OCR A Level Physics

Your notes

Work, Energy & Power

Contents

Work Done

Your notes

Work Done

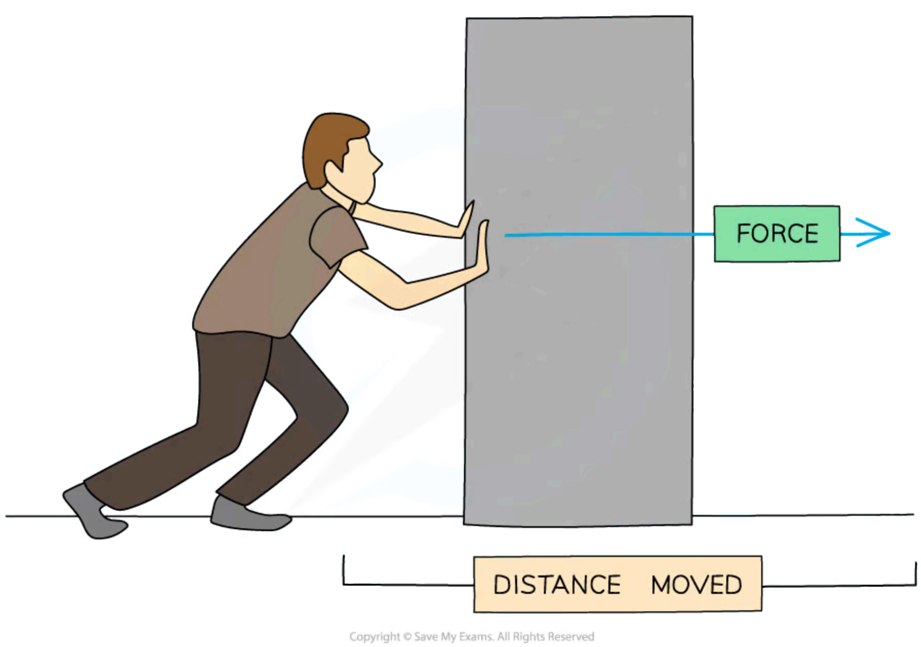
- Work is defined as

  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:

$$W = Fx$$

- Where:
  - W = work done (J)
  - F = average force applied (N)
  - x = displacement (m)
- 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**

Your notes

The Joule

- The Joule, *J*, is commonly used as the unit of energy or work
- The SI unit for energy is kg m^2 s^{-2}
- One joule is defined as:

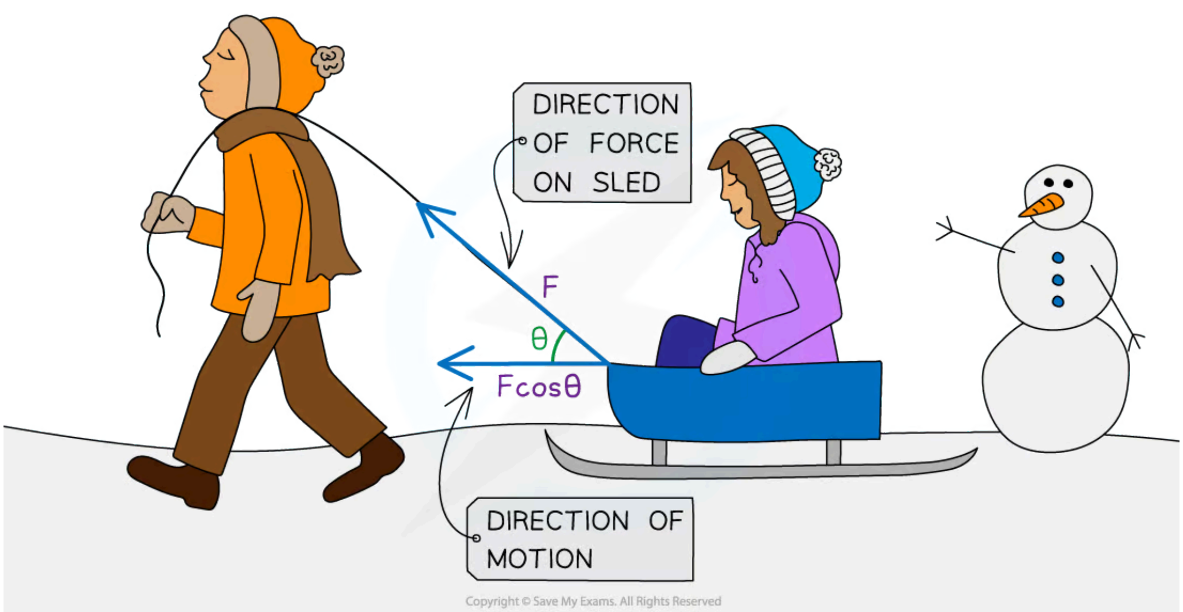
  The energy transferred to (or work done on) an object when a force of 1 N acts on that object parallel to its motion through a distance of 1 m

Work Done Equation

- 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:

$$W = Fx \cos \theta$$

- Where θ is the angle, in degrees, between the direction of the force and the motion
  - When θ is 0 (the force is in the direction of motion) then cos θ = 1 and $W = Fx$
- This may not always be cos θ, since this is just for horizontal motion
- For vertical motion, it would be sin θ
  - Always consider the horizontal and vertical components of the force
  - 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

Your notes

Worked Example

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

A. 7.2×10^3 J

B. 2.5×10^4 J

C. 1.1×10^4 J

D. 9.6×10^3 J

ANSWER: D

STEP 1

WORK DONE EQUATION

$W = F \times d$

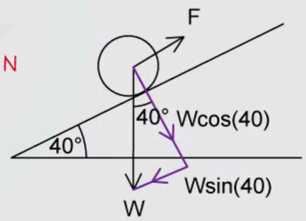
STEP 2

CALCULATE THE FORCE IN THE DIRECTION OF TRAVEL

THE FORCE NEEDED TO PUSH THE BARREL NEEDS TO OVERCOME THE COMPONENT OF THE BARREL'S WEIGHT. SINCE THE FORCE IS PARALLEL TO THE SLOPE, THE COMPONENT OF THE WEIGHT WE NEED IS THE ONE PARALLEL TO THE SLOPE.

