}$, depending on the kind of steel. We can make a quick estimate, based on Equation 12.34, that for rods with a 1-in^2 cross-sectional area, the breaking load for an aluminum rod is 3.2×10^4 lb, and the breaking load for a steel rod is about nine times larger.

Reference: Open Stax University Physics Volume 1

REVISION CHECKLIST

Specification reference	Checklist questions	
3.4.2.1	Can you calculate density using $\rho = \frac{m}{V}$?	☐
3.4.2.1	Can you explain Hooke's law and the elastic limit?	☐
3.4.2.1	Can you carry out calculations using $F = k\Delta L$, with k as stiffness and spring constant?	☐
3.4.2.1	Can you define and explain tensile strain and tensile stress?	☐
3.4.2.1	Can you define and explain elastic strain energy and breaking stress?	☐
3.4.2.1	Can you use the formula: energy stored = $\frac{1}{2} F\Delta L$ = area under force−extension graph	☐
3.4.2.1	Can you describe plastic behaviour, fractures and brittle behaviour, and sketch force–extension graphs to show these behaviours?	☐
3.4.2.1	Can you apply energy conservation to examples involving elastic strain energy and energy to deform?	☐
3.4.2.1	Can you explain how spring energy is transformed to kinetic and gravitational potential energy?	☐
3.4.2.1	Can you interpret simple stress–strain curves?	☐
3.4.2.1	Can you list and explain energy conservation issues in the context of ethical transport design?	☐
3.4.2.2	Can you calculate the Young modulus using the equation Young modulus = $\frac{\text{tensile stress}}{\text{tensile strain}} = \frac{F\,L}{A\,\Delta L}$?	☐
3.4.2.2	Can you use stress–strain graphs to find the Young modulus?	☐
3.4.2.2	Have you carried out a practical to determine the Young modulus by a simple method?	☐

INDEPENDENT STUDY TASK 1

Produce an **information sheet** on Hooke's Law.

This is an independent study task to carried out outside of lesson.

This work will not be assessed but will be monitored by your class teacher.

This must be completed by the deadline set by your class teacher

INDEPENDENT STUDY TASK 2

Produce an **information sheet** on properties of solids.

This is an independent study task to carried out outside of lesson.

This work will not be assessed but will be monitored by your class teacher.

This must be completed by the deadline set by your class teacher

INDEPENDENT STUDY TASK 3

Produce an **information sheet** on stress-strain graphs.

This is an independent study task to carried out outside of lesson.

This work will not be assessed but will be monitored by your class teacher.

This must be completed by the deadline set by your class teacher

INDEPENDENT STUDY TASK 4

Produce an **information sheet** on the Young modulus.

This is an independent study task to carried out outside of lesson.

This work will not be assessed but will be monitored by your class teacher.

This must be completed by the deadline set by your class teacher

DATASHEET

DATA - FUNDAMENTAL CONSTANTS AND VALUES

Quantity	Symbol	Value	Units
speed of light in vacuo	c	3.00×10^{8}	$\mathrm{m\,s^{-1}}$
permeability of free space	μ_0	$4\pi \times 10^{-7}$	$\mathrm{H\,m^{-1}}$
permittivity of free space	ε_0	8.85×10^{-12}	$\mathrm{F\,m^{-1}}$
magnitude of the charge of electron	e	1.60×10^{-19}	C
the Planck constant	h	6.63×10^{-34}	J s
gravitational constant	G	6.67×10^{-11}	$\mathrm{N\,m^{2}\,kg^{-2}}$
the Avogadro constant	N_A	6.02×10^{23}	$\mathrm{mol^{-1}}$
molar gas constant	R	8.31	$\mathrm{J\,K^{-1}\,mol^{-1}}$
the Boltzmann constant	k	1.38×10^{-23}	$\mathrm{J\,K^{-1}}$
the Stefan constant	σ	5.67×10^{-8}	$\mathrm{W\,m^{-2}\,K^{-4}}$
the Wien constant	α	2.90×10^{-3}	m K
electron rest mass (equivalent to 5.5×10^{-4} u)	m_e	9.11×10^{-31}	kg
electron charge/mass ratio	$\frac{e}{m_e}$	1.76×10^{11}	$\mathrm{C\,kg^{-1}}$
proton rest mass (equivalent to 1.00728 u)	m_p	$1.67(3) \times 10^{-27}$	kg
proton charge/mass ratio	$\frac{e}{m_p}$	9.58×10^{7}	$\mathrm{C\,kg^{-1}}$
neutron rest mass (equivalent to 1.00867 u)	m_n	$1.67(5) \times 10^{-27}$	kg
gravitational field strength	g	9.81	$\mathrm{N\,kg^{-1}}$
acceleration due to gravity	g	9.81	$\mathrm{m\,s^{-2}}$
atomic mass unit (1u is equivalent to 931.5 MeV)	u	1.661×10^{-27}	kg

