Edexcel International A Level (IAL) Physics

Your notes

Work, Energy & Power

Contents

Your notes

Work

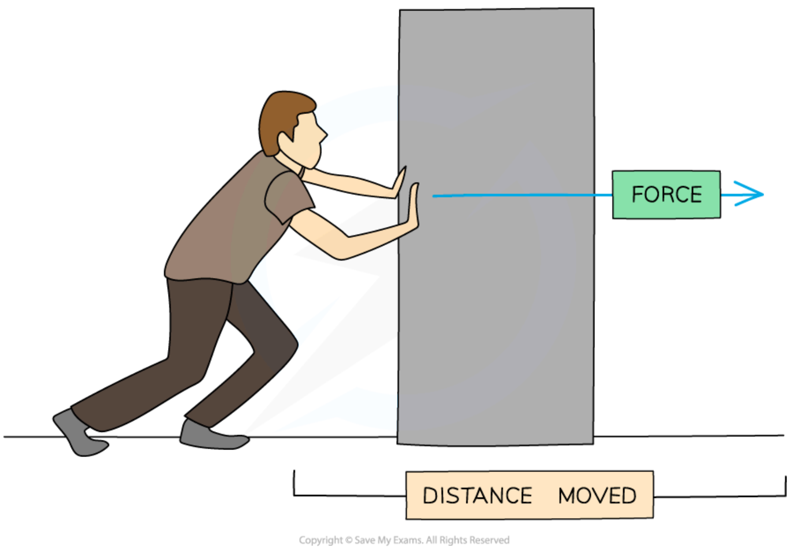
- Work is defined as

The amount of energy transferred when an external force causes an object to move over a certain distance

- If the force is **parallel** to the direction of the object's displacement, the work done can be calculated using the equation:

$$\Delta W = F \Delta s$$

- Where:
  - ΔW = change in work done (J)
  - F = average force applied in the **direction of the motion** (N)
  - s = displacement (m)
- Force in the **direction of the motion** means that when a force is applied at an angle, the **component** in the direction of motion is used in the calculation
- In the diagram below, the man's pushing force on the block is doing work as it is transferring energy to the block



Work is done when a force is used to move an object over a distance

- When pushing a block, **work is done against friction** to give the box kinetic energy to move
  - The kinetic energy is transferred to other forms of energy, such as heat and sound

- Usually, if a force acts **in** the direction that an object is moving, then the object will **gain energy**
- If the force acts in the **opposite** direction to the movement, then the object will **lose energy**

Calculating with Force at an Angle

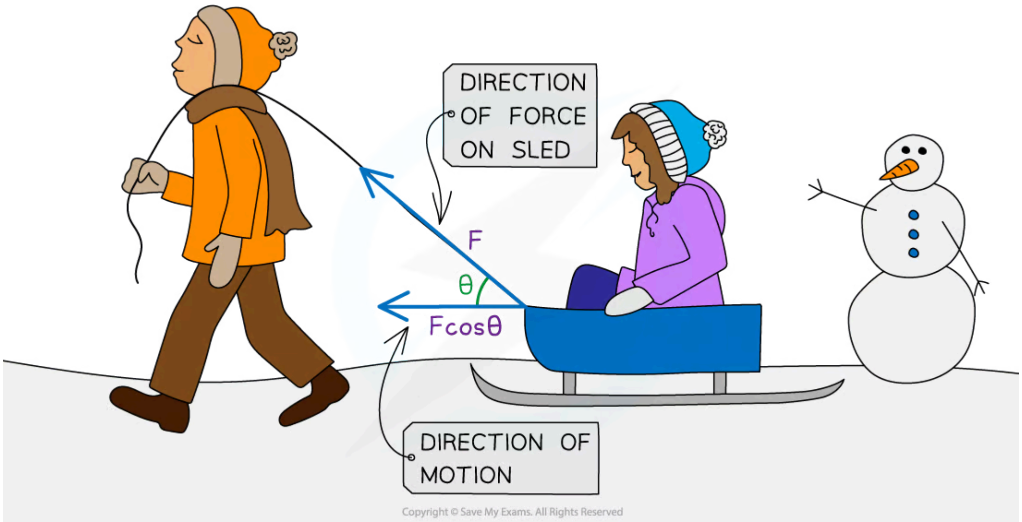
- Sometimes the direction of motion of an object is not parallel to the direction of the force
- If the force is at an angle θ to the object's displacement, the work done is calculated by:

$$W = Fs\cos\theta$$

or

$$W = Fs\sin\theta$$

- Where
  - θ = the angle, in degrees, between the direction of the force and the motion
- When the angle is between the force and the horizontal, use cosine
- When the angle is between the force and the vertical, use sine
  - The component needed is the one that is **parallel to the displacement**



When the force is at an angle, only the component of the force in the direction of motion is considered for the work done

Worked Example

The diagram shows a barrel of weight 2.5×10^3 N on a frictionless slope inclined at 40° to the horizontal.

