Cambridge AS & A Level · Physics (9702) · Notes

Deformation of solids AS

Read online at pastopic.com/cambridge/physics-9702/notes/deformation-of-solids

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Read first: Work, energy and power

What you need to know

By the end of this topic you should be able to:

1. **Understand that deformation is caused by tensile or compressive forces**: forces that stretch or squash an object. Everything here is in one dimension (along one line).
2. **Understand and use the terms** load, extension, compression and limit of proportionality.
3. **Recall and use Hooke's law.**
4. **Recall and use the spring constant**, $k = \dfrac{F}{x}$.
5. **Define and use** stress, strain and the Young modulus.
6. **Describe an experiment** to find the Young modulus of a metal in the form of a wire.
7. **Understand and use the terms** elastic deformation, plastic deformation and elastic limit.
8. **Understand that the area under a force–extension graph is the work done** in stretching.
9. **Find the elastic potential energy** of a material deformed within its limit of proportionality from the area under its force–extension graph.
10. **Recall and use** $E_P = \frac{1}{2}Fx = \frac{1}{2}kx^2$ for a material deformed within its limit of proportionality.

Work done $= Fs$ and the energy stores (E_K, E_P from height) come from Work, energy and power; many questions here add a spring to an energy problem.

Understand it

Tension, compression, load and extension

A pair of equal and opposite forces pulling on the ends of an object is **tensile**: it stretches the object. A pair pushing inwards is **compressive**: it squashes it. In both cases the object changes shape, which is called **deformation**.

- The **load** is the force causing the deformation (often the weight of a hanging mass).
- The **extension** x is the increase in length: stretched length minus original (unstretched) length.
- The **compression** is the decrease in length when the object is squashed.

Always work with the **change** in length, never the total length. A spring 12.0 cm long that becomes 15.0 cm long under a 1.5 N load has an extension of 3.0 cm $= 0.030$ m.

Hooke's law and the spring constant

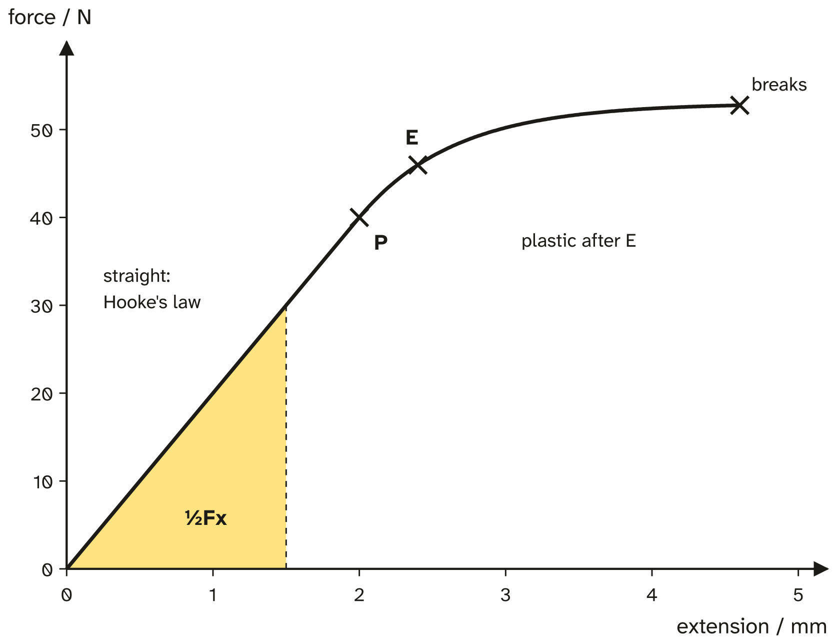
Hooke's law: the extension of an object is proportional to the force applied to it, provided the limit of proportionality is not exceeded.

$$F = kx \qquad k = \frac{F}{x}$$

k is the **spring constant**: the force needed per unit extension, in N m^{-1}. For the spring above, $k = \frac{1.5}{0.030} = 50$ N m^{-1}. A 2.5 N load would stretch it by $\frac{2.5}{50} = 0.050$ m, to a length of 17.0 cm. A **stiffer** spring has a larger k: it needs more force for the same extension.

