A LEVEL PHYSICS 9702 · AS LEVEL · TOPIC 6 · ~7 MIN READ

Deformation of solids

Hooke's law and the spring constant, stress, strain and the Young modulus, the experiment to measure it, elastic and plastic deformation, and elastic potential energy from the area under a force–extension graph.

Load & extension | Hooke's law | Limit of proportionality | Stress & strain | Young modulus | Measuring E | Elastic & plastic | Elastic potential energy

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Paper tag = **where it is examined** DATA & FORMULAE given in the exam C1 A1 B1 how marks are awarded

highlight = comes up again and again Test yourself at the end

IN 30 SECONDS

- **Hooke's law:** up to the limit of proportionality, extension is proportional to load: F = kx, where k is the spring constant.
- **Stress = force/area; strain = extension/original length;** the Young modulus E = stress/strain is a property of the material, not of the sample.
- **Elastic deformation** disappears when the load is removed; **plastic deformation** is permanent. The boundary is the elastic limit.
- **Area under a force–extension graph = work done.** Within the limit of proportionality, elastic potential energy = ½Fx = ½kx².

BY THE END YOU CAN

- Use the terms load, extension, compression and limit of proportionality.
- Recall and use Hooke's law and the spring constant.
- Define and use stress, strain and the Young modulus, and describe how to measure E for a wire.
- Distinguish elastic and plastic deformation and use the elastic limit.
- Find elastic potential energy from the area under a force–extension graph.

1 Hooke's law

Definitions

Hooke's law — the extension of a spring (or wire) is proportional to the applied load, provided the limit of proportionality is not exceeded.

Spring constant — force per unit extension, k = F/x (N m^{-1}).

Limit of proportionality — the point beyond which force is no longer proportional to extension.

- **Tensile** forces stretch (extension); **compressive** forces squash (compression). Treat both as one-dimensional.
- **Stiffer spring = bigger k = steeper F–x graph.** If the graph has extension on the y-axis, the gradient is 1/k.

2 Stress, strain and the Young modulus

Definitions

Stress — force per unit cross-sectional area, $\sigma = F/A$ (Pa).

Strain — extension per unit original length, $\varepsilon = x/L$ (no units).

Young modulus — stress divided by strain, $E = \sigma/\varepsilon = FL/(Ax)$ (Pa), for a material obeying Hooke's law.

- **"Original length"** must be in the strain definition. The 2024 Paper 2 report penalised strain defined without "original".
- **Why use E rather than k?** k depends on the sample's length and thickness; E depends only on the material. They are linked by **k = EA/L**.

WORKED EXAMPLE

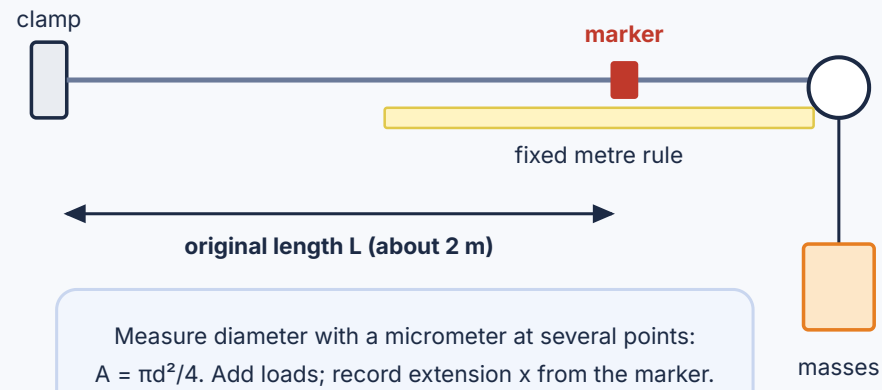
A steel wire of original length 2.0 m and diameter 0.50 mm extends by 3.9 mm under a load of 80 N. Find the Young modulus.

1. $A = \pi(0.25 \times 10^{-3})^2 = 1.96 \times 10^{-7}$ m² C1
2. stress = $80/1.96 \times 10^{-7} = 4.07 \times 10^{8}$ Pa; strain = $3.9 \times 10^{-3}/2.0 = 1.95 \times 10^{-3}$ C1
3. **$E = 4.07 \times 10^{8}/1.95 \times 10^{-3} = 2.1 \times 10^{11}$ Pa** A1

COMMON MISTAKE

Using the diameter as the radius, or not converting mm to m. 0.50 mm diameter gives $r = 0.25 \times 10^{-3}$ m, and $A = \pi r^2 = 1.96 \times 10^{-7}$ m². In 2024 many candidates lost marks on mm → m and mm² → m².

Measuring E for a metal wire



Measure diameter with a micrometer at several points: $A = \pi d^2/4$. Add loads; record extension x from the marker. Plot F against x: gradient = F/x, so E = (gradient) × L/A.

A long thin wire gives a measurable extension for a small strain.

A long, thin wire, a fixed scale and a marker: small strains become measurable extensions.