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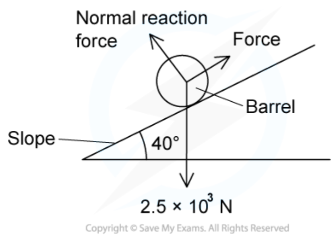


A force is applied to the barrel to move it up the slope at a constant speed. The force is parallel to the slope.

What is the work done in moving the barrel a distance of 6.0 m up the slope?

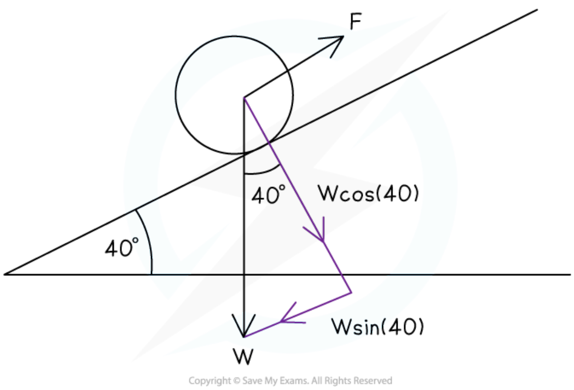
Answer:

Step 1: Write the known values from the question

- Force acting downwards, $F = 2.5 \times 10^3$ N
- Angle of the slope, $\theta = 40°$
- Displacement, s = 6.0 m

Step 2: Find the force in the direction of motion by resolving the forces

- Draw a diagram, showing the weight acting downwards
- Resolve the weight into two components
- The first component is parallel to the slope - the same as the direction of the motion; this is **W sin θ**
- The second is at right angles to the slope, showing the normal reaction force (this component, **W cos θ** is not used in this answer)



Force acting along the slope, $F = W \sin 40°$

$$F = 2.5 \times 10^3 \times \sin 40° = 1607 \text{ N}$$

Step 3: Write the equation for work done and substitute in the values

$$\Delta W = F \Delta s$$

$$\Delta W = 1607 \times 6.0 = 9642 \text{ J}$$

Your notes

Step 4: Give the answer to the correct number of significant figures

$$\Delta W = 9600 \text{ J or } 9.6 \times 10^3 \text{ J}$$

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Examiner Tips and Tricks

A common exam mistake is choosing the incorrect force which is not parallel to the direction of movement of an object.

You may have to resolve the force vector first in order to find the correct, parallel component.

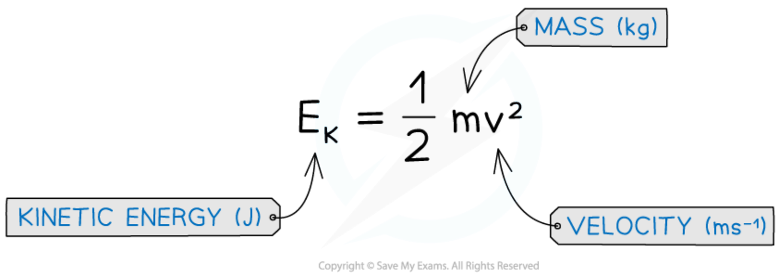
The applied force does **not** have to be in the same direction as the movement, as shown in the worked example. In fact, in most cases, we apply a force at an angle to move something, because it saves us having to lean down to the height of whatever we are pulling or pushing!