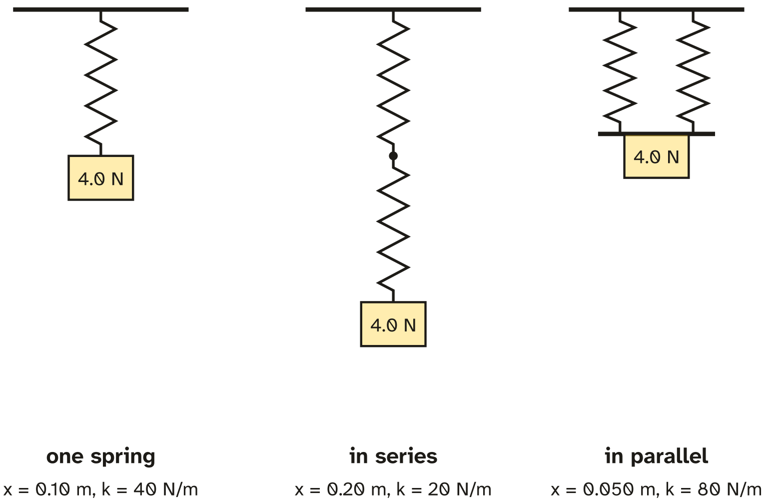
On a graph of force against extension, Hooke's law gives a **straight line through the origin**, and the **gradient is** k. If the graph is extension against force instead, the gradient is $\frac{1}{k}$. If it is force against **length**, the line is still straight with gradient k, but it meets the length axis at the unstretched length, not at zero.

The **limit of proportionality** is the point beyond which force and extension are no longer proportional: the graph stops being a straight line. The same laws apply to compression, with x the compression.



P = limit of proportionality, E = elastic limit
shaded area = ½ × 30 N × 1.5 mm = 0.0225 J

Springs in series and in parallel



- **In series** (end to end), each spring carries the **whole** load, and the extensions add. Two identical springs in series have half the spring constant of one: $\frac{1}{k} = \frac{1}{k_1} + \frac{1}{k_2}$.
- **In parallel** (side by side, joined by a bar that stays level), the springs **share** the load and have the same extension. Two identical springs in parallel have twice the spring constant: $k = k_1 + k_2$.
- For any arrangement, the combined k is (total load) ÷ (total extension). You never need a formula you can't rebuild from this.

Stress, strain and the Young modulus

The spring constant belongs to one particular object: a thicker or shorter wire of the same metal has a larger k. To describe the **material** itself, divide out the size of the sample.

- **Stress** σ is the force per unit cross-sectional area: $\sigma = \dfrac{F}{A}$. Unit: pascal, 1 Pa $= 1$ N m^{-2} $= 1$ kg m^{-1} s^{-2}.
- **Strain** ε is the extension per unit original length: $\varepsilon = \dfrac{x}{L}$. It is a ratio of two lengths, so it has **no unit**. It is sometimes given as a percentage: a strain of 0.5% is 0.005.
- **The Young modulus** E is the ratio of stress to strain, within the limit of proportionality:

$$E = \frac{\sigma}{\varepsilon} = \frac{F/A}{x/L} = \frac{FL}{Ax}$$

Its unit is the pascal, like stress (strain has no unit). The Young modulus is a property of the material: every wire of the same metal has the same E, whatever its length or thickness.

A steel wire of diameter 0.50 mm and length 2.50 m stretches by 1.2 mm under a tension of 20 N.

- Area: $A = \dfrac{\pi d^2}{4} = \pi \times (0.25 \times 10^{-3})^2 = 1.96 \times 10^{-7}$ m² (use the **radius**, in metres).
- Stress $= \dfrac{20}{1.96 \times 10^{-7}} = 1.02 \times 10^{8}$ Pa.

- Strain $= \dfrac{1.2 \times 10^{-3}}{2.50} = 4.8 \times 10^{-4}$.
- $E = \dfrac{1.02 \times 10^{8}}{4.8 \times 10^{-4}} = 2.12 \times 10^{11}$ Pa.

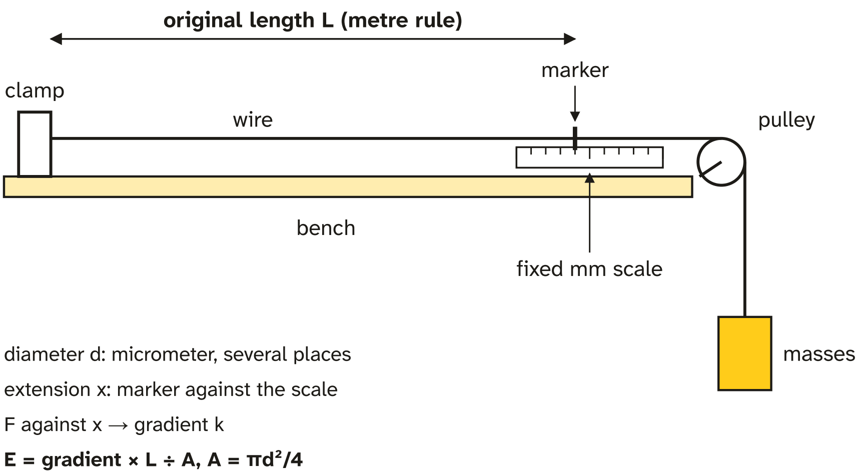
Linking E and k. From $E = \dfrac{FL}{Ax}$ and $k = \dfrac{F}{x}$:

$$k = \frac{EA}{L} \qquad x = \frac{FL}{EA}$$

For the steel wire, $k = \dfrac{2.12 \times 10^{11} \times 1.96 \times 10^{-7}}{2.50} = 1.67 \times 10^{4}$ N m^{-1}, the same as $\dfrac{20}{1.2 \times 10^{-3}}$. So for the same material and force:

- **Double the length**: double the extension ($x \propto L$), but the strain is unchanged.
- **Double the diameter**: the area is 4 times bigger, so the extension (and the stress) is a quarter.
- A stiffer material (larger E) stretches less. On a **stress–strain** graph, the gradient of the straight part is E .

Measuring the Young modulus of a wire

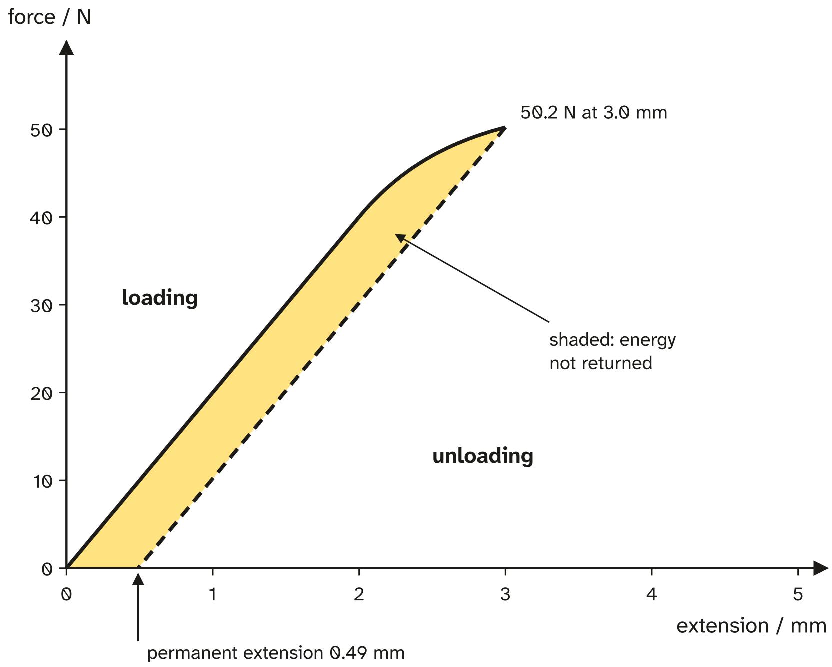


1. Use a **long, thin** wire so the extension is big enough to measure (a few metres long, well under a millimetre thick). Hang a small load first to straighten it.
2. Measure the **original length** L from the clamp to the marker with a metre rule (or tape).
3. Measure the **diameter** with a **micrometer screw gauge** at several places and in different directions, and average (the wire may not be perfectly round or uniform). Find $A = \dfrac{\pi d^2}{4}$.
4. Add masses one at a time. For each load $F = mg$, read the marker against the fixed scale and find the **extension** x from the starting reading.
5. Plot F against x. The straight part has gradient $k = \dfrac{F}{x}$, so $E = \dfrac{\text{gradient} \times L}{A}$.
6. Remove the loads and check the marker returns to zero, to show the limit of proportionality (and elastic limit) was not passed. Wear eye protection in case the wire snaps.

Elastic and plastic deformation

- **Elastic deformation**: the object returns to its original shape and size when the force is removed.
- **Plastic deformation**: the object does **not** return to its original shape; it keeps a permanent extension.
- **The elastic limit** is the largest force (or stress) that still gives elastic deformation. Beyond it, deformation is plastic.

The **limit of proportionality** and the **elastic limit** are different points. The first is where the graph stops being straight; the second is where permanent deformation begins. They are often close together, and the elastic limit is usually a little beyond the limit of proportionality (P then E in the first diagram). So between P and E a wire does not obey Hooke's law but still returns to its original length. A rubber band is elastic over a big stretch without obeying Hooke's law at all.



When a metal is loaded past its elastic limit and unloaded, the unloading line is roughly **parallel** to the first straight part, and it meets the axis at the **permanent extension** (0.49 mm here).

Work done and elastic potential energy

Stretching an object needs a force that moves its end, so work is done. Because the force changes as the extension grows, the work done is the **area under the force–extension graph** (the same idea as the area under any force–displacement graph).

