

UNIT 1

Force, work, energy and power

Key words

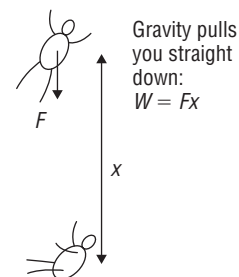
- work
- joule
- conservation of energy

✓ Quick check 1

We use forces to do things – to start things moving, to make them accelerate or decelerate, to change their shape. When a force changes the *energy* of something in this way, we say that it does **work**. Energy has been *transferred*.

Gravity pulls you straight down: $W = Fx$

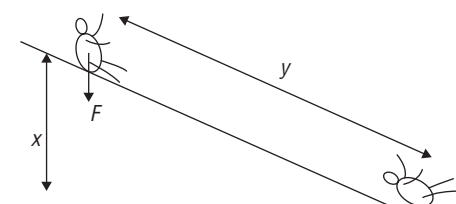
work done = energy transferred



Doing work

When a force F pushes an object for a distance x , the work W done by the force is Fx .

Take care when using $W = Fx$! The displacement x must be measured along the direction of the force.



Gravity pulls you down the slope, but the displacement in the direction of the force is x , not y ; $W = Fx$

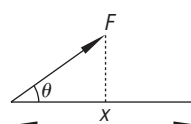
✓ Quick check 2, 3

work done = force $\times$ displacement *in the direction of the force* $W = Fx$

Although both force and displacement in a particular direction are vector quantities, their product (work done) is a scalar. Energy and work are both scalar quantities.

If the force acts at an angle to the distance moved, such that the angle between F and x is θ , we must consider the *component* of F in the direction of x . The equation for work done becomes:

work done $W = Fx \cos \theta$



Defining the joule

Since work done tells us how much energy is transferred by a force, both work and energy are measured in the same units, called **joules (J)**. The equation $W = Fx$ relates joules to newtons and metres.

1 joule = 1 newton $\times$ 1 metre; $1 \text{ J} = 1 \text{ N m}$

1 joule is the energy transferred when a force of 1 newton moves through 1 metre.

Equally, it is the energy transferred when a force of 0.5 N moves through 2 m, and so on. So, in fundamental units, $1 \text{ J} = 1 \text{ N m} = 1 \text{ kg m s}^{-2} \text{ m} = 1 \text{ kg m}^2 \text{ s}^{-2}$.

✓ Quick check 4

Energy conservation

Energy can take many different forms – thermal (heat), kinetic, gravitational potential, etc. It can be changed from one form to another, but the total amount always remains constant. This is the *principle of conservation of energy*:

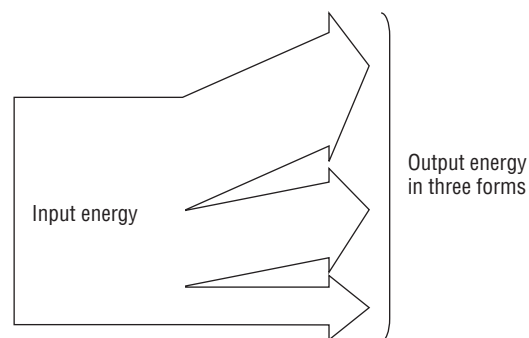
In a closed system, the total amount of energy remains constant.

This is represented in a *Sankey diagram* on the next page. The total width of the arrow remains constant, but it divides to show the proportions which change from one form to another.

Although energy cannot be created or destroyed, it can be wasted. In other words, when we change energy from one form to another, some may 'escape' in a form that we do not require and cannot use. (Usually this is heat, often it is sound.) The efficiency of an energy change tells us the fraction of the initial energy that ends up in useful forms, and is usually expressed as a percentage:

$$\text{efficiency} = \frac{\text{useful output energy}}{\text{total input energy}} \times 100\%$$

Note that efficiency is nearly always less than 100%, because heat energy is lost. (An electric heater could be considered to be 100% efficient.)