ALGEBRAIC EQUATION

quadratic equation $$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

ASTRONOMICAL DATA

Body	Mass/kg	Mean radius/m
Sun	1.99×10^{30}	6.96×10^{8}
Earth	5.97×10^{24}	6.37×10^{6}

GEOMETRICAL EQUATIONS

arc length	$= r\theta$
circumference of circle	$= 2\pi r$
area of circle	$= \pi r^2$
curved surface area of cylinder	$= 2\pi rh$
area of sphere	$= 4\pi r^2$
volume of sphere	$= \frac{4}{3}\pi r^3$

Particle Physics

Class	Name	Symbol	Rest energy/MeV
photon	photon	γ	0
lepton	neutrino	ν_e	0
		ν_μ	0
	electron	$e^\pm$	0.510999
	muon	$\mu^\pm$	105.659
mesons	π meson	$\pi^\pm$	139.576
		π^0	134.972
	K meson	$K^\pm$	493.821
		K^0	497.762
baryons	proton	p	938.257
	neutron	n	939.551

Properties of quarks

antiquarks have opposite signs

Type	Charge	Baryon number	Strangeness
u	$+\frac{2}{3}e$	$+\frac{1}{3}$	0
d	$-\frac{1}{3}e$	$+\frac{1}{3}$	0
s	$-\frac{1}{3}e$	$+\frac{1}{3}$	-1

Properties of Leptons

		Lepton number
Particles:	$e^-, \nu_e; \mu^-, \nu_\mu$	+1
Antiparticles:	$e^+, \overline{\nu_e}, \mu^+, \overline{\nu_\mu}$	−1

Photons and energy levels

photon energy $E = hf = hc/\lambda$

photoelectricity $hf = \phi + E_{k\,(max)}$

energy levels $hf = E_1 - E_2$

de Broglie wavelength $\lambda = \frac{h}{p} = \frac{h}{mv}$

Waves

wave speed $c = f\lambda$ *period* $f = \frac{1}{T}$

first harmonic $f = \frac{1}{2l}\sqrt{\frac{T}{\mu}}$

fringe spacing $w = \frac{\lambda D}{s}$ *diffraction grating* $d \sin\theta = n\lambda$

refractive index of a substance s, $n = \frac{c}{c_s}$

for two different substances of refractive indices n_1 *and* n_2,

law of refraction $n_1 \sin\theta_1 = n_2 \sin\theta_2$

critical angle $\sin\theta_c = \frac{n_2}{n_1}$ for $n_1 > n_2$

Mechanics

moments moment $= Fd$

velocity and acceleration $v = \frac{\Delta s}{\Delta t}$ $a = \frac{\Delta v}{\Delta t}$

equations of motion $v = u + at$ $s = \left(\frac{u+v}{2}\right)t$

$v^2 = u^2 + 2as$ $s = ut + \frac{at^2}{2}$

force $F = ma$

force $F = \frac{\Delta(mv)}{\Delta t}$

impulse $F\Delta t = \Delta(mv)$

work, energy and power $W = F s \cos\theta$

$E_k = \frac{1}{2} m v^2$ $\Delta E_p = mg\Delta h$

$P = \frac{\Delta W}{\Delta t}$, $P = Fv$

$efficiency = \frac{useful\ output\ power}{input\ power}$

Materials

density $\rho = \frac{m}{V}$ *Hooke's law* $F = k\,\Delta L$

Young modulus $= \frac{tensile\ stress}{tensile\ strain}$ *tensile stress* $= \frac{F}{A}$ *tensile strain* $= \frac{\Delta L}{L}$

energy stored $E = \frac{1}{2}F\Delta L$

Electricity

current and pd	$I = \frac{\Delta Q}{\Delta t}$ $\quad V = \frac{W}{Q}$ $\quad R = \frac{V}{I}$
resistivity	$\rho = \frac{RA}{L}$
resistors in series	$R_T = R_1 + R_2 + R_3 + \ldots$
resistors in parallel	$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$
power	$P = VI = I^2R = \frac{V^2}{R}$
emf	$\varepsilon = \frac{E}{Q}$ $\quad \varepsilon = I(R + r)$