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

THIS IS THE FORCE IN THE SAME DIRECTION AS THE DISPLACEMENT



STEP 3

SUBSTITUTE F AND d INTO THE WORK DONE EQUATION

$W = 1607\ \text{N} \times 6.0\ \text{m} = 9.6 \times 10^3\ \text{J}$

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 component that is parallel. The force does **not** have to be in the same direction as the movement, as shown in the worked example.

Your notes

Conservation of Energy

Your notes

The Principle of Conservation of Energy

- The Principle of Conservation of Energy states that:

  Energy cannot be created or destroyed, it can only be transferred from one form to another

- This means the total amount of energy in a closed system remains constant, although how much of each form there is may change

Types of Energy

FORM	WHAT IS IT?
KINETIC	THE ENERGY OF A MOVING OBJECT.
GRAVITATIONAL POTENTIAL	THE ENERGY SOMETHING GAINS WHEN YOU LIFT IT UP, AND WHICH IT LOSES WHEN IT FALLS.
ELASTIC	THE ENERGY OF A STRETCHED SPRING OR ELASTIC BAND.(SOMETIMES CALLED STRAIN ENERGY)
CHEMICAL	THE ENERGY CONTAINED IN A CHEMICAL SUBSTANCE.
NUCLEAR	THE ENERGY CONTAINED WITHIN THE NUCLEUS OF AN ATOM.
INTERNAL	THE ENERGY SOMETHING HAS DUE TO ITS TEMPERATURE (OR STATE). (SOMETIMES REFERRED TO AS THERMAL OR HEAT ENERGY)

Energy Dissipation

- When energy is transferred from one form to another, not all the energy will end up in the desired form (or place)
- Dissipation is used to describe ways in which energy is wasted
- Any energy not transferred to useful energy stores is wasted because it is lost to the surroundings

- These are commonly in the form of **thermal (heat), light or sound** energy
- What counts as **wasted energy** depends on the system
- For example, in a **television**:

electrical energy → light energy + sound energy + thermal energy

- Light and sound energy are useful energy transfers whereas thermal energy (from the heating up of wires) is wasted
- Another example, in a **heater**:

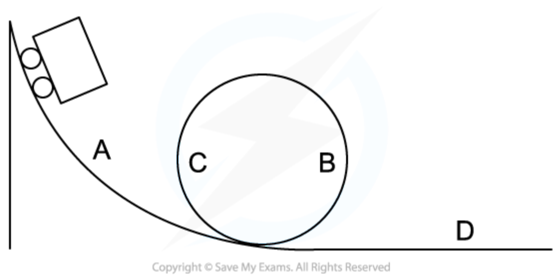
electrical energy → thermal energy + sound energy

- The thermal energy is useful, whereas sound is not

Worked Example

The diagram shows a rollercoaster going down a track.

The rollercoaster takes the path A → B → C → D.



Which statement is true about the energy changes that occur for the rollercoaster down this track?

A. KE - GPE - GPE - KE

B. KE - GPE - KE - GPE

C. GPE - KE - KE - GPE

D. GPE - KE - GPE - KE

Answer: D

- **At point A:**

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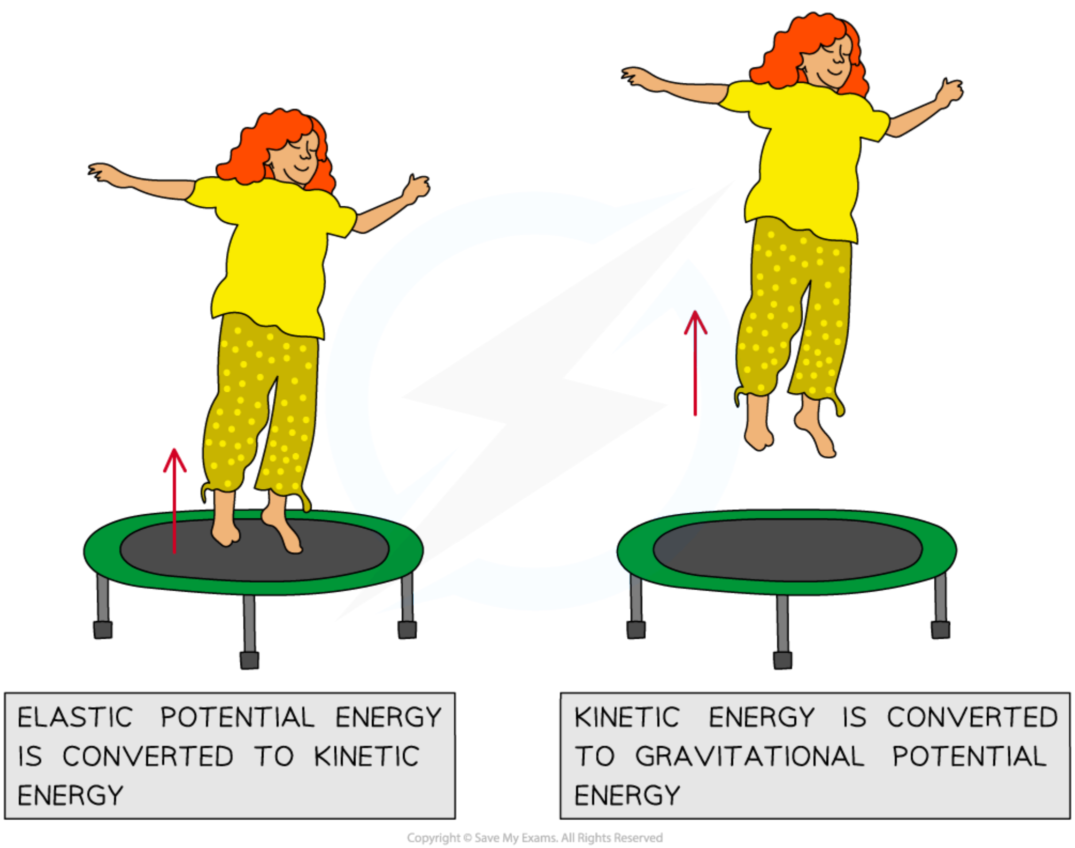
Your notes