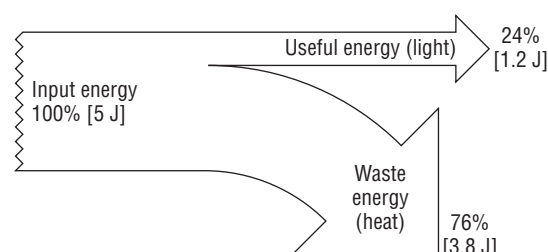
WORKED EXAMPLE

A **light-emitting diode (LED)** is supplied with 5.0 J of electrical energy each second, and produces 1.2 J of light energy and 3.8 J of heat energy. What is its efficiency?

STEP 1 Identify the useful output energy. In this case, it is light energy = 1.2 J

STEP 2 Calculate the efficiency.

$$\text{Efficiency} = \frac{1.2 \text{ J}}{5.0 \text{ J}} \times 100\% = 24\%$$



✓ Quick check 5

Power

Power, P , is the rate of doing work, or the rate of transferring energy:

$$\text{power} = \frac{\text{work done}}{\text{time taken}} \quad P = \frac{W}{t}$$

Power is measured in **watts, W**.

$$1 \text{ watt} = 1 \text{ joule per second} \quad 1 \text{ W} = 1 \text{ J s}^{-1}$$

$$1 \text{ kilowatt} = 1 \text{ kW} = 1000 \text{ J s}^{-1}$$

✓ Quick check 6, 7

QUICK CHECK QUESTIONS



- In the diagram at the top of the opposite page, gravity does 2500 J of work on the person as they fall. How much energy is transferred by this force?
- A car's engine provides a forward force of 500 N. It is opposed by a resistive force of 200 N. The car accelerates forwards for 20 m. How much work is done by each force? By how much does the car's energy increase?
- In the lower diagram on the opposite page, the person's weight F is 400 N and the distance they slide down the ramp is 8 m. If the angle of the slope to the horizontal is 30° , use the equation $W = Fx \cos \theta$ to calculate the work done by F in pulling them down the slope.
- Show that $1 \text{ J} = 1 \text{ kg m}^2 \text{ s}^{-2}$.
- A light bulb is supplied with 60.0 J of electrical energy each second. It produces 58.5 J of heat energy in this time. What is the efficiency with which it produces light?
- The engines of a light aircraft provide a power of 50 kW. How much energy do they transfer in 1 minute?
- Calculate the power of an engine which transfers 30 kJ in 1 minute.

Hint

Take care! The angle between F and x is not 30° .

Kinetic and potential energy

Key words

- kinetic energy
- gravitational potential energy

Two important forms of energy are **kinetic energy** (KE) and **potential energy** (PE). Potential energy may be due to the position of an object in a gravitational field (**gravitational potential energy**, GPE), or due to its shape (elastic potential energy, explained on page 26).

Kinetic energy

A moving object has kinetic energy E_k , which depends on its mass m and its velocity v . Like all forms of energy, KE is measured in joules (J).

To calculate KE, we use:

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

Notice that this has the correct units of $\text{kg m}^2 \text{s}^{-2}$.

■ WORKED EXAMPLE

A car of mass 800 kg is moving at 15 m s^{-1} . What is its KE?

Substituting in $E_k = \frac{1}{2}mv^2$ gives:

$$E_k = \frac{1}{2} \times 800 \times 15^2 = \frac{1}{2} \times 800 \times 225 = 90\,000 \text{ J}$$

Gravitational potential energy

When an object of weight mg is raised through a height h , work is done against gravity. The energy given to the object as a result is called its **gravitational potential energy** (GPE). This is increased by an amount E_p given by:

$$\text{gain in GPE} = \text{weight} \times \text{gain in height}; \quad E_p = mgh$$

An object's GPE increases as it moves upwards (h is positive) and decreases as it moves downwards (h is negative).

Note that the equation 'gain in GPE = weight $\times$ gain in height' is a form of the equation that defines *work done*, with force = weight and distance moved = gain in height.