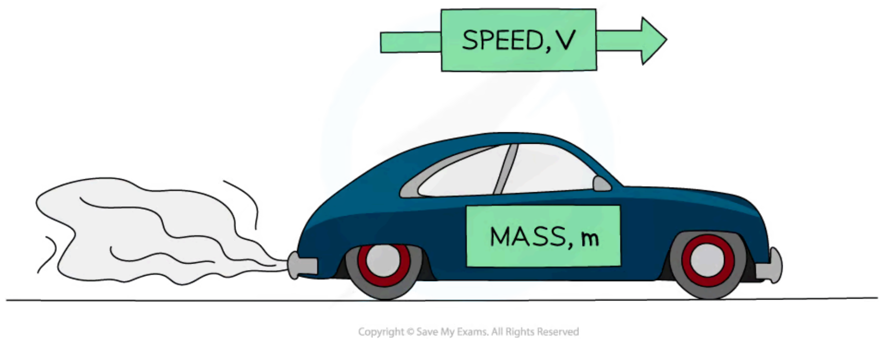
Kinetic Energy

Your notes

Kinetic Energy

- Kinetic energy (usually written E_k and sometimes KE) is the energy an object has due to its **motion** (or velocity)
  - The faster an object moves, the greater its kinetic energy
- When an object is falling, it is **gaining** kinetic energy since it is gaining speed
  - This energy transferred from the gravitational potential energy it is losing
  - An object will maintain this kinetic energy unless its speed changes
- Kinetic energy can be calculated using the following equation:





Kinetic energy (KE): The energy an object has when it is moving

Derivation of Kinetic Energy Equation

- A force can make an object accelerate; work is done by the force and energy is transferred to the object
- Using this concept of work done and an equation of motion, the extra work done due to an object's speed can be derived
- The derivation for this equation is shown below:

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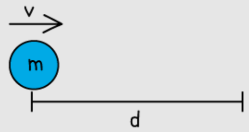
Derivation of $KE = \frac{1}{2}mv^2$

CONSIDER A MASS m AT REST WHICH ACCELERATES TO A SPEED v OVER A DISTANCE d



WORK DONE IN ACCELERATING THE MASS

$$W = F \times d$$

AND $F = ma$ FROM NEWTON'S SECOND LAW

RECALL THE SUVAT EQUATION

$$v^2 = u^2 + 2as$$

IF $u = 0$ AND $s = d$

$$v^2 = 2ad$$

REARRANGING FOR a

$$a = \frac{v^2}{2d}$$

SUBSTITUTE BACK INTO $F = ma$

$$F = ma = \frac{mv^2}{2d}$$

SUBSTITUTE THIS FORCE F INTO THE WORK DONE EQUATION

$$W = \frac{mv^2}{2d} \times d = \frac{1}{2}mv^2$$

THE MASS IS NOW ABLE TO DO EXTRA WORK $= \frac{1}{2}mv^2$ DUE TO ITS SPEED

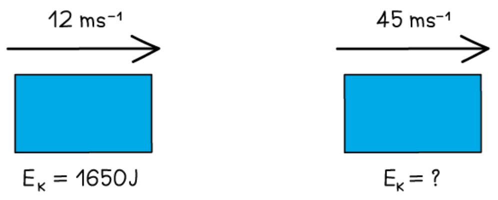
IT HAS KINETIC ENERGY $= \frac{1}{2}mv^2$

Worked Example

A body travelling with a speed of 12 m s^{-1} has kinetic energy 1650 J.

If the speed of the body is increased to 45 m s^{-1}, estimate its new kinetic energy.

Answer:



STEP 1 EQUATION FOR KINETIC ENERGY

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

STEP 2 MASS WILL NOT CHANGE, SO CAN BE CALCULATED FROM ITS INITIAL KINETIC ENERGY

REARRANGE FOR MASS m

$$m = \frac{2 \times KE}{v^2} = \frac{2 \times 1650}{12^2} = 23 \text{ kg}$$

STEP 3 SUBSTITUTE INTO KINETIC ENERGY EQUATION

USING VALUE OF MASS AND NEW VALUE OF VELOCITY

$$E_K = \frac{1}{2} \times 23 \times 45^2 = 23000 \text{ J} \quad (2 \text{ s.f})$$

Examiner Tips and Tricks

When using the kinetic energy equation, note that only the speed is squared, not the mass or the ½.

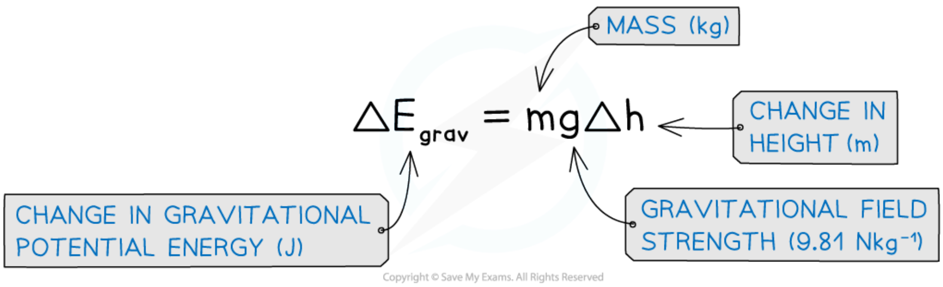
If a question asks about the 'loss of kinetic energy', remember **not** to include a negative sign since energy is a **scalar** quantity.