    - The rollercoaster is raised above the ground, therefore it has **GPE**
    - As it travels down the track, **GPE** is converted to **KE** and the roller coaster speeds up
- **At point B:**
    - **KE** is converted to **GPE** as the rollercoaster rises up the loop
- **At point C:**
    - This **GPE** is converted back into **KE** as the rollercoaster travels back down the loop
- **At point D:**
    - The flat terrain means the rollercoaster only has **KE**

Applications of Energy Conservation

- Common examples of energy transfers are:
    - A falling object (in a vacuum): **gravitational potential energy → kinetic energy**
    - A battery: **chemical energy → electrical energy → light energy** (if connected to a bulb)
    - Horizontal mass on a spring: **elastic potential energy → kinetic energy**



Energy transfers whilst jumping on a trampoline

- There may also be work done against resistive forces such as **friction**
- For example, if an object travels up a rough inclined surface, then

Loss in kinetic energy = Gain in gravitational potential energy + Work done against friction

Energy Equations

- The most common equations used in the conservation of energy calculations are:

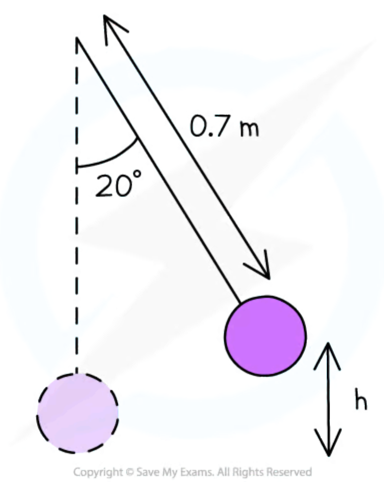
$$\text{Kinetic energy} = \frac{1}{2}mv^2$$

$$\text{Gravitational potential energy} = mg\Delta h$$

$$\text{Elastic potential energy} = \frac{1}{2}k(\Delta L)^2$$

Worked Example

A simple pendulum has a mass of 640 g and a length of 0.7 m. It is pulled out to an angle of 20° from the vertical. The pendulum is released. Assuming negligible air resistance, calculate the maximum speed of the pendulum bob as it passes through the vertical position.



Your notes

Your notes

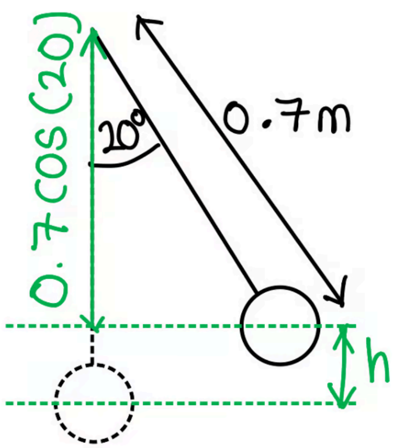
Answer:

Step 1: Determine the energy transfers

When the pendulum bob is at its maximum height, it has gravitational potential energy.

As it is dropped to the vertical position, all this is converted into kinetic energy

Step 2: Calculate the height dropped



Height Δh dropped = 0.7 – 0.7cos(20)

Step 3: Calculate the loss in gravitational potential energy (GPE)

$$GPE = mg\Delta h = (640 \times 10^{-3}) \times 9.81 \times (0.7 - 0.7\cos(20))$$

$$GPE = 0.265 \text{ J}$$

Step 4: Determine the equation for the speed

The GPE = KE at the vertical position

$$KE = GPE = \frac{1}{2}mv^2$$

$$v = \sqrt{\frac{2 \times GPE}{m}}$$

Step 5: Substitute in the values

$$v = \sqrt{\frac{2 \times 0.265}{640 \times 10^{-3}}} = 0.91 \text{ m s}^{-1}$$

Your notes

Examiner Tips and Tricks

You may not always be given the energy transfers happening in the system in exam questions. By familiarising yourself with the transfers and stores of energy, you will be expected to relate these to the situation in question. For example, a ball rolling down a hill is transferring gravitational potential energy to kinetic energy whilst a spring converts elastic potential energy into kinetic energy.

Energy & Work

Your notes

Energy & Work

- Energy is the capacity to do work, therefore:

Transfer of energy = Work Done

- This principle can be used to form mathematic equations for each type of energy
- The type of transfer of energy depends on the scenario
- The most common types of energy that are transformed between each other are:

Kinetic

- Kinetic is the work done by any object which is in motion

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

- Where:
  - m = mass (kg)
  - v = speed of velocity (m s^{-1})

Gravitational Potential

- Gravitational potential is the work done against gravity when an object is lifted

$$E_p = mg\Delta h$$

- Where:
  - m = mass (kg)
  - g = acceleration due to gravity (m s^{-2})
  - Δh = change in height (m)

Thermal

- Thermal (heat) is the work done on or by a system to transfer heat

$$E = mc\Delta T$$

- Where:
  - m = mass (kg)

- c = specific heat capacity (J kg^{-1} K^{-1})
- ΔT = change in temperature (K or °C)

Elastic Potential

- Elastic potential energy is the work done in stretching or compressing an object

$$E = \tfrac{1}{2} Fx = \tfrac{1}{2} kx^2$$

- Where:
  - F = stretching or compressing force (N)
  - x = extension (or compression) (m)
  - k = force constant (N m^{-1})