Within the limit of proportionality the graph is a straight line through the origin, so the area is a triangle. The work done is stored as **elastic potential energy** (also called **strain energy**):

$$E_P = \tfrac{1}{2}Fx = \tfrac{1}{2}kx^2 = \frac{F^2}{2k}$$

The $\frac{1}{2}$ is there because the force rises steadily from 0 to F; its average is $\frac{1}{2}F$. For the wire in the first diagram at 30 N and 1.5 mm, $E_P = \frac{1}{2} \times 30 \times 1.5 \times 10^{-3} = 0.0225$ J.

- $E_P \propto x^2$: a spring with $k = 50$ N m^{-1} stores $\frac{1}{2} \times 50 \times 0.050^2 = 0.0625$ J at 0.050 m, and 0.25 J at 0.10 m. Doubling the extension doubles the force **and** the extension, so the energy is 4 times bigger.
- **Stretching from x_1 to x_2** adds $\frac{1}{2}k(x_2^2 - x_1^2)$: the area of the trapezium between them, $\frac{1}{2}(F_1 + F_2)(x_2 - x_1)$.
- **Beyond the limit of proportionality** the work done is still the area under the graph, but not a triangle: count squares or split it into shapes. $\frac{1}{2}Fx$ only works for the straight part.
- **Plastic deformation wastes energy**: in the second diagram, stretching to 3.0 mm takes 0.086 J of work, but only 0.063 J (the triangle under the unloading line) comes back. The other 0.023 J, the area between the lines, becomes thermal energy. The same happens for rubber whose unloading curve lies below its loading curve.
- The area under a **stress–strain** graph is the energy stored per unit volume of the wire, $\frac{1}{2}\sigma\varepsilon$.

Key facts and formulas

"Given" means it is on the data sheet in the exam. "Learn it" means you must remember it. None of this topic's formulas are on the data sheet.

Formula	Status
Hooke's law $F = kx$ (within the limit of proportionality)	Learn it
Spring constant $k = \dfrac{F}{x}$ (N m^{-1})	Learn it
Stress $\sigma = \dfrac{F}{A}$ (Pa $=$ N m^{-2})	Learn it
Strain $\varepsilon = \dfrac{x}{L}$ (no unit)	Learn it
Young modulus $E = \dfrac{\sigma}{\varepsilon} = \dfrac{FL}{Ax}$ (Pa)	Learn it
$k = \dfrac{EA}{L}$ for a wire	Learn it
Area of a circular cross-section $A = \pi r^2 = \dfrac{\pi d^2}{4}$	Learn it
Elastic potential energy $E_P = \frac{1}{2}Fx = \frac{1}{2}kx^2$ (within the limit of proportionality)	Learn it
Work done $=$ area under the force–extension graph	Learn it
Springs in series $\dfrac{1}{k} = \dfrac{1}{k_1} + \dfrac{1}{k_2}$; in parallel $k = k_1 + k_2$	Learn it
$g = 9.81$ m s^{-2}	Given

How to do it

In the Paper 1 and Paper 2 questions we have tagged for this topic (119 different questions, 2021–2025; 5 more appear on two papers), the types came up this often. 30 of the 119 questions mix two or more types, so the counts add up to more than 119.

Question type	Questions
Elastic potential energy and work from graphs	47
Stress, strain and the Young modulus	44
Definitions, terms and reading the graphs	36
Spring constant, Hooke's law and combined springs	23
Springs and wires in longer problems	15

1. Elastic potential energy and work from graphs (47 questions)

1. **Find the extension** (not the length) in metres: read it from the graph or use $x = \frac{F}{k}$.
2. **Within the limit of proportionality**, use $E_P = \frac{1}{2}Fx$ or $\frac{1}{2}kx^2$ (or the triangle's area on the graph).
3. **Check units**: mm or cm → m before multiplying; the answer is in J.

Variations you will meet:

- **Graph of force against length**: extension $=$ length $-$ unstretched length (where the line meets the length axis). The area under a length graph is still a triangle starting at the unstretched length.
- **Graph with extension on the y-axis**: the energy is still $\frac{1}{2}\times$ force $\times$ extension; pick the area between the line and the **extension** axis.
- **Extra energy** from one force to a bigger one: $\frac{1}{2}(F_1 + F_2)(x_2 - x_1)$ or $\frac{1}{2}k(x_2^2 - x_1^2)$. Not $\frac{1}{2}k(x_2 - x_1)^2$.
- **Ratios**: at fixed k, $E_P \propto x^2$ and $E_P \propto F^2$. If E_P goes up 4 times, F and x double. For the same force on two springs, $E_P = \frac{F^2}{2k}$, so the stiffer spring stores **less**.
- **Several springs**: find the force and extension of **one** spring, find its energy, then multiply by the number of springs (or use the total load and total extension of the combination: same answer). Two parallel springs under F with extension x each store $\frac{1}{2} \cdot \frac{F}{2} \cdot x = \frac{1}{4}Fx$.
- **"Which area is the work done?"**: the area between the loading line and the extension axis. For a sample loaded then unloaded, the area **between** the two curves is the energy not returned (thermal energy); the area under the unloading curve is the energy given back.
- **Beyond the limit of proportionality**: count squares under the curve (estimate), or split into a triangle plus a rectangle or trapezium; explain that $\frac{1}{2}Fx$ doesn't apply because the graph isn't straight.
- **Graph shapes**: E_P against x is a parabola through the origin (curving up), not a straight line; x against E_P is a curve like $\sqrt{E_P}$.
- **Compression and extension** both **increase** the stored energy from zero.
- **Area under a stress–strain graph**: energy per unit volume, $\frac{E_P}{AL}$.