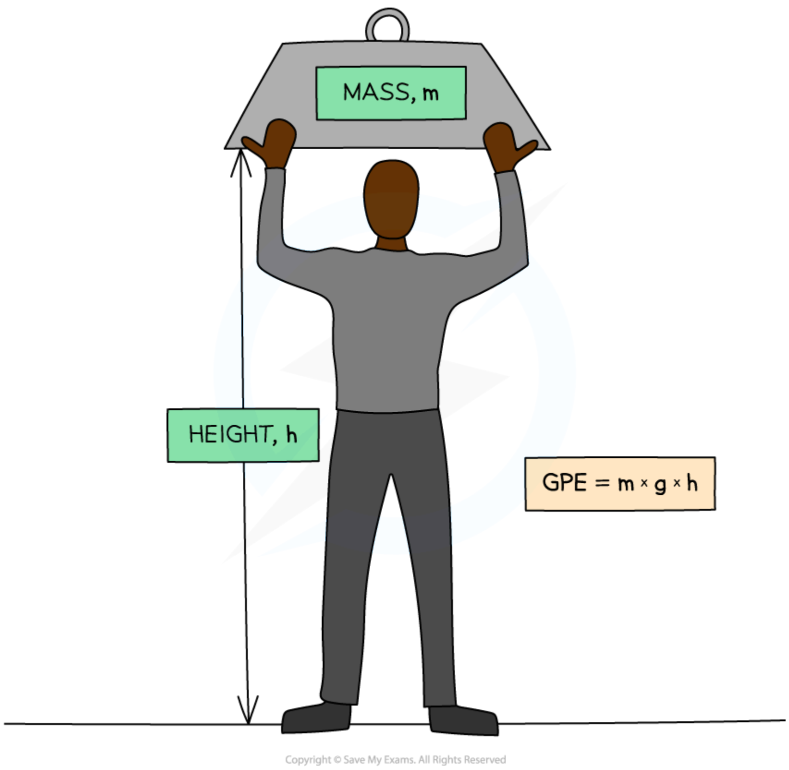
Your notes

Your notes

Gravitational Potential Energy

- Gravitational potential energy (usually written E_p, but sometimes GPE) is energy stored in a mass due to its position in a gravitational field
  - If a mass is **lifted** up, it will **gain** E_p (converted **from** other forms of energy)
  - If a mass **falls**, it will **lose** E_p (and be converted **to** other forms of energy)
- The equation for gravitational potential energy for energy changes in a **uniform gravitational field** is:



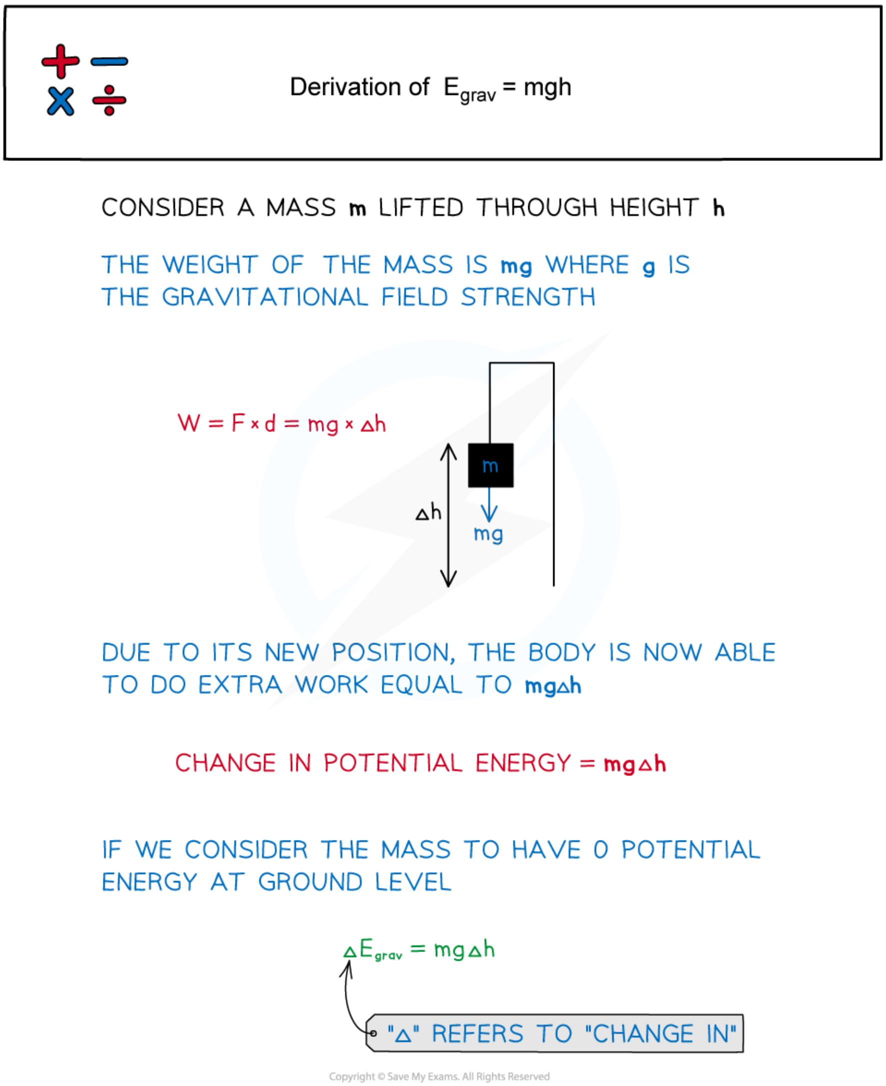


Gravitational potential energy (GPE): The energy an object has when lifted up

- The potential energy on the Earth's surface at ground level is taken to be equal to 0
- This equation is only relevant for energy changes in a **uniform gravitational field** (such as near the Earth's surface)

Derivation of GPE Equation

- When a heavy object is lifted, work is done since the object is provided with an upward force against the downward force of gravity
  - Therefore, **energy is transferred to the object**
- This equation can therefore be derived from the work done



Worked Example

To get to his apartment a man has to climb five flights of stairs.

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The height of each flight is 3.7 m and the man has a mass of 74 kg.

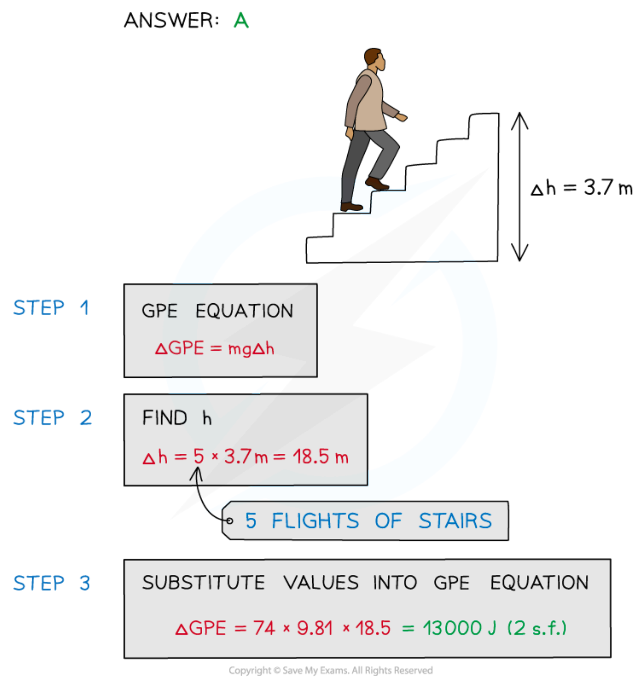
What is the approximate gain in the man's gravitational potential energy during the climb?

A. 13 000 J

B. 2700 J

C. 1500 J

D. 12 500 J



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Examiner Tips and Tricks

Gravitational potential energy questions often use falling objects, where you are expected to realise that, since energy is conserved, the gravitational potential energy **at the start** is equal to the kinetic energy **at the end**.