Nuclear

- Nuclear is the work done by nuclei during the processes of fusion and fission

$$E = \Delta mc^2$$

- Where:
  - Δm = mass defect (kg)
  - c = speed of light

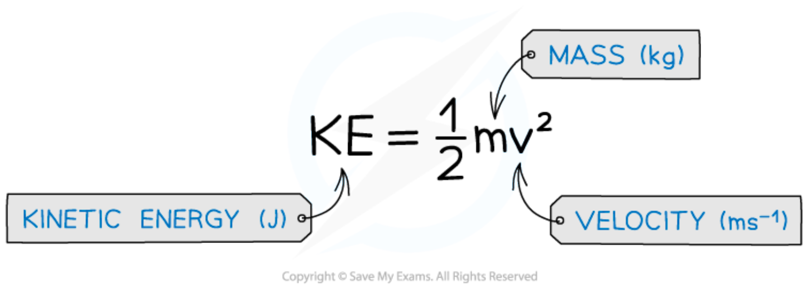
Your notes

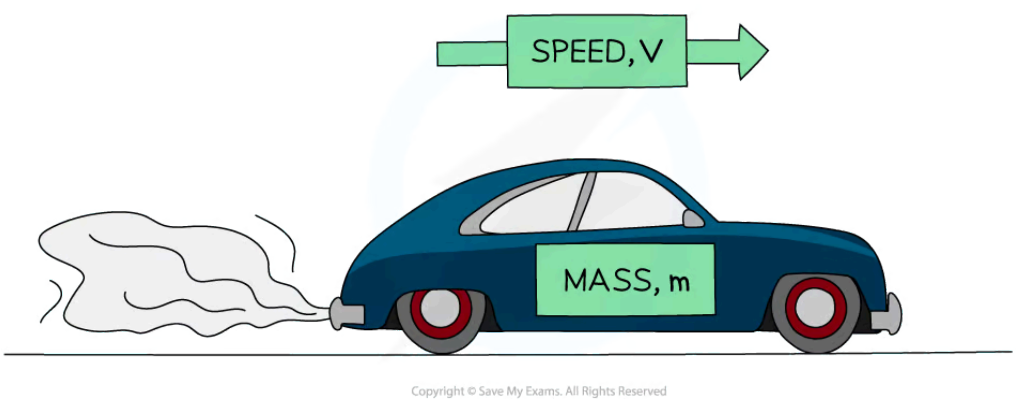
Your notes

Kinetic Energy

Kinetic Energy (E_k)

- Kinetic energy (E_k) is the energy an object has due to its **motion** (or velocity)
  - The faster an object is moving, 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 (KE): The energy an object has when its 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

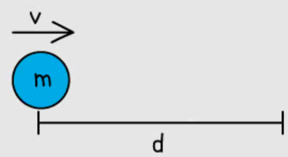
- Using this concept of work done and an equation of motion, the extra work done due to an object's speed can be derived
- The derivation for this equation is shown below:

Your notes

Your notes

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

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

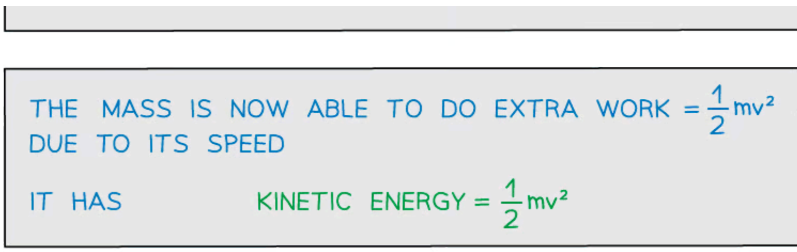
SUBSTITUTE BACK INTO $F = ma$

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

SUBSTITUTE THIS FORCE F INTO THE WORK DONE EQUATION

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

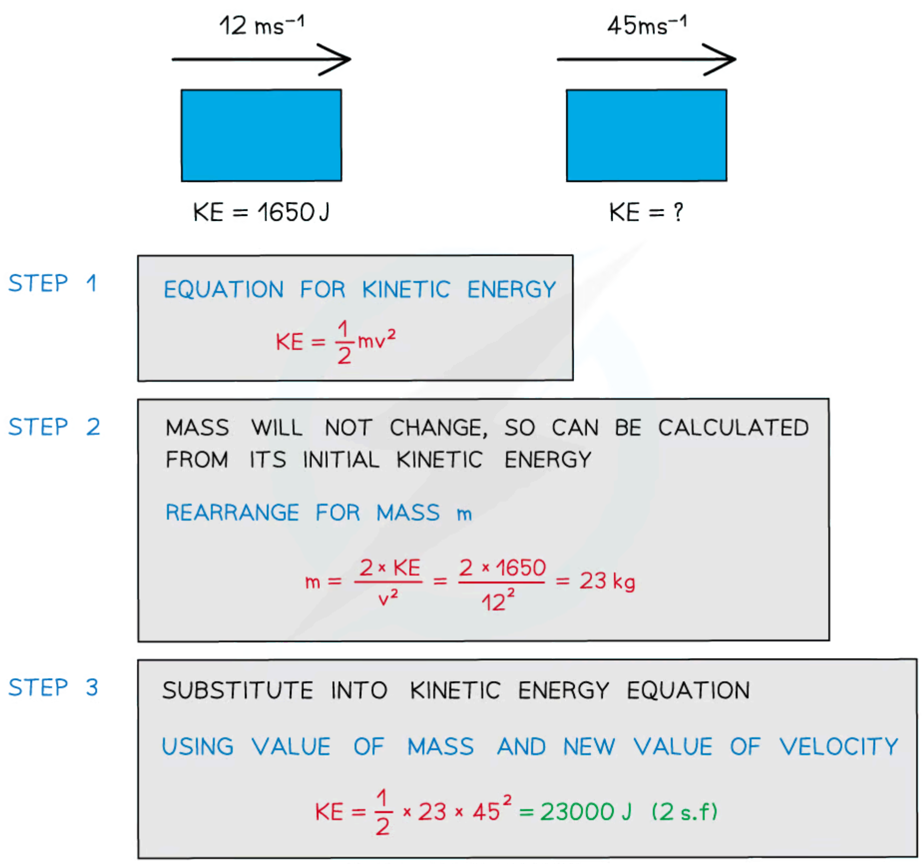
Your notes



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}, what is its new kinetic energy?

Answer:



Your notes

Examiner Tips and Tricks

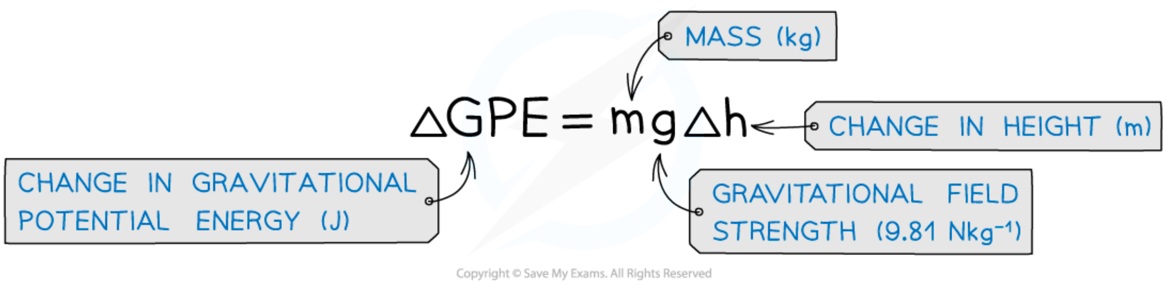
In your exam, you will be expected to know how to derive the kinetic energy equation from first principles, so make sure to practice this derivation!