2. Stress, strain and the Young modulus (44 questions)

1. **Convert everything to SI**: mm → m, mm² → m² ($\times 10^{-6}$), GPa → Pa ($\times 10^9$).
2. **Area from diameter**: $A = \pi \left(\frac{d}{2}\right)^2$. Keep the full value; don't round it yet.

3. **Use** $E = \dfrac{FL}{Ax}$ and rearrange for what's asked; or find stress and strain separately and divide.

Variations you will meet:

- **Spring constant of a wire**: $k = \dfrac{EA}{L}$. **Volume** of a wire from E, k and L: $V = AL = \dfrac{kL^2}{E}$.
- **Ratios for the same material** (E fixed): $x \propto \dfrac{FL}{d^2}$. Half the length and twice the diameter gives $\frac{1}{2} \times \frac{1}{4} = \frac{1}{8}$ of the extension.
- **Stress at different cross-sections of one bar**: the force is the same all along, so stress $\propto \dfrac{1}{d^2}$; the **maximum stress** is where the bar is **thinnest** (use the smallest diameter).
- **Which quantities are the same?** Two wires of the same size and load but different metals: same stress, different strain, different E. Two wires of the same metal: same E always.
- **Reading a stress–strain graph**: gradient of the straight part $= E$ (watch strain given as %, and stress in 10^8 Pa); a steeper line is a stiffer material with smaller extension for the same stress.
- **Composite wire** (two metals end to end): both carry the same force; each part's extension is $\propto$ its length, so find each metal's extension per metre and scale.
- **Several rods or wires sharing a load**: divide the load first, then use one rod's stress.
- **Strain from a spring's data**: strain $= \dfrac{x}{L}$ with $x = \dfrac{F}{k}$.
- **Wire at an angle** (a cord supporting a load in a V): find the tension by resolving (two tensions $\times \cos$ of half the angle $=$ weight), then the extension from the new and old lengths.
- **Expressions**: $E = \dfrac{\sigma}{\varepsilon} = \dfrac{FL}{Ax}$; strain $= \dfrac{L - L_0}{L_0} = \dfrac{L}{L_0} - 1$.

3. Definitions, terms and reading the graphs (36 questions)

- **Hooke's law**: force is proportional to extension (within the limit of proportionality).
- **Spring constant**: force per unit extension.
- **Stress**: force per unit cross-sectional area. **Strain**: extension per unit original length. **Young modulus**: stress ÷ strain.
- **Limit of proportionality**: the point beyond which force is no longer proportional to extension (the end of the straight line).
- **Elastic limit**: the point beyond which the deformation is plastic (the object won't return to its original length). It is **not** the same as the limit of proportionality.
- **Elastic deformation**: returns to its original shape and size when the load is removed. **Plastic**: permanent change of shape.
- **Units**: stress and Young modulus in Pa (N m^{-2}, kg m^{-1} s^{-2}); strain none; spring constant N m^{-1} (kg s^{-2}).
- **Reading a loading–unloading graph**: if unloading follows the same line back to zero, the deformation is **elastic only** (not plastic). If it returns to zero extension by a different curve, it is still elastic (no permanent extension), and a curved line means Hooke's law is not obeyed. If it ends at a positive extension, it was plastic.

- **Labelling a graph**: the straight part is the Hooke's law region; the limit of proportionality is at its end; the elastic limit is at or beyond it; plastic region after that; the break is the end of the line.
- **Everyday examples**: a plank that stays bent after a heavy load is removed is plastic; a bouncing ball or a scale spring is elastic.
- **"Which stays constant when the load increases?"**: the Young modulus (and the spring constant), not the stress or strain.

4. Spring constant, Hooke's law and combined springs (23 questions)

1. **Take two points** on the straight part of the graph, or the origin and one point.
2. **Find the change in force and the change in length** (extension), both in SI units.
3. $k = \dfrac{\Delta F}{\Delta x}$ in N m-1.

