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4.8 The Young Modulus

PHYSICS

AQA A Level Revision Notes

A Level Physics AQA

4.8 The Young Modulus

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4.8.1 The Young Modulus

The Young Modulus

- The Young modulus is the measure of the ability of a material to withstand changes in length with an added load
  - This gives information about the stiffness of a material
  - This is useful for engineers to make sure the materials they are using can withstand sufficient forces

- The Young Modulus is defined as the **ratio of tensile stress and tensile strain**

$$\text{Young Modulus} = \frac{\text{Tensile stress}}{\text{Tensile strain}} = \frac{FL}{A\Delta L}$$

- Where:
  - F = force (N)
  - L = original length (m)
  - A = cross-sectional area (m^2)
  - ΔL = extension (m)

- Since strain is dimensionless, the units of the Young Modulus is **pascals (Pa)**
- The Young Modulus of a material is typically a very large number, in the order of GPa

Table of the Young's Modulus for Materials

Material	Young's Modulus / GPa
Aluminium	70
Copper	117
Brass	120
Iron	170
Nickel	210
Steel	110

Worked Example

A metal wire that is supported vertically from a fixed point has a load of 92 N applied to the lower end.

The wire has a cross-sectional area of 0.04 mm^2 and obeys Hooke's law.

The length of the wire increases by 0.50%. What is the Young modulus of the metal wire?A. 4.6×10^7 Pa B. 4.6×10^{12} Pa C. 4.6×10^9 Pa D. 4.6×10^{11} Pa

ANSWER: D

STEP 1

YOUNG MODULUS EQUATION

$$E = \frac{\text{STRESS}}{\text{STRAIN}} = \frac{FL}{A\Delta L}$$

STEP 2

CALCULATE STRESS

$$\text{STRESS} = \frac{F}{A} = \frac{92\ \text{N}}{0.04 \times 10^{-6}\ \text{m}^2} = 2.3 \times 10^9\ \text{Pa}$$

$1\ \text{mm}^2 = 1 \times 10^{-6}\ \text{m}^2$

STEP 3

CALCULATE STRAIN

$$\text{STRAIN} = \frac{\Delta L}{L} = 0.5\% = 0.005$$

EXTENSION

STEP 4

SUBSTITUTE INTO YOUNG MODULUS EQUATION

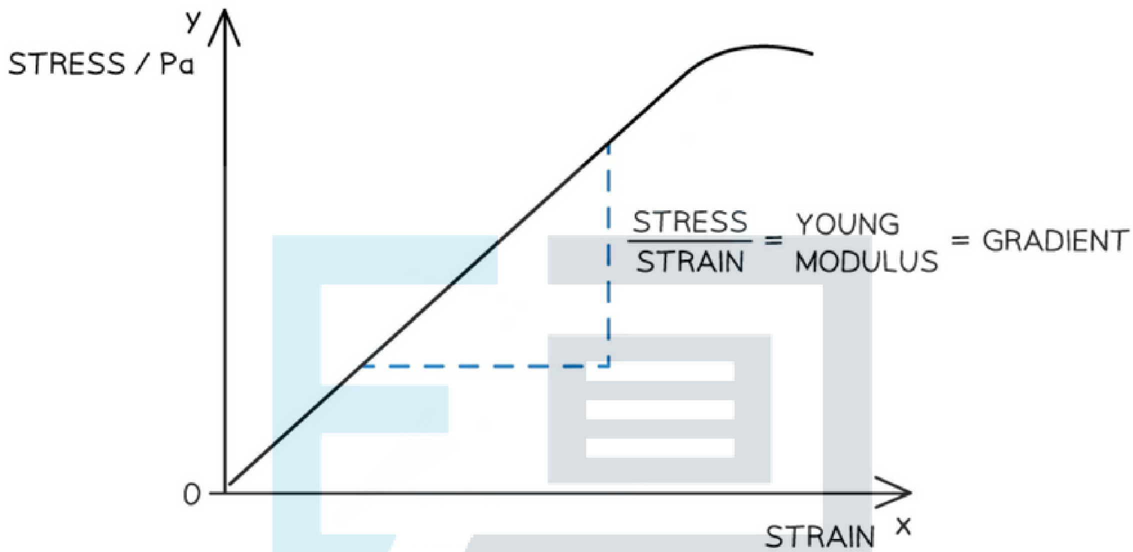
$$E = \frac{\text{STRESS}}{\text{STRAIN}} = \frac{2.3 \times 10^9\ \text{Pa}}{0.005} = 4.6 \times 10^{11}\ \text{Pa}$$