Gravitational Potential Energy

Your notes

Gravitational Potential Energy (E_p)

- Gravitational potential energy (E_p) 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:



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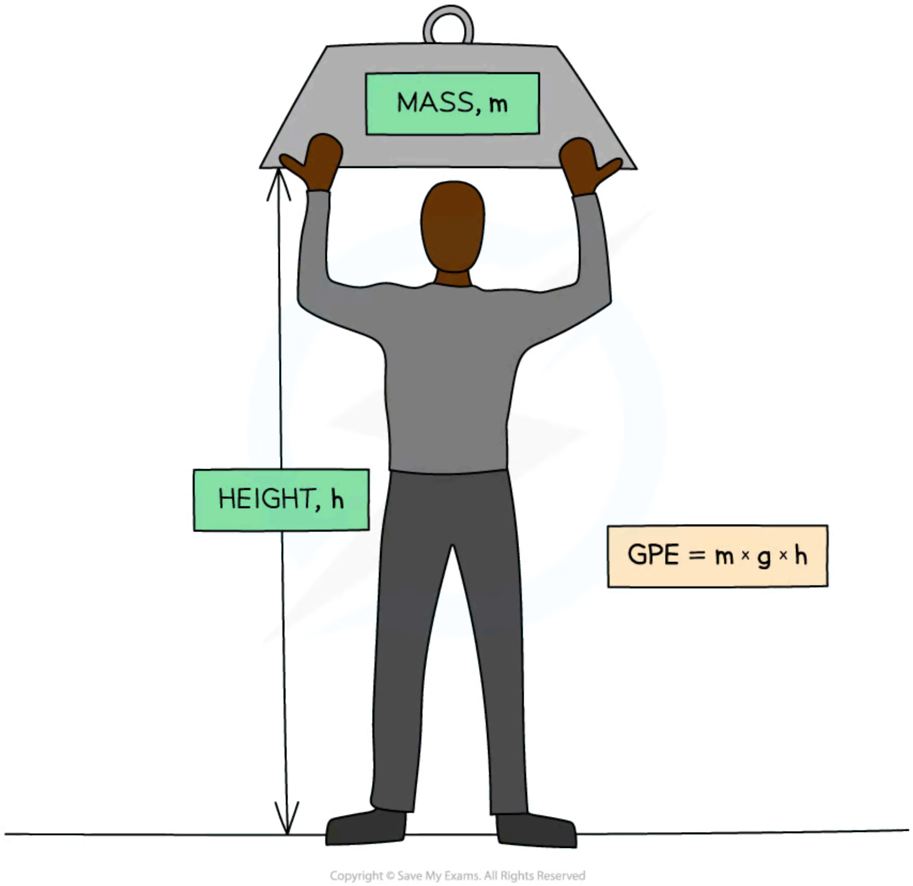


Gravitational potential energy (GPE): The energy an object has when lifted up

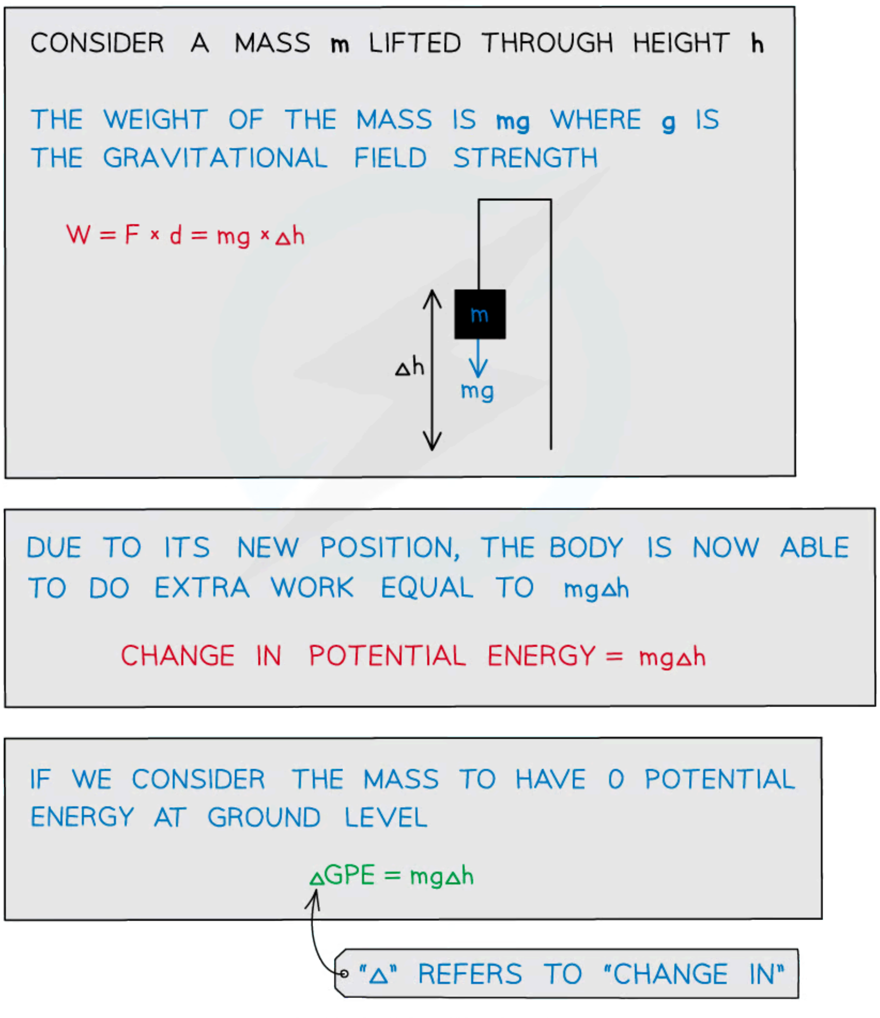
- The potential energy on the Earth's surface at ground level is taken to be equal to 0
- This equation is only relevant for energy changes in a **uniform gravitational field** (such as near the Earth's surface)