Variations you will meet:

- **Two force–length readings** and no unstretched length: $k = \dfrac{F_2 - F_1}{L_2 - L_1}$. Then unstretched length $= L_1 - \dfrac{F_1}{k}$.
- **Unstretched length** from a force–length graph: where the line meets the length axis (where the force becomes non-zero).
- **Graph of extension against force**: $k = \dfrac{1}{\text{gradient}}$.
- **Series and parallel**: series, extensions add (k halves for two identical springs); parallel, forces share (k doubles). For mixed arrangements, work outwards: combine each parallel pair, then add series extensions. Check with $k =$ total load ÷ total extension.
- **Ordering graphs by stiffness**: compare $\frac{F}{x}$, with both axes in the same units.

5. Springs and wires in longer problems (15 questions)

These mix this topic with energy, moments or upthrust. Find the force on the spring or wire from the other topic, then use Hooke's law, stress or E_P.

- **Spring launcher** (spring pushes a ball or block on a frictionless surface): $\frac{1}{2}kx^2 = \frac{1}{2}mv^2$. $E_P \propto x^2$, so the launch speed $\propto x$. A ball sent up a slope or rod: E_P at the start $= mg\Delta h$ gained (+ work against friction).
- **Object dropped onto a spring**: at maximum compression $E_K = 0$, so E_P (spring) $= E_K$ at contact $+$ $mg\times$ (compression). Then the maximum force is $F = \frac{2E_P}{x}$, and the resultant force is $F - mg$.
- **Bungee rope**: the rope starts stretching once the fall passes its unstretched length. At the lowest point, all the lost mgh is stored as $\frac{1}{2}kx^2$ and $E_K = 0$, so the speed is zero there.
- **Mass hung on a spring and released from rest**: it falls until $mgx = \frac{1}{2}kx^2$, so $x_{\max} = \frac{2mg}{k}$, twice the equilibrium extension $\frac{mg}{k}$.
- **Beam held by a spring or wire** (moments): the principle of moments gives the tension; then $x = \frac{F}{k}$ or stress $= \frac{F}{A}$ and $E = \frac{\text{stress}}{\text{strain}}$. Moving a load changes the tension, so the strain and E_P change with it.

- **Spring holding a cylinder in a liquid** (upthrust): spring force $=$ weight $-$ upthrust. More upthrust means less tension, smaller extension and less strain energy.
- **Pulley on a spring**: the cable pulls on both sides of the pulley, so the spring force is $2T$.
- **Qualitative**: "state and explain the effect on the strain energy": say what happens to the force, then to the extension, then to $\frac{1}{2}Fx$.

Worked examples

The bold codes show where marks are earned, as in Cambridge mark schemes. The number is how many marks.

- **A1** accuracy mark: for a correct answer; it needs the M mark before it.
- **B1** mark for a correct result on its own, with no method needed.

Example 1

A steel wire of length 1.8 m and diameter 0.60 mm hangs from a fixed point. A load of 45 N is attached to its lower end. The Young modulus of steel is 2.0×10^{11} Pa and the wire obeys Hooke's law.

Calculate the extension of the wire. **[3]**

Solution

$A = \pi \times (0.30 \times 10^{-3})^2 = 2.83 \times 10^{-7}$ m² **C1** $E = \dfrac{FL}{Ax}$, so $x = \dfrac{FL}{AE}$ **C1** $x = \dfrac{45 \times 1.8}{2.83 \times 10^{-7} \times 2.0 \times 10^{11}} = 1.4 \times 10^{-3}$ m (1.4 mm). **A1**

Example 2

A spring hangs from a fixed support. Its length is 0.25 m with no load and 0.40 m when a force of 6.0 N is applied. It obeys Hooke's law over this range.

(a) State Hooke's law. **[1]**

(b) Calculate the spring constant. **[2]**

(c) Calculate the elastic potential energy stored when the force is 4.8 N. **[2]**

(d) Determine the work done in increasing the force from 4.8 N to 6.0 N. **[2]**

Solution

(a) The extension is proportional to the force applied (within the limit of proportionality). **B1**

(b) Extension $= 0.40 - 0.25 = 0.15$ m **C1** $k = \dfrac{6.0}{0.15} = 40$ N m⁻¹. **A1**

(c) $x = \dfrac{4.8}{40} = 0.12$ m **C1** $E_P = \frac{1}{2}Fx = \frac{1}{2} \times 4.8 \times 0.12 = 0.29$ J. **A1**

(d) Work done $= \frac{1}{2}k(x_2^2 - x_1^2) = \frac{1}{2} \times 40 \times (0.15^2 - 0.12^2)$ **C1** $= 0.16$ J. **A1** (Or the trapezium: $\frac{1}{2} \times (4.8 + 6.0) \times 0.03 = 0.16$ J.)