Exam Tip

To remember whether stress or strain comes first in the Young modulus equation, try thinking of the phrase 'When you're stressed, you show the strain' i.e. Stress ÷ Strain.

The Young Modulus from Stress-Strain Graphs

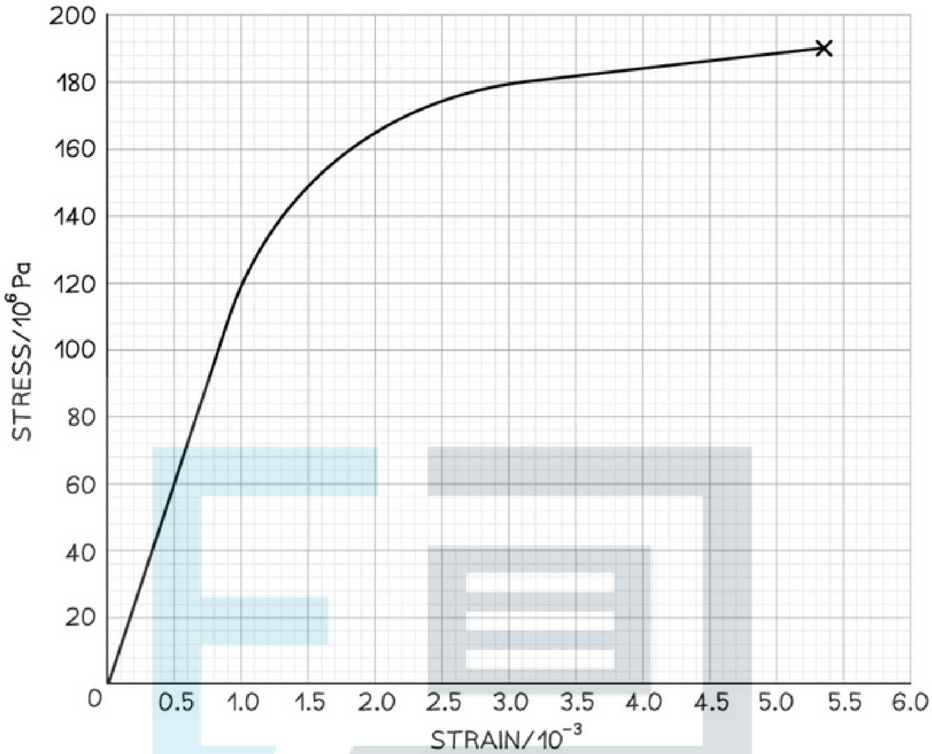
- The Young Modulus is equal to the **gradient** of a stress-strain graph when it is linear (a straight line)
  - This is the region in which Hooke's Law is obeyed
- The area under the graph in this region is equal to the **energy stored per unit volume** of the material



A stress-strain graph is a straight line with its gradient equal to the Young modulus