- **Measure:** original length L with a metre rule (from the clamp to the marker); diameter d with a micrometer screw gauge at several points and orientations (average); extension x for increasing loads from the marker against the fixed scale.
- **Analyse:** plot load F against extension x for the straight part. E = gradient × L/A.
- **Good practice:** use a long, thin wire so the extension is large enough to measure; remove kinks with a small initial load; check the wire returns to its original length when unloaded (it stayed elastic); wear eye protection in case the wire snaps.

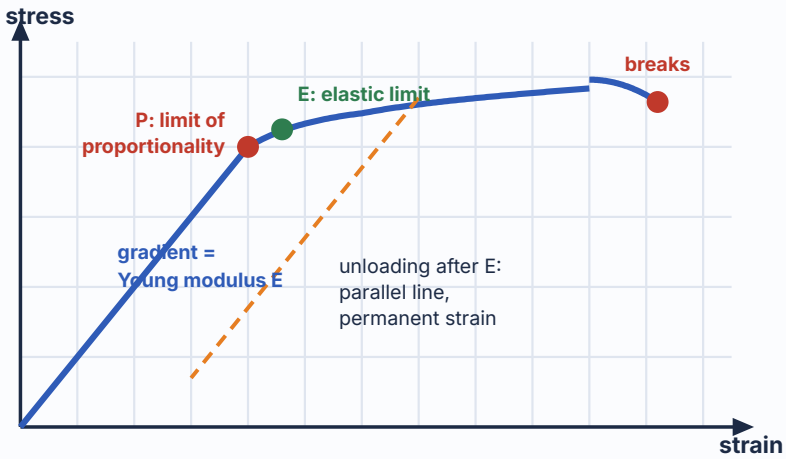
3 Elastic and plastic behaviour

Two kinds of deformation

Elastic deformation — the material returns to its original shape and size when the load is removed.

Plastic deformation — the material does not return to its original shape; it is permanently deformed.

Elastic limit — the maximum load (or stress) beyond which the material no longer returns to its original length.



Up to E: elastic (returns to its original length).
Beyond E: plastic (permanently stretched).

Stress–strain graph for a ductile metal wire: straight up to P, elastic up to E, plastic beyond.

- **The limit of proportionality and the elastic limit are different points.** The elastic limit is usually a little beyond the limit of proportionality. The 2024 Paper 2 report found students mixing them up, and with the breaking point.
- **Unloading after plastic deformation:** the graph returns along a line parallel to the original straight section, leaving a permanent extension.

4 Elastic potential energy

Area under the graph

- **Work done stretching** = area under the force–extension graph (force × small extension, added up).
- **Within the limit of proportionality** the graph is a straight line through the origin, so the area is a triangle.

$$E_p = \tfrac{1}{2}Fx = \tfrac{1}{2}kx^2$$ LEARN IT

elastic potential energy, valid only within the limit of proportionality

- **Beyond the limit,** estimate the area by counting squares or splitting into shapes. If the material is deformed plastically, not all the work done is recovered when unloaded: some is transferred to thermal energy.

WORKED EXAMPLE

A spring of spring constant 250 N m^{-1} is compressed by 4.0 cm and used to launch a 20 g ball horizontally. Find the launch speed, assuming all the elastic energy becomes kinetic.

1. $E_p = \tfrac{1}{2} \times 250 \times 0.040^2 = 0.20$ J C1
2. **$\tfrac{1}{2} \times 0.020 \times v^2 = 0.20 \Rightarrow v = 4.5$ m s^{-1}** A1

COMMON MISTAKE

Forgetting the square in $\tfrac{1}{2}kx^2$ (2024 Paper 2), or setting Ek = Ep when the object also gains height (then Ep(elastic) = Ek + mgh).

LINKING QUESTION

The work done is the area under a graph, as in Work, energy and power; uncertainties in d and L dominate the Young modulus uncertainty (Physical quantities and units); and springs return as oscillators in Oscillations.

Test yourself — cover the answers first

QUICK CHECK

1. Define the Young modulus.
2. What are the units of strain?
3. A spring extends 2.0 cm under 5.0 N. Find k.
4. Write k in terms of E, A and L for a wire.
5. Find the energy stored in a wire that extends 1.2 mm under 60 N (within the limit).

EXAM-STYLE

6. Explain why a long, thin wire is used in the Young modulus experiment.
7. A copper wire (E = 1.2 × 10^{11} Pa) has length 1.5 m and cross-sectional area 1.0 × 10^{-6} m^2. Find its spring constant and the load needed for a 0.60 mm extension.
8. Sketch the force–extension graph for loading and unloading a wire taken beyond its elastic limit, and state what the area between the curves represents.

Show answers

1. stress/strain (within the limit of proportionality)
2. none (it is a ratio of lengths)
3. 250 $N\ m^{-1}$
4. $k = EA/L$
5. $\frac{1}{2} \times 60 \times 1.2 \times 10^{-3} = 0.036$ J
6. for a given stress the extension is proportional to L, so a long wire gives a larger, measurable extension; a thin wire gives a large stress for a small load, and smaller percentage uncertainty in x
7. $k = EA/L = 8.0 \times 10^{4}$ $N\ m^{-1}$; $F = kx = 48$ N
8. unloading line parallel to the initial straight part, ending at a permanent extension; the area between loading and unloading curves is energy transferred to thermal energy (not recovered)

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