✓ Quick check 1, 2

✓ Quick check 3, 4

KE and GPE changes

There are many situations where an object is moving up and down, and there is an interchange between KE and GPE. If no energy is lost as heat, we can assume that the change in KE is equal (and opposite) to the change in GPE. (This is an example of the principle of conservation of energy.)

We can write this as an equation,

$$E_k + E_p = \text{constant}$$

Hint

Air resistance results in the loss of energy as heat.

✓ Quick check 5

■ WORKED EXAMPLE

A stone falls from a height of 5 m. How fast is it moving when it reaches the ground?

STEP 1 The *decrease* in the stone's GPE as it falls is equal to its *gain* in KE.

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

STEP 2 Cancel m from both sides:

$$gh = \frac{1}{2}v^2$$

STEP 3 Substitute values and solve for v :

$$9.81 \text{ m s}^{-2} \times 5 \text{ m} = 0.5v^2$$

$$v^2 = 98.1 \text{ m}^2 \text{ s}^{-2}$$

$$v = 9.9 \text{ m s}^{-1}$$

Note that the fact that m cancels out means that we would get the same answer for any value of m , i.e. all stones of whatever mass would fall at the same rate (neglecting air resistance).

✓ Quick check 6, 7

QUICK CHECK QUESTIONS



- 1 A stone of mass 2 kg is moving at 20 m s^{-1} . What is its KE?
- 2 A car of mass 600 kg accelerates from 10 m s^{-1} to 20 m s^{-1} . By how much has its KE increased?
- 3 A car of mass 1000 kg is travelling at 20 m s^{-1} . What is its kinetic energy? It climbs a hill 200 m high. By how much does its gravitational potential energy increase?
- 4 An aircraft of mass 400 000 kg is travelling at a height of 8000 m. It increases its height to 9500 m. By how much does its GPE increase? (In this example, use $g = 10 \text{ m s}^{-2}$.)
- 5 As a stone falls, its GPE decreases by 20 J. By how much does its KE increase? What assumption is made in answering this question?
- 6 A rollercoaster car of mass 2000 kg runs downhill from a stationary start. If it runs downwards through a vertical height of 25 m, calculate its KE and speed at the foot of the hill. (Assume there are no frictional energy losses.)
- 7 A stone falls 5 m under gravity. Assuming that 2% of its energy is lost due to air resistance, with what speed is it moving at the lowest point of its fall?

Hint

Calculate the two values of KE, and subtract.

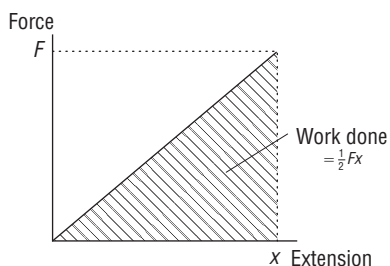
Key words

- tensile
- compressive
- elastic limit
- force constant
- elastic potential energy
- stress
- strain
- Young modulus

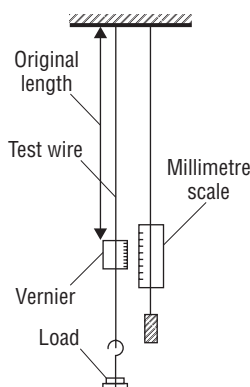
Hint

You may find 'stiffness' easier to remember than 'force constant'.

Quick check 1



Quick check 2, 3

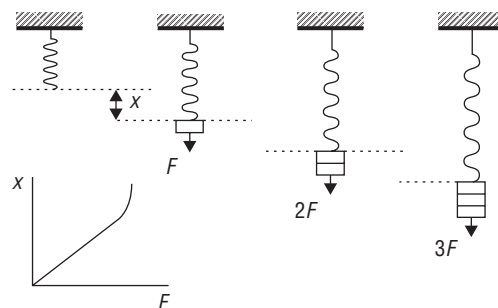


It takes a pair of forces to *stretch* a solid object; such forces are called **tensile**. Forces which *squash* an object are called **compressive**. Tensile forces can stretch and break an object. It is easiest to start by describing how a spring stretches.