Worked Example

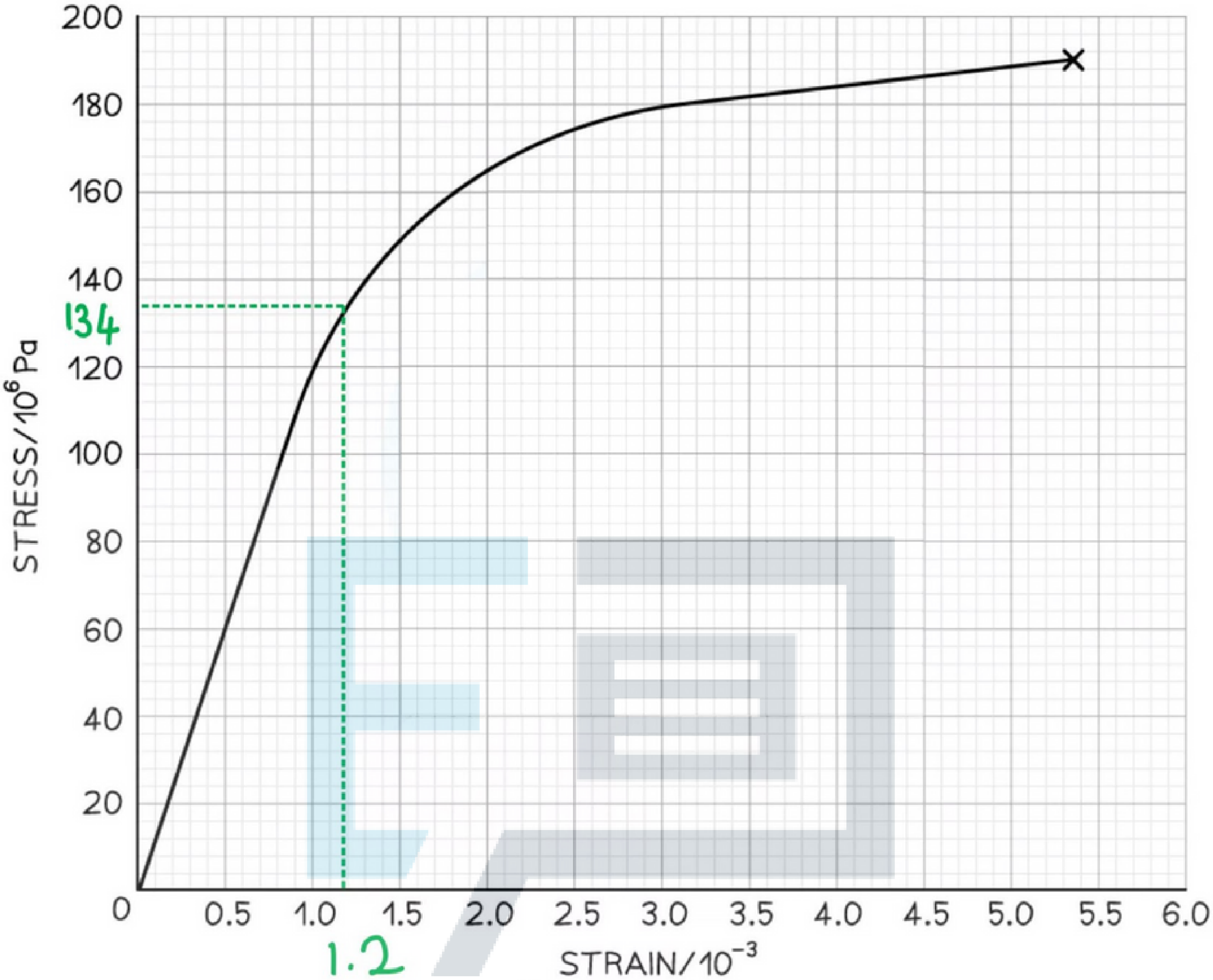
The graph below shows the stress-strain graph for a copper wire.



Use the graph to calculate the Young Modulus of copper.