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

Your notes

Derivation of GPE = mgh



Worked Example

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

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

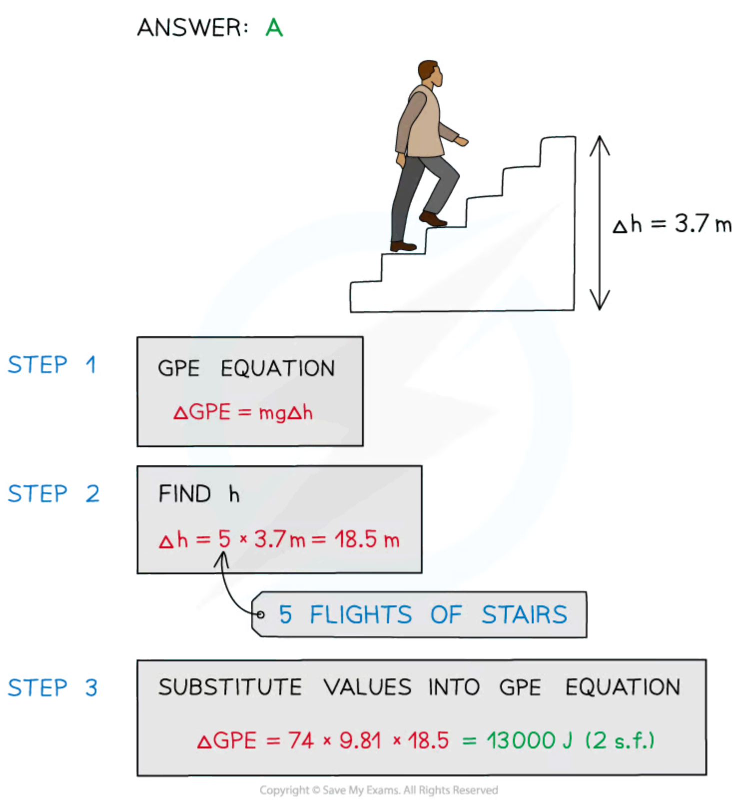
What is the approximate gain in the man's gravitational potential energy during the climb?

A. 13 000 J

B. 2700 J

C. 1500 J

D. 12 500 J



Examiner Tips and Tricks

In your exam, you will be expected to know how to derive the gravitational potential energy equation from first principles, so make sure to practice this derivation!

Exchange Between E_k and E_p

Your notes

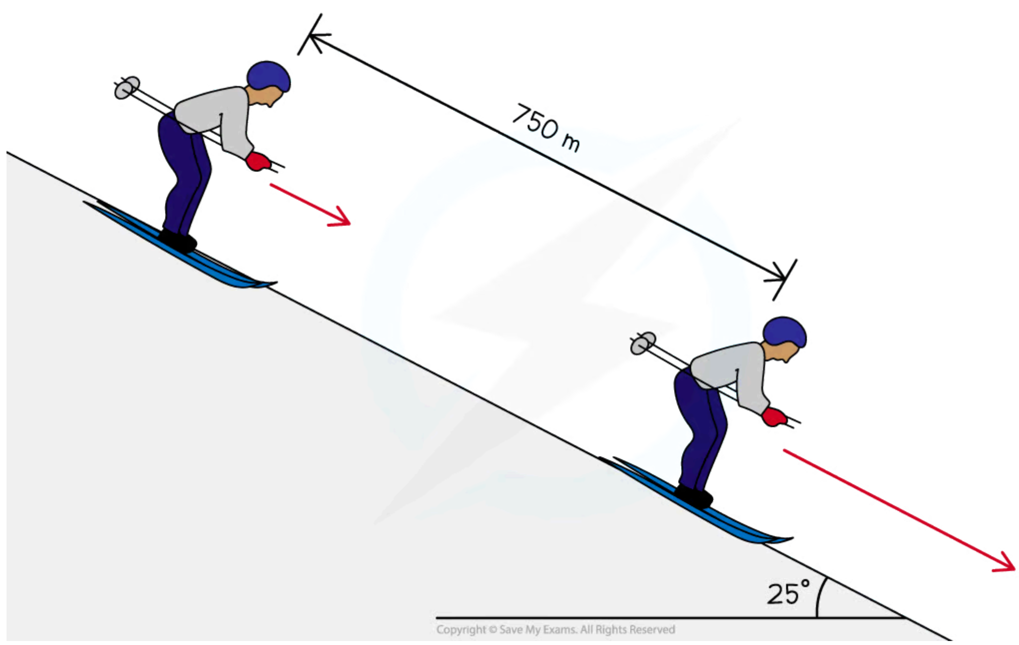
Your notes

- There are many scenarios that involve the transfer of kinetic energy into gravitational potential, or vice versa
- Some examples are:
  - A swinging pendulum
  - Objects in freefall
  - Sports which involve falling, such as skiing and skydiving
- Using the **principle of conservation of energy**, and taking any drag forces as negligible:

Loss in potential energy = Gain in kinetic energy

Worked Example

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

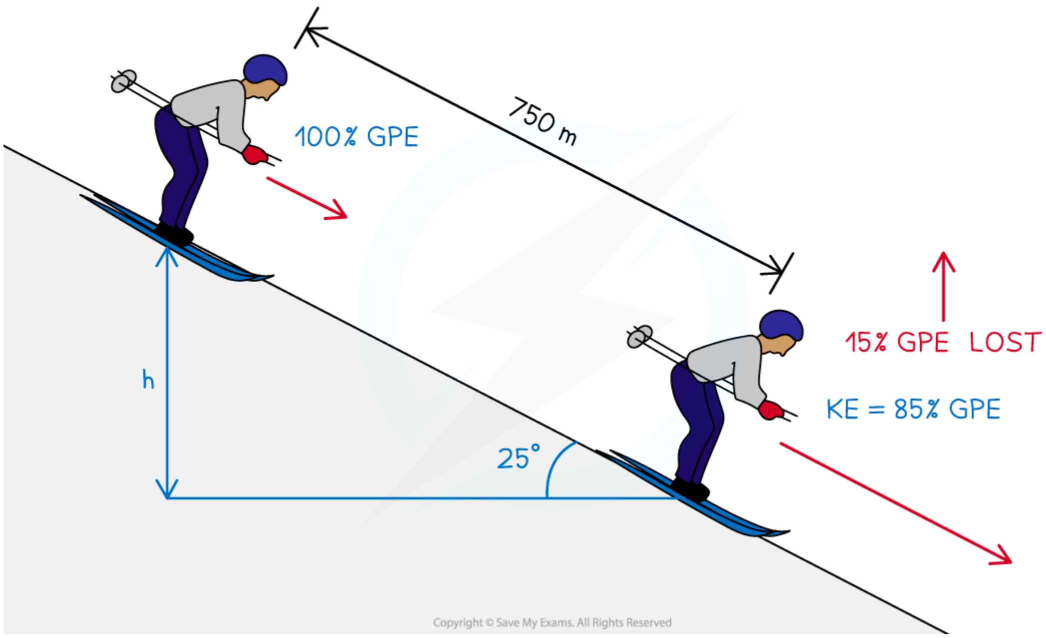


Calculate the final speed of the skier, assuming that he starts from rest and 15% of his initial gravitational potential energy is **not** transferred to kinetic energy.

Answer:

Your notes

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_p

$$E_k = 0.85\, E_p$$

$$\tfrac{1}{2} mv^2 = 0.85 \times mgh$$

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*

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

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

Your notes

Examiner Tips and Tricks

GPE:

- This equation only works for objects close to the Earth's surface where we can consider the gravitational field to be uniform.
- At A level, you might have to consider examples where the gravitational field is not uniform, such as in space, where this equation for GPE will not be relevant.

KE:

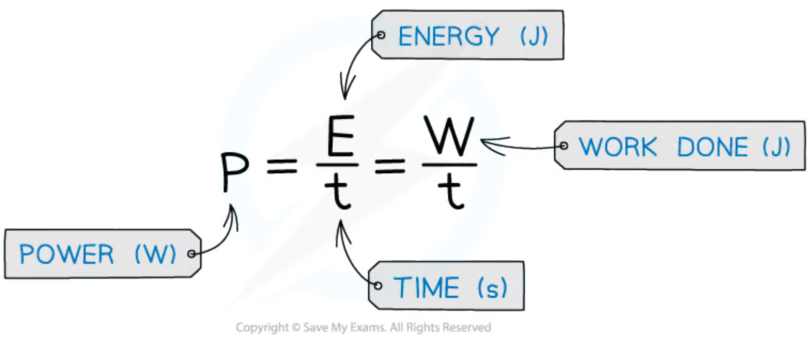
- When using the kinetic energy equation, note that only the speed is squared, not the mass or the ½.
- If a question asks about the 'loss of kinetic energy', remember **not** to include a negative sign since energy is a scalar quantity.

Power

Your notes

Power

- The power of a machine is the **rate at which it transfers energy**
- 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**
- The SI unit for power is the **Watt (W)**



- Power is also used in electricity, with labels on lightbulbs which indicate their power, such as 60 W or 100 W
  - These indicate the amount of energy transferred by an electrical current rather than by a force doing work

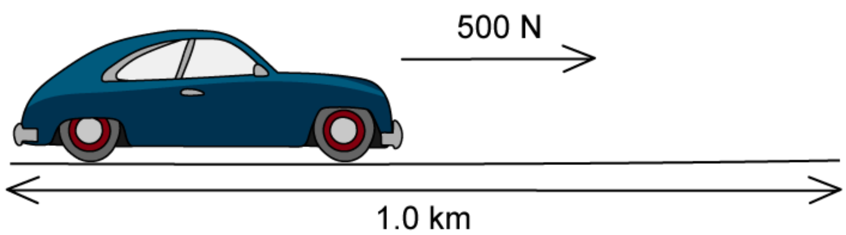
The Watt

- The Watt, *W*, is commonly used as the unit power (and radiant flux)
  - It is defined as **1 W = 1 J s^{-1}**
- The SI unit for energy is kg m^2 s^{-3}
- One watt is defined as:

A transfer of energy of 1 J in 1 s

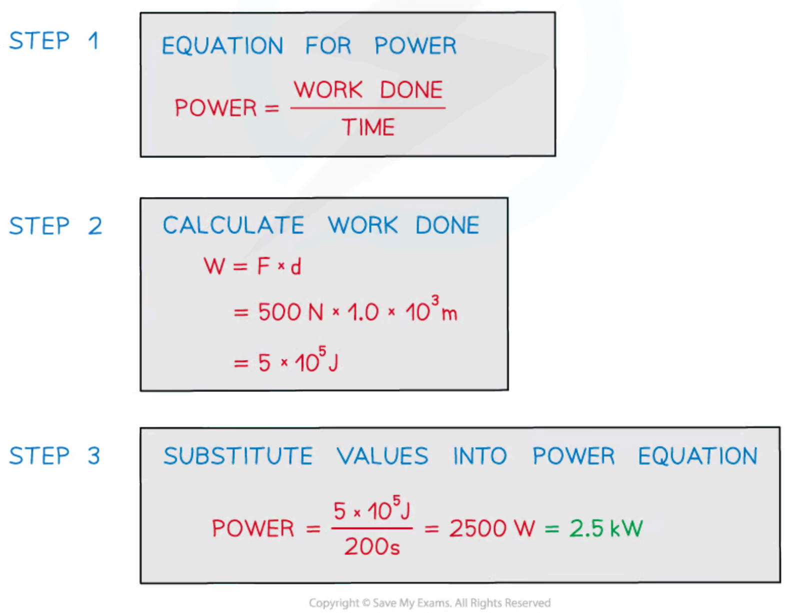
Worked Example

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



What is the average power developed by the engine?