Hooke's law

The greater the **load** (the force stretching the spring), the greater its **extension** (increase in length). Eventually the load is so great that the spring becomes permanently stretched. The graph shows two things:

- At first the graph is a straight line, so load F is proportional to extension x ; $F \propto x$.
- Beyond the **elastic limit**, the spring does not return to its original length when the load is removed.



The proportionality can be turned into an equation; the constant of proportionality is called the **force constant** k .

$$F = kx$$

k is measured in N m^{-1} . It is sometimes known as the *stiffness* of the spring. k tells you how many newtons are needed to stretch the spring by 1 metre.

Elastic potential energy

An object that is stretched or compressed elastically is a store of **elastic potential energy**. The area under a force–extension graph is equal to the work done by the force. For a spring when the load is less than the elastic limit, the area under the graph is $\frac{1}{2} \times \text{force} \times \text{distance}$; this tells you the work done in stretching the spring, which is known as the elastic potential energy. This can be calculated as follows:

$$\text{Elastic potential energy} = \frac{1}{2} Fx = \frac{1}{2} kx^2$$

Stretching a wire

Measure the original length of the test wire using a metre rule; measure its diameter using a micrometer, and calculate its cross-sectional area.

Gradually increase the load on the test wire. For each load, note the reading from the vernier scale.

Calculate values of stress and strain from values of load and extension, and plot a stress–strain graph.

The extension x of the wire depends on four factors:

- its original length l ,
- the load F stretching it,
- the cross-sectional area A ,
- the stiffness of the material of which it is made.

These are combined as follows:

$$\text{strain} = \frac{\text{extension}}{\text{original length}} \quad \text{strain} = \frac{x}{l}$$

$$\text{stress} = \frac{\text{load}}{\text{area}} \quad \text{stress} = \frac{F}{A}$$

The greater the stress, the greater the strain that results. For many materials:

$$\frac{\text{stress}}{\text{strain}} = \text{constant}$$

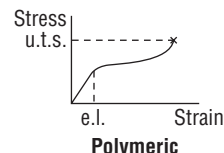
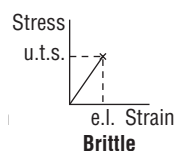
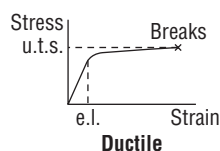
and this constant is known as the **Young modulus**, Y , of the material. Y is measured in N m^{-2} or *pascals* (Pa). Its value is typically expressed in MPa or GPa (millions or billions of pascals); 1 MPa = 1 megapascal = 10^6 Pa; 1 GPa = 1 gigapascal = 10^9 Pa.

$$\text{Young modulus} = \frac{\text{stress}}{\text{strain}}$$

Stress–strain graphs

For low stresses, below the elastic limit (e.l.), the material will return to its original length when the load is removed. This is **elastic deformation**. For higher stresses, the material becomes permanently deformed. This is **plastic deformation**.

The Young modulus is the gradient of the *initial* (straight line) part of the graph. Once the stress reaches its highest value (the **ultimate tensile strength**, u.t.s.) the material will break.



Materials may be classified as follows:

- A **ductile** material stretches a lot beyond the elastic limit, e.g. copper.
- A **brittle** material snaps when it reaches the elastic limit, e.g. glass.
- A **polymeric** material does not show linear behaviour, e.g. polyethene.

✓ Quick check 5

QUICK CHECK QUESTIONS



- 1 A spring is 1.2 m long when unstretched, and 1.4 m long when a load of 50 N is applied. Its elastic limit is 80 N. Calculate the extension produced by the 50 N load, and the spring's stiffness (force constant).
- 2 A spring is stretched elastically by a force of 400 N so that its length increases from 2.0 m to 2.4 m. Calculate the elastic potential energy stored.
- 3 A spring of force constant $k = 2400 \text{ N m}^{-1}$ is stretched by 5.0 cm. Calculate the elastic potential energy stored.
- 4 A stress of 20 MPa is applied to a wire of Young modulus 10 GPa. What strain is produced? If the wire's initial length was 0.8 m, what extension does the stress produce?
- 5 The table shows stress–strain data for an iron wire. Use the data to plot a stress–strain graph; deduce the Young modulus for iron; and state whether the wire shows plastic or brittle behaviour.

stress/MPa	0	50	100	150	200	250
strain (%)	0	0.025	0.050	0.075	0.100	wire breaks

Hint

You can think of stress as the same as pressure; each is a force divided by an area.