Step 1: Determine the stress and strain where the linear region ends

The Young Modulus is the gradient of the linear region of a stress-strain graph



Step 2: Calculate the gradient of the graph in this region

$$\text{Young Modulus} = \frac{134 \times 10^6}{1.2 \times 10^{-3}} = 1.1 \times 10^{11} \text{ Pa}$$

Required Practical: The Young Modulus

Aims of the Experiment

- The aim of the experiment is to measure the Young Modulus of a metal in the form of a wire
- This requires a clamped horizontal wire over a pulley
- This experiment can also be done with a vertical wire attached to the ceiling with a mass attached

Variables

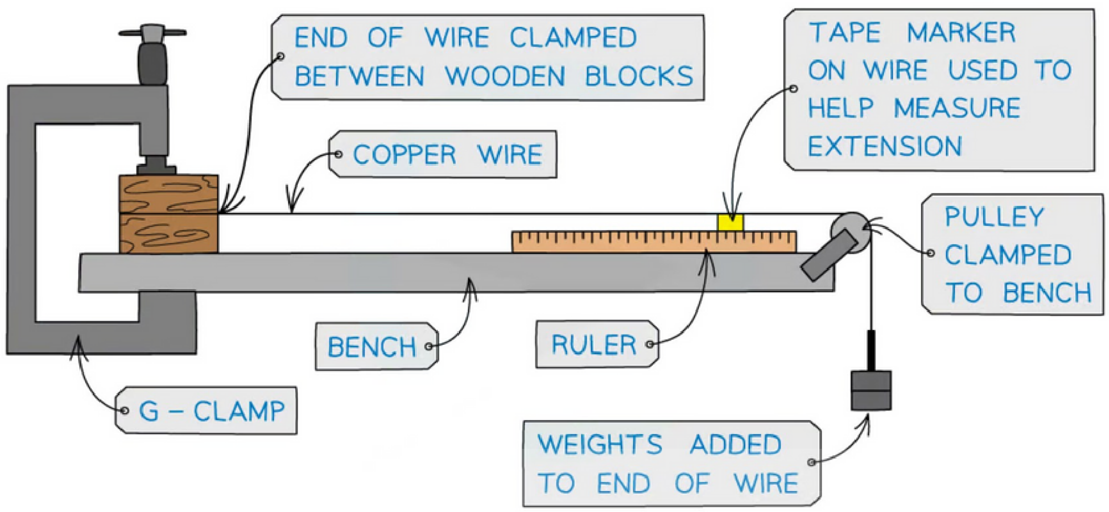
- Independent variable = Force (or load) (N)
- Dependent variable = Extension (m)
- Control variables:
  - The original length of wire
  - The thickness of the wire
  - The metal used for the wire

Equipment List

Equipment	Purpose
Bench	To hold the equipment
G-clamp	To stabilise the apparatus
Copper wire	Use to calculate the Young modulus of copper
Metre ruler	To measure the length of the wire and extension
Pulley	To allow the mass to hang vertically, and introduces less friction than the edge of the table
Tape marker	To accurately measure the extension with the applied load. This should touch the ruler
Wooden blocks	Clamps together the wire to keep it taut and straight
Mass hanger + 100g mass	To hang from the pulley and add a load to the wire to create an extension
Micrometer	Use to measure the diameter of the wire

- Resolution of measuring equipment:
  - Metre ruler = 1 mm
  - Micrometer = 0.001 mm

Method



This method is an example of the procedure for varying load and measuring the extension of a copper wire. This is just one way of measuring the relationship between them.

1. Measure the diameter of the wire with a micrometre screw gauge or digital callipers. Take at least 3 readings and find an average
2. Set up the apparatus so the wire is taut. No masses should be on the mass hanger just yet
3. Measure the original length of the wire using a metre ruler and mark a reference point with tape preferably near the beginning of the scale eg. at 1 cm
4. Record initial reading on the ruler of the reference point
5. Add a 100 g mass onto the mass hanger
6. Read and record the new reading of the tape marker from the meter ruler
7. Repeat this method by adding a 100 g mass (at least 5 – 10 times) and record the new scale reading from the metre ruler

- An example of a table with some possible loads and extensions might look like:

MASS m/g	LOAD F/N	NEW MARKER READING / m	EXTENSION ΔL / m
100			
200			
300			
400			
500			
600			

Analysis of Results

- The Young modulus is found from the equation

$$\text{Young Modulus} = \frac{\text{Tensile stress}}{\text{Tensile strain}} = \frac{FL}{A\Delta L}$$

- Where:
  - F = force (or load) (N)
  - L = original length of the wire (m)
  - A = cross-sectional area of the wire (m^2)
  - ΔL = extension (m)

- Rearranging the Young Modulus equation for the force, F:

$$F = \left(\frac{\text{Young Modulus} \times A}{L}\right)\Delta L$$

- Comparing this to the equation of a straight line: y = mx
  - y = F
  - x = ΔL
  - Gradient = (Young Modulus × A)/L

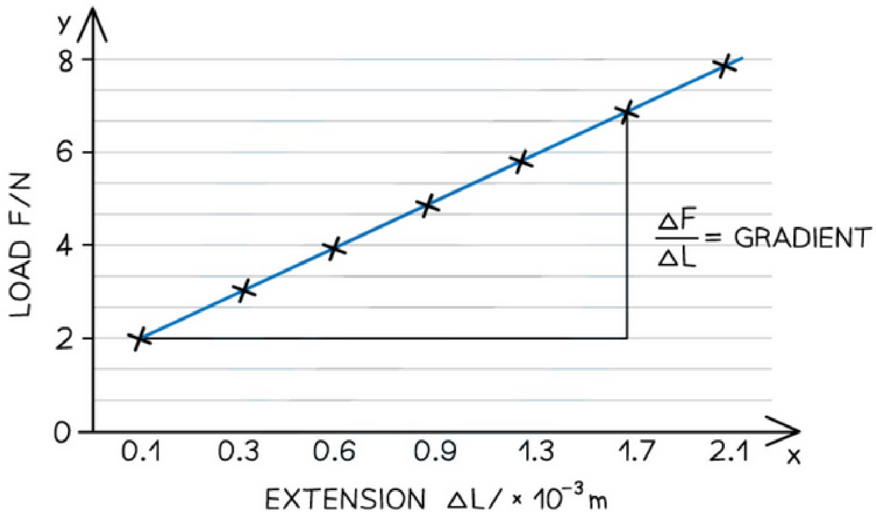
1. Calculate the cross-sectional area of the wire
   - The area of circle is given by:

$$\text{Cross-sectional area } A = \frac{\pi d^2}{4}$$

   - Where: d = diameter of the wire (m)

2. Plot a graph of load (force) against extension
   - The load is found by multiplying each mass by g (9.81 N kg^{-1})

3. Determine the gradient of this graph
   - $F/\Delta L$ is the gradient of the force-extension graph



4. Multiply the gradient by the ratio of the original length and cross-sectional area of the wire to calculate the Young Modulus

$$\text{The Young modulus} = \text{gradient} \times \frac{L}{A}$$

Evaluating the Experiment

Systematic Errors:

- Use a vernier scale for more precise readings
  - This is more likely to produce an accurate value for the extension
- If the wire is extended past its elastic limit, it will be permanently deformed
  - To reduce the risk of this, remove the load and check the wire returns to its original length before taking any new readings

Random Errors:

- Parallax error from reading the marker on the ruler
- Random errors are reduced by repeating the experiment for all the loads and finding an average extension
- Reduce the uncertainty on the cross-sectional area by measuring the diameter in several places and calculating an average

Safety Considerations

- Wear safety goggles at all times in case the wire snaps
- Make sure a cushion or soft surface is kept directly below the mass hanger, in case it falls off

Worked Example

A student investigates the relationship between the force on a wire and its extension. They set up the experiment by keeping the string taut with a 100 g mass. Adding on an extra 100 g each time and measuring the extension, they obtain the following table of results