Circular motion

magnitude of angular speed	$\omega = \frac{v}{r}$
	$\omega = 2\pi f$
centripetal acceleration	$a = \frac{v^2}{r} = \omega^2 r$
centripetal force	$F = \frac{mv^2}{r} = m\omega^2 r$

Simple harmonic motion

acceleration	$a = -\omega^2 x$
displacement	$x = A\cos(\omega t)$
speed	$v = \pm\omega\sqrt{(A^2 - x^2)}$
maximum speed	$v_{max} = \omega A$
maximum acceleration	$a_{max} = \omega^2 A$
for a mass-spring system	$T = 2\pi\sqrt{\frac{m}{k}}$
for a simple pendulum	$T = 2\pi\sqrt{\frac{l}{g}}$

Thermal physics

energy to change temperature	$Q = mc\Delta\theta$
energy to change state	$Q = m\,l$
gas law	$pV = nRT$
	$pV = NkT$
kinetic theory model	$pV = \frac{1}{3}N\,m\,(c_{rms})^2$
kinetic energy of gas molecule	$\frac{1}{2}m\,(c_{rms})^2 = \frac{3}{2}kT = \frac{3RT}{2N_A}$

Gravitational fields

force between two masses	$F = \frac{Gm_1m_2}{r^2}$
gravitational field strength	$g = \frac{F}{m}$
magnitude of gravitational field strength in a radial field	$g = \frac{GM}{r^2}$
work done	$\Delta W = m\Delta V$
gravitational potential	$V = -\frac{GM}{r}$
	$g = -\frac{\Delta V}{\Delta r}$

Electric fields and capacitors

force between two point charges	$F = \frac{1}{4\pi\varepsilon_0}\frac{Q_1Q_2}{r^2}$
force on a charge	$F = EQ$
field strength for a uniform field	$E = \frac{V}{d}$
work done	$\Delta W = Q\Delta V$
field strength for a radial field	$E = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}$
electric potential	$V = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r}$
	$E = \frac{\Delta V}{\Delta r}$
capacitance	$C = \frac{Q}{V}$
	$C = \frac{A\varepsilon_0\varepsilon_r}{d}$
capacitor energy stored	$E = \frac{1}{2}QV = \frac{1}{2}CV^2 = \frac{1}{2}\frac{Q^2}{C}$
capacitor charging	$Q = Q_0(1 - e^{-t/RC})$
decay of charge	$Q = Q_0 e^{-t/RC}$
time constant	RC

Magnetic fields

force on a current $F = BIl$

force on a moving charge $F = BQv$

magnetic flux $\Phi = BA$

magnetic flux linkage $N\Phi = BAN\cos\theta$

magnitude of induced emf $\varepsilon = N\frac{\Delta\Phi}{\Delta t}$

$N\Phi = BAN\cos\theta$

emf induced in a rotating coil $\varepsilon = BAN\omega\sin\omega t$

alternating current $I_{rms} = \frac{I_0}{\sqrt{2}}$ $V_{rms} = \frac{V_0}{\sqrt{2}}$

transformer equations $\frac{N_s}{N_p} = \frac{V_s}{V_p}$

$efficiency = \frac{I_s V_s}{I_p V_p}$

Nuclear physics

the inverse square law for γ radiation $I = \frac{k}{x^2}$

radioactive decay $\frac{\Delta N}{\Delta t} = -\lambda N$, $N = N_0 e^{-\lambda t}$

activity $A = \lambda N$

half-life $T_{½} = \frac{\ln 2}{\lambda}$

nuclear radius $R = R_0 A^{1/3}$

energy-mass equation $E = mc^2$

OPTIONS

Astrophysics

1 astronomical unit = 1.50×10^{11} m

1 light year = 9.46×10^{15} m

1 parsec = 206265 AU = 3.08×10^{16} m
= 3.26 light year

Hubble constant, H $= 65$ km s^{-1} Mpc^{-1}

$$M = \frac{\text{angle subtended by image at eye}}{\text{angle subtended by object at unaided eye}}$$