Examiner tip

You may be asked to describe how you would determine the Young modulus of a metal in the form of a wire.

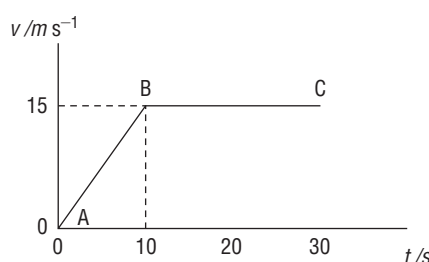
✓ Quick check 4

End-of-unit questions

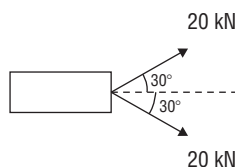
See Appendix 3 on page 79 for data and equations provided in the examination.

Module 1: Motion

- 1
 - a A quantity may be either a scalar or a vector quantity. Define *scalar* and *vector*.
 - b Which of the following quantities are vectors, and which are scalars?
Force, velocity, distance, acceleration, kinetic energy, power.
- 2
 - a Write down a word equation that defines acceleration.
 - b The graph shows how the velocity of a car varied during the first part of a journey. Determine the car's acceleration during the parts of the journey represented by AB and BC.



- c Copy the graph and add to it to indicate how you would expect the car's velocity to change if it was involved in a sudden collision with a brick wall.
- 3 The diagram shows a heavy load being dragged by two tractors. The tension in each cable is 20 kN.



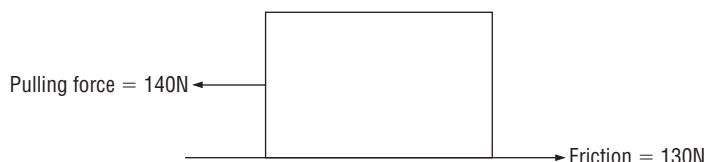
Draw a vector triangle and use it to find the resultant of these two forces.

- 4 A car is travelling at 10 m s^{-1} . The driver accelerates at a rate of 2 m s^{-2} for 6 s.
 - a How far does the car travel during this time?
 - b What speed will it reach?
- 5 A boy stands on the edge of a cliff. He throws a stone upwards so that it leaves his hand, 2.0 m above the clifftop, with an initial velocity of 8.0 m s^{-1} . It rises upwards and then falls vertically downwards to the foot of the cliff. (You may assume that air resistance is negligible throughout the stone's motion.)
 - a Calculate the greatest height to which the stone will rise (above the point where it leaves the boy's hand).
 - b If the cliff is 20 m high, calculate the stone's vertical velocity when it reaches the foot of the cliff.
 - c What is the stone's average velocity during its motion?
 - d How much time elapses between the moment when the stone leaves the boy's hand and when it reaches the foot of the cliff?

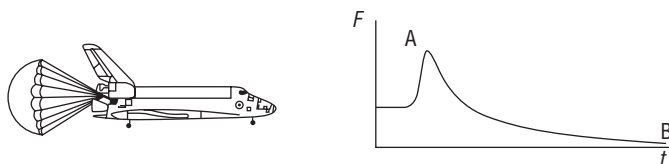
- 6 Describe an experiment to measure the acceleration of free fall g , using a falling object. State the measurements you would make and how you would deduce the value of g from them.

Module 2: Forces in action

- 7 A box is being pulled along level ground. The diagram shows the horizontal forces acting on the box.