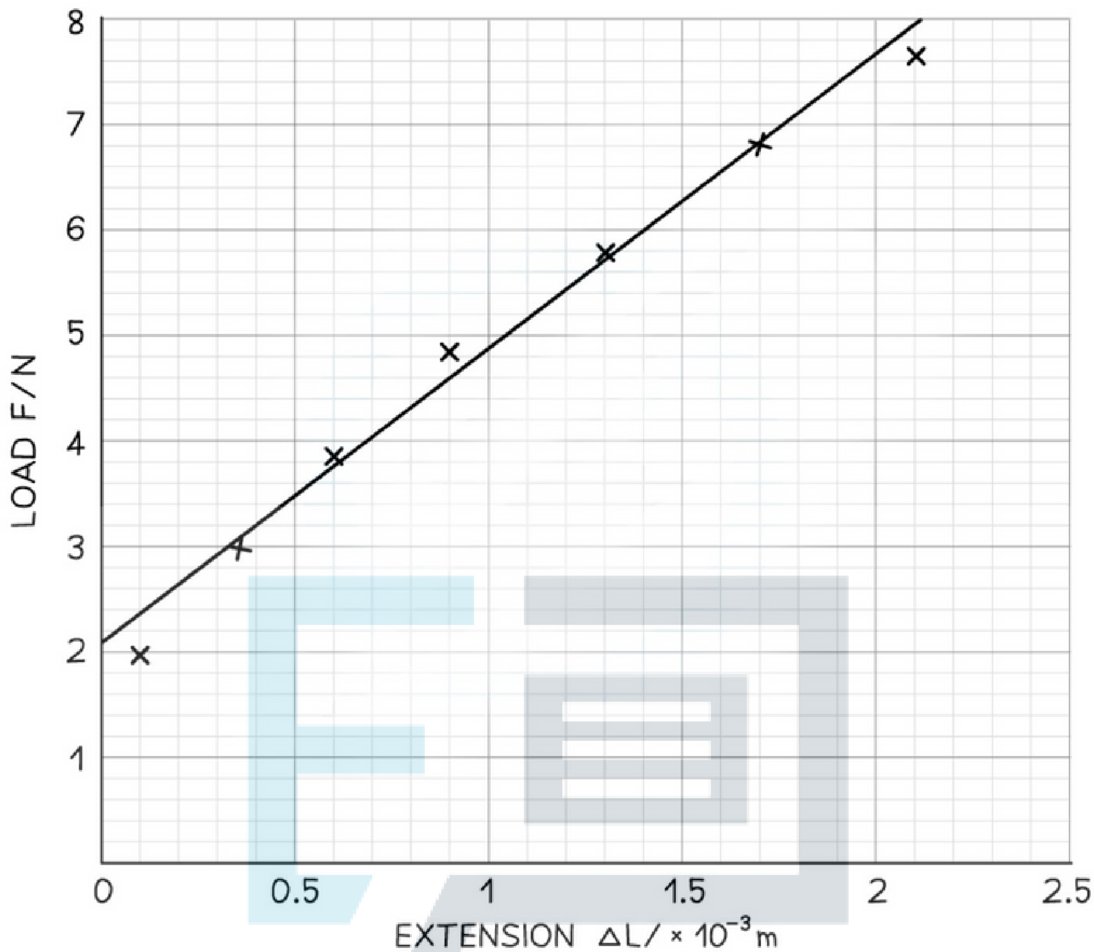
Mass m/g	Load F/N	Initial length/mm	Final length/mm	Extension ΔL / x 10^{-3} m
200	2.0	500	500.1	0.1
300	2.9	500.1	500.4	0.3
400	3.9	500.4	501.0	0.6
500	4.9	501.0	501.9	0.9
600	5.9	501.9	503.2	1.3
700	6.9	503.2	504.9	1.7
800	7.8	504.9	507.0	2.1

The following additional data for the wire is:

Length l / m	1.382
Diameter 1 / mm	0.277
Diameter 2 / mm	0.280
Diameter 3 / mm	0.275
Average Diameter d / mm	0.277
Cross-sectional area A / m^2	6.03×10^{-8}