Answer:



Examiner Tips and Tricks

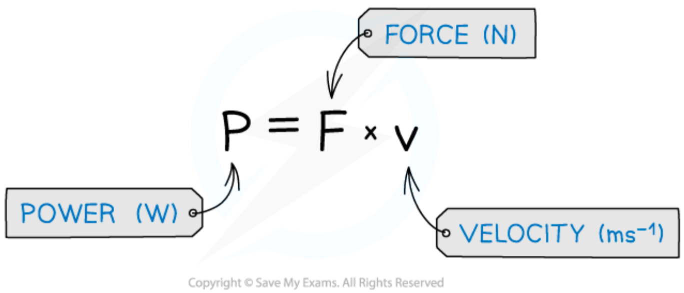
Your notes

Your notes

Think of power as "energy per second". Thinking of it this way will help you to remember the relationship between power and energy: "Watt is the unit of power?"

Power & Force

- Moving power is defined by the equation:



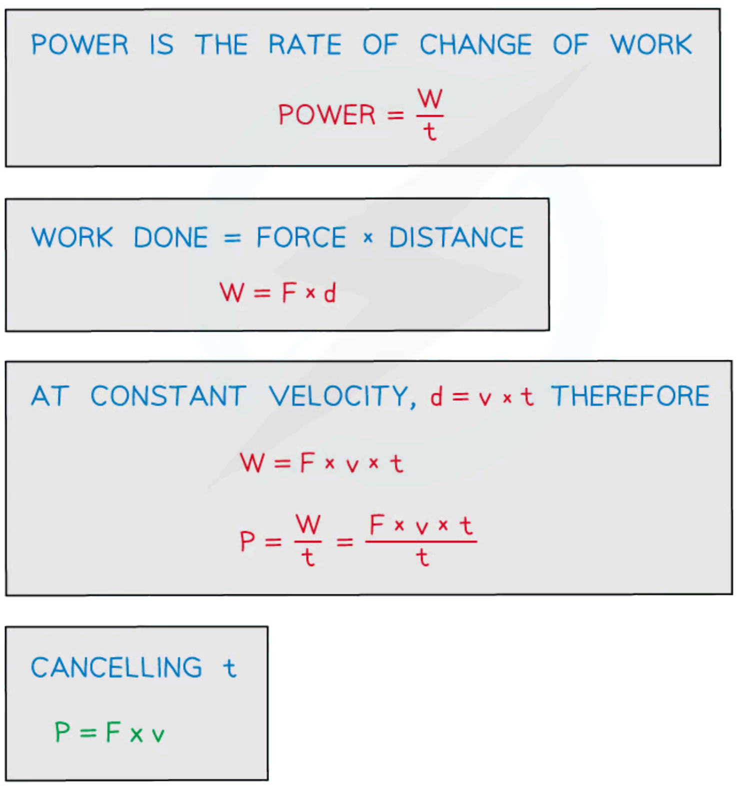
- This equation is only relevant where a **constant force** moves a body at **constant velocity**. Power is required in order to produce an acceleration
- The force must be applied in the **same** direction as the velocity

Derivation of P = Fv

- The derivation for this equation is shown below:

Your notes

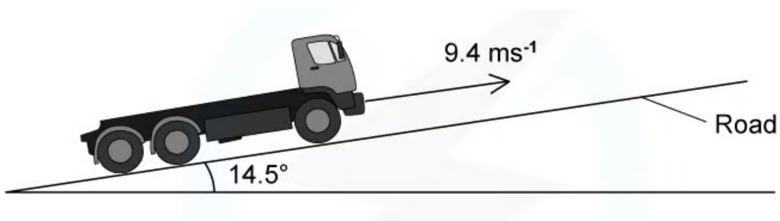
Derivation of $P = F \times v$



Worked Example

A lorry moves up a road that is inclined at 14.5° to the horizontal.

Your notes



The lorry has a mass of 3500 kg and is travelling at a constant speed of 9.4 m s^{-1}. The force due to air resistance is negligible. Calculate the useful power from the engine to move the lorry up the road.

Answer:

STEP 1

EQUATION FOR POWER

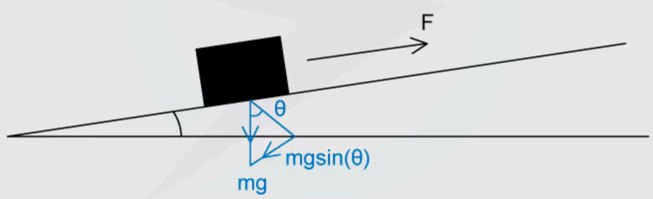
$P = F \times v$

STEP 2

CALCULATE THE FORCE

THE FORCE NEEDED TO MOVE THE LORRY UP THE ROAD IS THAT WHICH OVERCOMES THE COMPONENT OF ITS WEIGHT ACTING DOWN THE SLOPE

$F = mg\sin\theta = 3500 \times 9.81 \times \sin(14.5) = 8596.8 \text{ N}$



STEP 3

SUBSTITUTE INTO POWER EQUATION

$P = 8\,596.8 \times 9.4 = 80\,809.9 \text{ W} = 81\,000 \text{ W} = 81 \text{ kW}$ (2.s.f.)

Examiner Tips and Tricks

The force represented in exam questions will often be a drag force. Whilst this is in the opposite direction to its velocity, remember the force needed to calculate the power is equal to (or above) this drag force to overcome it therefore you equate it to that value.

Your notes

Your notes

Efficiency

Efficiency

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

  The ratio of the useful power output from a system to its total power 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 thermal energy in a heater, the heat energy is **useful**, and the sound energy produced is **wasted**
- Efficiency is represented as a percentage, and can be calculated using the equation:

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

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

$$\text{Power} = \frac{\text{Energy}}{\text{Time}}$$

- The efficiency equation can also be written in terms of energy:

$$\text{Efficiency} = \frac{\text{Useful energy output}}{\text{Total energy input}} \times 100\%$$

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

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 out

- The power output is the 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

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

Examiner Tips and Tricks

Efficiency can be in a ratio (between 0 and 1) or percentage format (between 0% and 100%).

If the question asks for efficiency as a ratio, give your answer as a **fraction** or **decimal**. If the answer is required as a percentage, remember to multiply the ratio by **100** to convert it: if the ratio = 0.25, percentage = 0.25 × 100 = 25 %.

Remember that efficiency has **no units**. It is a ratio with both the numerator and denominator with the same units.

Your notes