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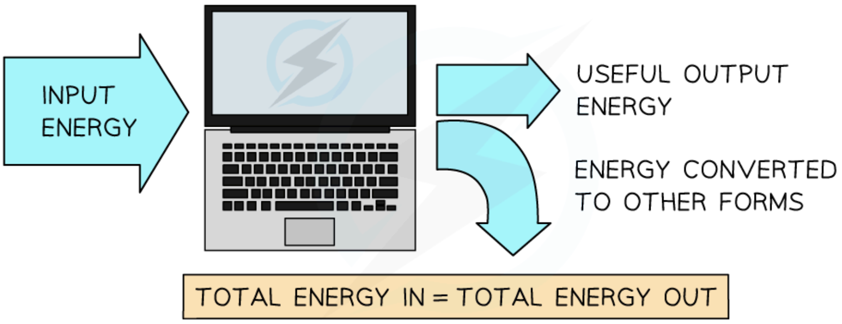
The Principle of Conservation of Energy

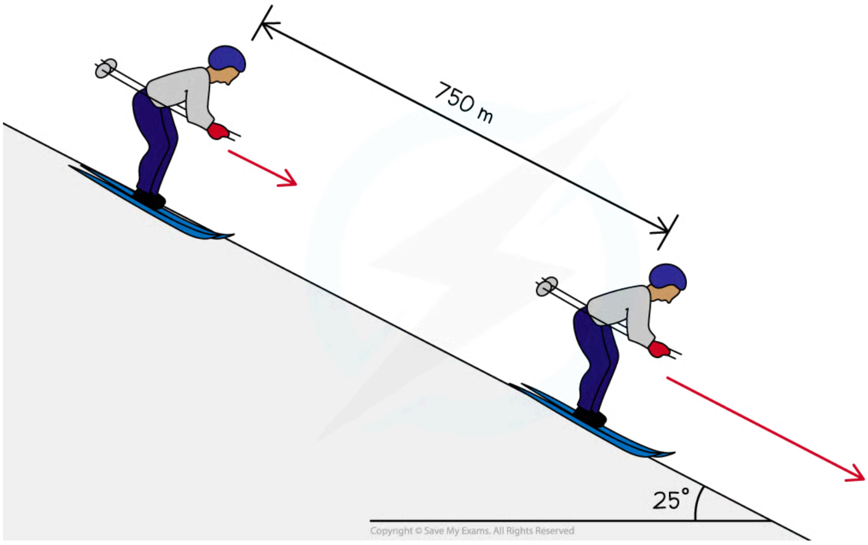
- The principle of conservation of energy is a law of Physics which always applies to a closed system



- To apply conservation of energy, heat losses are usually ignored during the calculation stage
- In reality there are always some energy losses from the system
  - These should be mentioned when comparing calculated, ideal values to real-life situations
- Conservation of energy is often applied in questions about exchanges between **kinetic energy** and **gravitational energy**
- Common examples include:
  - A swinging pendulum
  - Objects in free fall
  - Sports such as skiing or skydiving where gravity is causing motion and few drag forces apply
- The gravitational potential energy stored initially is transferred to kinetic energy, or vice versa
- This allows either;
  - Final velocity to be found from the distance the object moved, or
  - Height of a drop from the final velocity

Worked Example

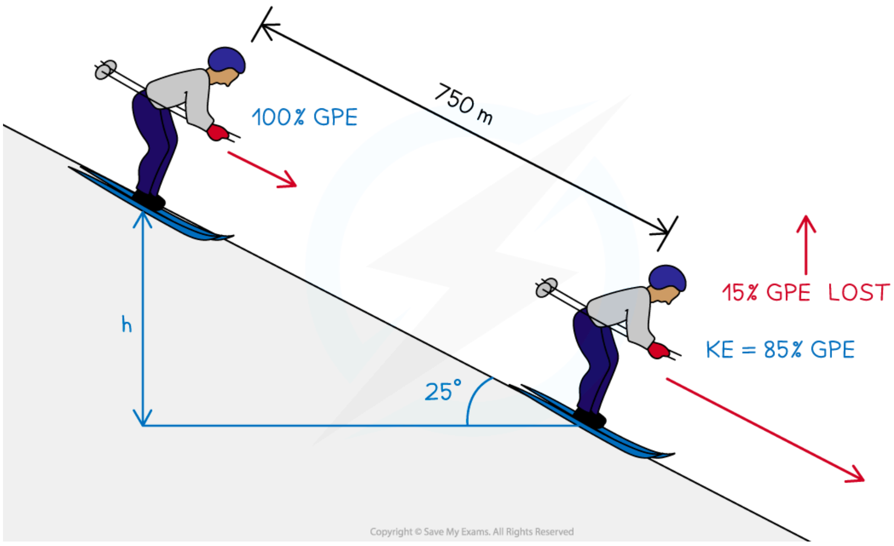
The diagram below shows a skier on a slope descending 750 m at an angle of 25° to the horizontal.



Calculate the final speed of the skier, assuming that he starts from rest and 15% of his initial gravitational potential energy is **not** transferred to kinetic energy.