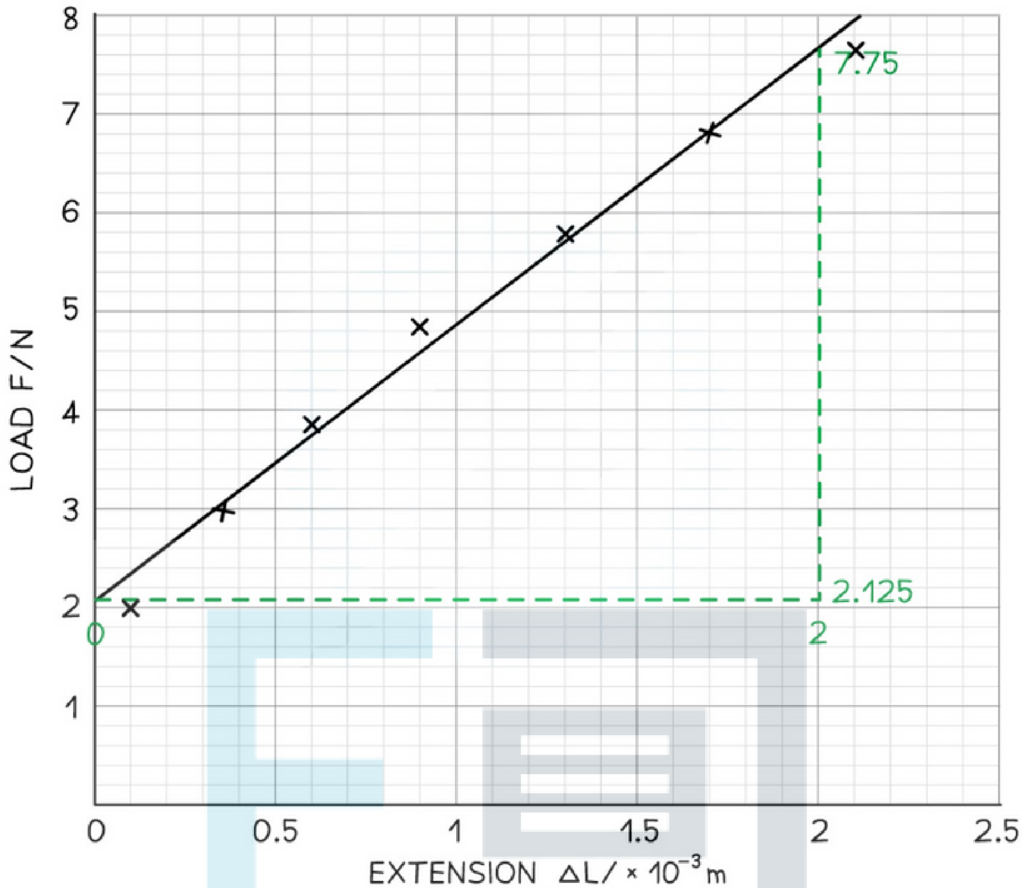
Calculate the value of the Young Modulus of the wire.

Step 1: Plot a graph of the load (force) against the extension



- Make sure the axes are properly labelled and the line of best fit is drawn with a ruler

Step 2: Calculate the gradient of the graph



$$\frac{\Delta F}{\Delta L} = \frac{7.75 - 2.125}{2 - 0} = 2.8125 \text{ N m}^{-1}$$

Step 3: Substitute values into the Young Modulus Equation

- Original length of wire, $L = 1.382$ m
- Cross-sectional area, $A = 6.03 \times 10^{-8}$ m^2
- Gradient = 2.8125 N m^{-1}

$$\text{The Young modulus} = 2.8125 \times \frac{1.382}{6.03 \times 10^{-8}} = 6.4 \times 10^{7} \text{ Pa}$$

Exam Tip

Although every care should be taken to make the experiment as reliable as possible, you will be expected to suggest improvements in producing more accurate and reliable results (e.g. repeat readings and use a longer length of wire)