Example 3

(a) Define stress and strain. **[2]**

(b) A copper wire has original length 2.20 m and diameter 0.42 mm. A tensile force of 12.0 N gives it an extension of 1.60 mm, within its limit of proportionality. Calculate the Young modulus of copper. **[3]**

(c) A second copper wire has the same length but half the diameter. The same 12.0 N force is applied. State and explain its extension. **[2]**

(d) In an experiment to find the Young modulus, state how the diameter of the wire is measured, and why more than one reading is taken. **[2]**

Solution

(a) Stress is force per unit cross-sectional area. **B1** Strain is extension per unit original length. **B1**

(b) $A = \pi \times (0.21 \times 10^{-3})^2 = 1.385 \times 10^{-7}$ m² **C1** $E = \dfrac{FL}{Ax} = \dfrac{12.0 \times 2.20}{1.385 \times 10^{-7} \times 1.60 \times 10^{-3}}$ **C1** $= 1.19 \times 10^{11}$ Pa. **A1**

(c) Half the diameter gives a quarter of the area, and $x = \dfrac{FL}{EA}$ with F, L and E unchanged **B1** so the extension is 4 times bigger: $4 \times 1.60 = 6.40$ mm. **B1**

(d) With a micrometer screw gauge **B1** at several places along the wire (and in different directions), then averaged, because the wire may not be uniform or perfectly round. **B1**

Example 4

A block of mass 0.20 kg rests on a frictionless horizontal surface against a spring of spring constant 320 N m⁻¹. The block is pushed so that the spring is compressed by 0.050 m, then released. The spring obeys Hooke's law.

(a) Calculate the elastic potential energy stored in the compressed spring. **[2]**

(b) Calculate the speed of the block as it leaves the spring. **[2]**

(c) Calculate the acceleration of the block at the instant it is released. **[2]**

(d) The block then slides up a frictionless ramp. Calculate the greatest height it reaches. **[2]**

(e) The compression is doubled. State and explain the new speed of the block as it leaves the spring. **[2]**

Solution

(a) $E_P = \frac{1}{2}kx^2$ **C1** $= \frac{1}{2} \times 320 \times 0.050^2 = 0.40$ J. **A1**

(b) $\frac{1}{2}mv^2 = 0.40$ **C1** $v = \sqrt{\frac{2 \times 0.40}{0.20}} = 2.0$ m s⁻¹. **A1**

(c) $F = kx = 320 \times 0.050 = 16$ N **C1** $a = \frac{F}{m} = \frac{16}{0.20} = 80$ m s⁻². **A1**

(d) $mgh = 0.40$ **C1** $h = \frac{0.40}{0.20 \times 9.81} = 0.20$ m. **A1**

(e) $E_P \propto x^2$, so the stored energy is 4 times bigger (1.6 J) **B1** $E_K \propto v^2$, so the speed doubles, to 4.0 m s⁻¹. **B1**

Common mistakes

- **Using the length instead of the extension.** Examiner reports in several years name this error, in both k and E_P. A spring that goes from 20 cm to 26 cm under 3.6 N has $k = \frac{3.6}{0.06} = 60$ N m⁻¹, not $\frac{3.6}{0.26} = 13.8$ N m⁻¹.
- **Power-of-ten slips reading graphs.** Extensions in mm or cm must become metres, areas in mm² must become m² (0.30 mm² $= 3.0 \times 10^{-7}$ m², not 3.0×10^{-4}), and GPa is 10^9 Pa. Several reports mention it when a graph has mm or cm on an axis.
- **Using the diameter as the radius.** For $d = 0.80$ mm, $A = \pi \times (0.40 \times 10^{-3})^2 = 5.03 \times 10^{-7}$ m². Using 0.80 mm as r gives 2.01×10^{-6} m², 4 times too big.
- **Thinking energy doubles when the extension doubles.** $E_P = \frac{1}{2}Fx$ and the force doubles too, so the energy goes up 4 times: a spring with $k = 200$ N m⁻¹ stores 0.04 J at 2.0 cm but 0.16 J at 4.0 cm. Reports describe this misconception, and the matching wrong graph (a straight line for E_P against x).
- **Forgetting the $\frac{1}{2}$** (writing $E_P = Fx$), or equating a **force** to an energy.
- **Confusing strain with strain energy.** Strain is $\frac{x}{L}$ (no unit); strain energy is $\frac{1}{2}Fx$ in joules. Read the question twice.
- **Treating the limit of proportionality and the elastic limit as the same thing.** The graph can stop being straight while the wire is still elastic.
- **Energy in only one spring** when the question asks for the total in several springs (or the other way round). Examiners note this with parallel springs.
- **Rounding too early.** Keep the full area and stress in your calculator; rounding the stress to 2 significant figures before dividing has cost marks.
- **Giving the total extension instead of the Hooke's law limit** when asked for the largest extension where Hooke's law is obeyed: read the end of the straight part.