Answer:

Step 1: Write down the known quantities



- Vertical height, h = 750 sin 25°
- $E_k = 0.85\ E_p$

Step 2: Equate the equations for E_k and E_{grav}

$$E_k = 0.85\ E_{grav}$$

$$½\ mv^2 = 0.85 \times mgh$$

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Step 3: Rearrange for final speed, *v*

$$\frac{1}{2}\cancel{m}v^2 = 0.85 \times \cancel{m}gh$$

$$v^2 = 0.85 \times 2gh$$

$$v = \sqrt{0.85 \times 2gh}$$

Step 4: Calculate the final speed, *v*

$$v = \sqrt{0.85 \times 2 \times 9.81 \times 750 \sin 25°} = 72.7$$

$$\text{Final speed, } v = 73 \text{ m s}^{-1}$$

Examiner Tips and Tricks

Gravitational energy:

- This equation only works for objects close to the Earth's surface where we can consider the gravitational field to be uniform.

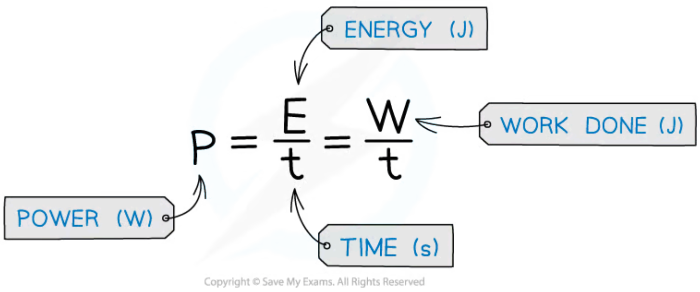
Kinetic energy:

- When using the kinetic energy equation, note that only the speed is squared, not the mass or the ½.
- If a question asks about the 'loss of kinetic energy', remember **not** to include a negative sign since energy is a scalar quantity.

Your notes

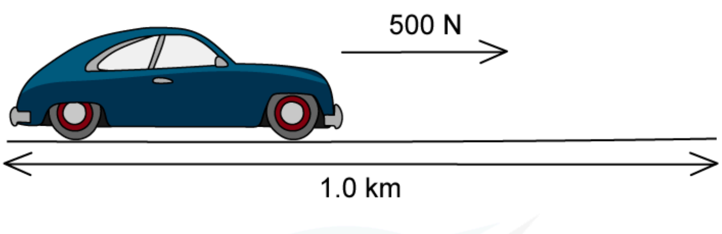
Power

- The power of a mechanical process is the **rate at which energy is transferred**
  - Since work done is equal to the energy transferred, power can also be defined as the rate of doing work or **the work done per unit time**
- Power is measured in **Watts (W)**
  - Since power is energy used per unit time, **1 W = 1 J s^{-1}**
- Power can be calculated using the equation:



Worked Example

A car engine exerts the following force for 1.0 km in 200 s.



Determine what is the average power developed by the engine.

Answer:

Your notes

STEP 1

EQUATION FOR POWER

$$\text{POWER} = \frac{\text{WORK DONE}}{\text{TIME}}$$

STEP 2

CALCULATE WORK DONE

$$W = F \times d$$

$$= 500\ \text{N} \times 1.0 \times 10^3\ \text{m}$$

$$= 5 \times 10^5\ \text{J}$$

STEP 3

SUBSTITUTE VALUES INTO POWER EQUATION

$$\text{POWER} = \frac{5 \times 10^5\ \text{J}}{200\text{s}} = 2500\ \text{W} = 2.5\ \text{kW}$$

Examiner Tips and Tricks

Power is also used in electricity, with labels on lightbulbs which indicate their power, such as 60 W or 100 W, which indicate the amount of energy transferred by an electrical current rather than by a force doing work. Just remembering 'energy per unit time' will help, as it doesn't matter what kind of energy is being transferred.

When working with power equations the numbers are often very large, so expect to see kW, MW and even GW in questions.

(In case you forgot... ***kW*** means × 10^3. ***MW*** means × 10^6, and ***GW*** means × 10^9. If you weren't sure, go and revise S.I. Units!)