in normal adjustment $M = \frac{f_o}{f_e}$

Rayleigh criterion $\theta \approx \frac{\lambda}{D}$

magnitude equation $m - M = 5\log\frac{d}{10}$

Wien's law $\lambda_{max} T = 2.9 \times 10^{-3}$ m K

Stefan's law $P = \sigma A T^4$

Schwarzschild radius $R_s \approx \frac{2GM}{c^2}$

Doppler shift for v << c $\frac{\Delta f}{f} = -\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$

red shift $z = -\frac{v}{c}$

Hubble's law $v = Hd$

Medical physics

lens equations $P = \frac{1}{f}$

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

$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$

threshold of hearing $I_0 = 1.0 \times 10^{-12}$ W m^{-2}

intensity level $intensity\ level = 10\log\frac{I}{I_0}$

absorption $I = I_0 e^{-\mu x}$

$\mu_m = \frac{\mu}{\rho}$

ultrasound imaging $Z = \rho c$

$\frac{I_r}{I_i} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$

half-lives $\frac{1}{T_E} = \frac{1}{T_B} + \frac{1}{T_P}$

Engineering physics

moment of inertia $I = \Sigma mr^2$

angular kinetic energy $E_k = \frac{1}{2}I\omega^2$

equations of angular motion

$\omega_2 = \omega_1 + \alpha t$

${\omega_2}^2 = {\omega_1}^2 + 2\alpha\theta$

$\theta = \omega_1 t + \frac{\alpha t^2}{2}$

$\theta = \frac{(\omega_1 + \omega_2)t}{2}$

torque $T = I\alpha$

$T = Fr$

angular momentum $\text{angular momentum} = I\omega$

angular impulse $T\Delta t = \Delta(I\omega)$

work done $W = T\theta$

power $P = T\omega$

thermodynamics $Q = \Delta U + W$

$W = p\Delta V$

adiabatic change $pV^\gamma = \text{constant}$

isothermal change $pV = \text{constant}$

heat engines

efficiency $= \frac{W}{Q_H} = \frac{Q_H - Q_C}{Q_H}$

maximum theoretical efficiency $= \frac{T_H - T_C}{T_H}$

work done per cycle = area of loop

input power = calorific value × fuel flow rate

indicated power = (area of $p - V$ loop) × (number of cycles per second) × (number of cylinders)

output or brake power $P = T\omega$

friction power = indicated power – brake power

heat pumps and refrigerators

refrigerator: $COP_{ref} = \frac{Q_C}{W} = \frac{Q_C}{Q_H - Q_C}$

heat pump: $COP_{hp} = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_C}$

Turning points in physics

electrons in fields $F = \frac{eV}{d}$

$F = Bev$

$r = \frac{mv}{Be}$

$\frac{1}{2}mv^2 = eV$

Millikan's experiment $\frac{QV}{d} = mg$

$F = 6\pi\eta rv$

Maxwell's formula $c = \frac{1}{\sqrt{\mu_0\varepsilon_0}}$

$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2meV}}$

special relativity $t = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$

$l = l_0\sqrt{1 - \frac{v^2}{c^2}}$

$E = mc^2 = \frac{m_0c^2}{\sqrt{1 - \frac{v^2}{c^2}}}$

Electronics

resonant frequency $f_0 = \frac{1}{2\pi\sqrt{LC}}$

Q-factor $Q = \frac{f_0}{f_B}$

operational amplifiers: open loop $V_{out} = A_{OL}(V_+ - V_-)$

inverting amplifier $\frac{V_{out}}{V_{in}} = -\frac{R_f}{R_{in}}$

non-inverting amplifier $\frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R_1}$

summing amplifier $V_{out} = -R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \cdots\right)$

difference amplifier $V_{out} = (V_+ - V_-)\frac{R_f}{R_1}$

Bandwidth requirement:

for AM $\text{bandwidth} = 2f_M$

for FM $\text{bandwidth} = 2(\Delta f + f_M)$

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All relevant information has been credited in the document.

This document has been produced for educational purposes only.

This document has been produced for the AQA A Level Physics Specification.

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If you when using this document, you believe there is an improvement to made, please state this in the space below….

Only constructive and reasoned feedback will be considered.