How to get the marks

- **Definitions** (one mark each; use the words):
  - Hooke's law: force is proportional to extension (provided the limit of proportionality isn't exceeded).
  - Stress: force per unit cross-sectional area. Strain: extension per unit original length.

  - Young modulus: stress ÷ strain (the ratio of stress to strain).
  - Spring constant: force per unit extension.
  - Elastic deformation: the object returns to its original shape when the load is removed; plastic: it doesn't.
  - Elastic limit: the point beyond which deformation is plastic. Limit of proportionality: beyond which force is not proportional to extension.
- **Method marks (C1)**: write the equation before the numbers: $k = \frac{F}{x}$, $E = \frac{FL}{Ax}$, $E_P = \frac{1}{2}Fx$ or "area under graph". A correct equation with substituted values earns a mark even if the arithmetic later slips.
- **Show the extension** as a subtraction ($0.40 - 0.25$) when you read lengths from a graph; that line is often a mark on its own.
- **"Show that"**: every step on its own line, the subject of each equation stated, and a final value to one more significant figure than quoted.
- **"State and explain"** comparisons: give the result **and** the equation reason, for example "extension is 4 times bigger, because the area is a quarter and $x = \frac{FL}{EA}$".
- **"Explain why the area is the elastic potential energy"**: area = work done; the deformation is elastic so all the work is stored (and can be recovered).
- **"Explain why the work done isn't all recovered"**: the deformation is plastic, so some energy becomes thermal energy.
- **Sketches**: Hooke's law is a straight line **through the origin**; E_P against x is a curve through the origin getting steeper. For a stress–strain line with double E, draw it through the origin with twice the gradient, ending at the same stress limit if one is given.
- **Graph marks**: crosses on the line at the right point (P at the end of the straight part), and labels as asked.
- **Units and significant figures**: Pa for stress and E, no unit for strain, N m^{-1} for k, J for energy. Match the data (2 or 3 figures).
- **Multiple choice**: work it out first. The wrong options are usually length instead of extension, diameter instead of radius, energy doubling instead of quadrupling, or one spring instead of the whole set.

Quick check

1. A spring is 8.0 cm long with no load and 11.5 cm long when a 2.8 N force is applied. Calculate its spring constant.
2. A wire of cross-sectional area 0.20 mm² is under a tension of 36 N and has a strain of 9.0×10^{-4}. Calculate the stress and the Young modulus.
3. A spring of spring constant 150 N m^{-1} is stretched by 6.0 cm. Calculate the elastic potential energy stored. What is it if the extension is doubled?
4. Two identical springs, each with spring constant 60 N m^{-1}, support a 9.0 N load. Calculate the total extension when they are (a) in series, (b) in parallel.
5. A metal wire is loaded and then unloaded. At the end it is 0.4 mm longer than at the start. Name the type of deformation and what has been exceeded.

Answers

1. Extension $= 11.5 - 8.0 = 3.5$ cm $= 0.035$ m, so $k = \dfrac{2.8}{0.035} = 80$ N m^{-1}.
2. $A = 0.20 \times 10^{-6} = 2.0 \times 10^{-7}$ m^2. Stress $= \dfrac{36}{2.0 \times 10^{-7}} = 1.8 \times 10^8$ Pa. $E = \dfrac{1.8 \times 10^8}{9.0 \times 10^{-4}} = 2.0 \times 10^{11}$ Pa.
3. $E_P = \frac{1}{2} \times 150 \times 0.060^2 = 0.27$ J. Doubling the extension multiplies it by 4: 1.08 J.
4. (a) In series each spring carries 9.0 N and stretches $\frac{9.0}{60} = 0.15$ m, so the total is 0.30 m (combined $k = 30$ N m^{-1}). (b) In parallel each carries 4.5 N, so the extension is $\frac{4.5}{60} = 0.075$ m (combined $k = 120$ N m^{-1}).
5. Plastic deformation: it has a permanent extension, so the elastic limit was exceeded.

Past questions to try

- **9702/21/O/N/21 Q3**: stress, strain and Young modulus as expressions, then strain energy from a graph and why plastic stretching loses energy.
- **9702/23/M/J/24 Q3**: marking the limit of proportionality and elastic limit, then k, E and the work done to breaking point.
- **9702/22/F/M/21 Q3**: Hooke's law, k and strain energy from a graph, with a spring holding a cylinder in a liquid.
- **9702/21/M/J/24 Q4**: defining strain, the Young modulus of a copper wire and comparing stress and strain in a thicker wire.