- Calculate the resultant force acting on the box.
 - If the mass of the box is 40 kg, what is its acceleration?
 - If the volume of the box is 0.05 m^3 , what is its density?
 - The area of the box in contact with the ground is 0.12 m^2 . What pressure does it exert on the ground?
- 8
- State the SI unit of force.
 - Write an equation to show how this unit is related to the kilogram, metre and second (three of the base units of the SI system).
- 9 When the space shuttle comes in to land, it deploys a parachute to slow it down. The graph shows how the horizontal force F on the shuttle varies with time t .

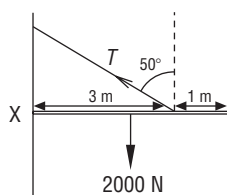


- The parachute is deployed at point A on the graph. Explain why the force on the shuttle decreases in the region AB.
 - Copy the graph. On the same axes, add a further line to show how the shuttle's velocity changes.
- 10
- 'The gravitational field strength g at the Earth's surface is 9.81 N kg^{-1} .' Explain what is meant by this statement.
 - An astronaut measures his weight on Earth as 882 N. He travels to the surface of Mars, where the gravitational field strength is 3.8 N kg^{-1} . What will be the values of his mass and weight on Mars?
 - Show that 9.81 N kg^{-1} is the same as 9.81 m s^{-2} .

Examiner tip

If you are asked to 'State ...', give a concise answer without any supporting argument or description.

- 11 a** With the aid of a diagram, explain what is meant by the moment of a force. The diagram shows a diving board that projects horizontally from point X. Its weight (2000 N) acts halfway along its length, as shown. It is supported by a cable attached 1 m from the far end, which makes an angle of 50° with the vertical.



- b** Calculate the moment of the board's weight about point X.
- c** Show that the tension T in the cable must be 2074 N if its moment is to counteract the moment of the board's weight.
- 12** Police investigating a road accident discover that one of the cars has bald tyres; most of the tread has been worn away. They suggest to the driver that he should have noticed problems when he attempted to make the car accelerate.
- a** The driver claims that he was travelling at 20 m s^{-1} when he braked. The police say that he should have been able to stop in a distance of 40 m if his tyres had been roadworthy. What would the driver's deceleration have been if he had stopped in this distance?
- b** Police tests show that the driver's bald tyres could not have provided a deceleration greater than 2 m s^{-2} . What braking distance would be required if the car was travelling at 20 m s^{-1} ?
- c** The driver was saved from serious harm in the accident because his car was fitted with an air bag. Explain how this can reduce the impact force in a collision.

Hint

See Examiner tip on page 21.

Module 3: Work and energy

- 13** An aircraft of mass $100 \times 10^3 \text{ kg}$ is moving at 150 m s^{-1} . It reduces its height above the ground from 5000 m to 3000 m and increases its speed to 200 m s^{-1} . Calculate the change in its gravitational potential energy, and in its kinetic energy.
- 14** An experiment is conducted on a rubber cord of unstretched length 2.0 m. The cord has a rectangular cross-section of dimensions 0.5 mm by 5 mm. The cord is hung vertically and a weight of 100 N attached to its lower end. Its length increases to 2.4 m. Calculate:
- a** the stress in the cord
- b** the strain
- c** the Young modulus of the rubber.

- 15** A spring is stretched by hanging increasing weights on its end, and its length is measured for each value of the load. The table shows the results.

load (N)	0	10	20	30	40
length (m)	0.060	0.062	0.064	0.066	0.068

- a** Plot a suitable graph and use it to determine the force constant of the spring.
- b** The final load of 40 N does not exceed the spring's elastic limit. Explain what is meant by *elastic limit*.
- c** Use the graph to calculate the strain energy stored when the spring is stretched by the 40 N load.
- 16 a** Sketch a force–extension graph for a ductile material.
- b** Indicate the regions in which you would expect its behaviour to be elastic, and where it will be plastic.
- c** State the essential difference between elastic and plastic deformation of a solid material.

Examiner tip

In an examination you may be expected to plot a graph on a grid printed in the exam booklet.

The axes may be labelled and units given, but if not, choose suitable scales and label the axes fully.

Examiner tip

If you are asked to sketch a graph, the shape and position of the curve need to be correct. Label the axes if they are not already labelled for you.