Efficiency

- The efficiency of a system is a measure of how well energy is transferred in a system
- Efficiency is defined as:

  The ratio of the useful power or energy transfer output from a system to its total power or energy transfer input

- If a system has **high** efficiency, this means most of the energy transferred is **useful**
- If a system has **low** efficiency, this means most of the energy transferred is **wasted**
- Determining which type of energy is useful or wasted depends on the system
  - When electrical energy is converted to light in a lightbulb, the light energy is **useful** and the heat energy produced is **wasted**
  - When electrical energy is converted to heat for a heater, the heat energy is **useful** and the sound energy produced is **wasted**
- Efficiency can be given as a ratio (between 0 and 1) or a percentage (between 0 and 100%)
- Since efficiency is a ratio, it has **no units**
- Calculate energy efficiency and power efficiency in the same way, using one of the following equations;

$$\text{EFFICIENCY} = \frac{\text{USEFUL ENERGY OUTPUT}}{\text{TOTAL ENERGY INPUT}} \times 100\%$$

- The energy can be of any form e.g. gravitational potential energy, kinetic energy

$$\text{EFFICIENCY} = \frac{\text{USEFUL POWER OUTPUT}}{\text{TOTAL POWER INPUT}} \times 100\%$$

- Where power is defined as the energy transferred per unit of time

$$\text{Power} = \frac{\text{Energy transferred}}{\text{Time}} = \frac{E}{t}$$

Your notes

Worked Example

An electric motor has an efficiency of 35 %. It lifts a 7.2 kg load through a height of 5 m in 3 s.

Calculate the power of the motor.

Answer:

Step 1: Write down the efficiency equation

$$\text{Efficiency} = \frac{\text{Power output}}{\text{Power input}} \times 100$$

Step 2: Rearrange for the power input

$$\text{Power input} = \frac{\text{Power output} \times 100}{\text{Efficiency}}$$

Step 3: Calculate the power output

- The power output is equal to energy ÷ time
- The electric motor transferred electric energy into gravitational potential energy to lift the load

Gravitational potential energy = mgh = 7.2 × 9.81 × 5 = 353.16 J

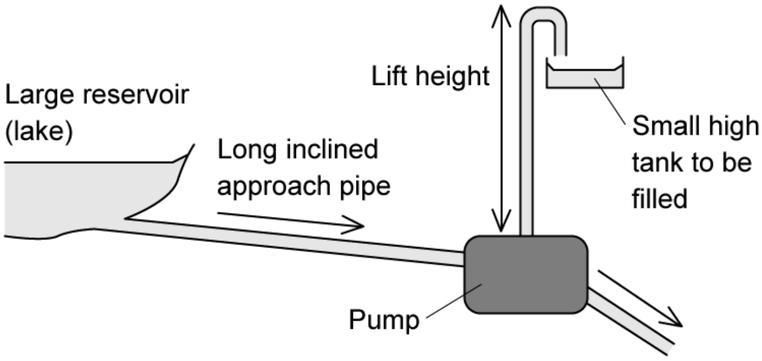
Power = 353.16 ÷ 3 = 117.72 W

Step 4: Substitute values into power input equation

$$\text{Power input} = \frac{117.72 \times 100}{35} = 336 \text{ W}$$

Worked Example

The diagram shows a pump called a hydraulic ram.



In one such pump, the long approach pipe holds 700 kg of water. A valve shuts when the speed of this water reaches 3.5 m s^{-1} and the kinetic energy of this water is used to lift a small quantity of water by height of 12m.

The efficiency of the pump is 20%.

Determine the mass of water which could be lifted 12 m

Answer:

Step 1: Identify the energy conversions and write them in an equation

- The kinetic energy of the moving water is converted to gravitational potential energy as it is lifted
- The equation should be that;

$$initial\ E_k = final\ E_{grav} \rightarrow \frac{1}{2}mv^2 = mg\Delta h$$

Step 2: Include the efficiency in the equation

- Efficiency = 20% meaning 20% of the kinetic energy is converted;

$$0.2 \times \frac{1}{2}mv^2 = mg\Delta h$$

Step 3: Substitute in the values and calculate

$$0.2 \times \frac{1}{2} \times 700 \times (3.5^2) = m \times 9.81 \times 12$$

$$857.5 = 117.72\ m$$

$$m = 7.284$$

Step 4: Write the answer with the correct significant figures and units

- Mass of water lifted, m = 7.3 kg (2 s.f.)

Your notes

Your notes

Examiner Tips and Tricks

In efficiency calculations decide **before starting** where the energy is lost from the system.

In the example above, the pump is what converts the water's **kinetic energy** into **gravitational potential energy**, and it is the pump whose efficiency we are given. That means the losses are from the kinetic energy.

Don't just calculate then deduct the efficiency at the end - this can lead to lots of work for no marks. Which isn't very efficient!