Cambridge (CIE) IGCSE Physics

Your notes

Energy, Work & Power

Contents

Energy stores

- **Energy** is a property of an object that is **stored** or **transferred**
- Energy must be transferred to an object to perform **work on** or **heat up** that object
- Energy is measured in units of **joules (J)**

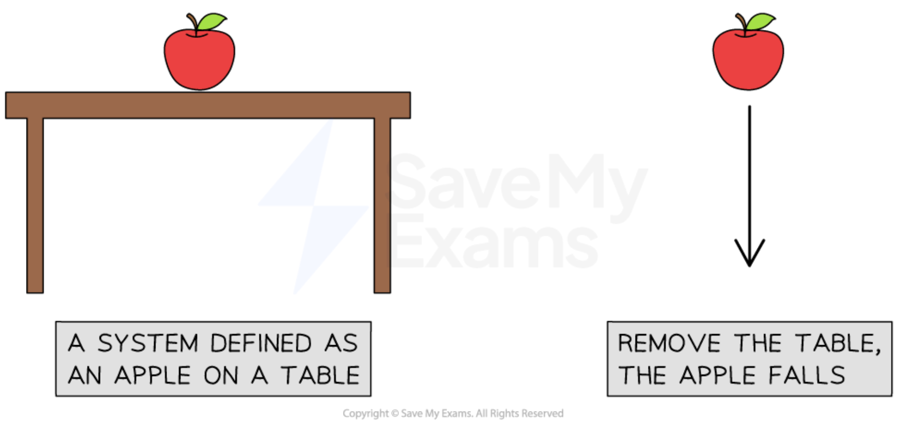
Systems

- Energy will often be described as part of an energy **system**
- In physics, a system is defined as:

An object or group of objects

- In physics, defining the system is a way of **narrowing** the parameters to **focus** only on what is relevant to the situation being observed
- A system could be as **large** as the whole Universe, or as **small** as an apple sitting on a table
- When a system is in **equilibrium**, nothing changes, and so nothing happens
- When there is a **change** to a system, energy is **transferred**
- If an apple sits on a table and that table is suddenly removed, the apple will fall
- As the apple falls, energy is transferred

Example of a system



In physics, a system is an object or group of objects being observed or studied. Energy is transferred when a change happens within a system

Energy stores

- Energy is stored in objects in different **energy stores**

Table of energy stores

Energy Store	Description
Kinetic	Moving objects have energy in their kinetic store
Gravitational	Objects gain energy in their gravitational potential store when they are lifted through a gravitational field
Elastic	Objects have energy in their elastic potential store if they are stretched, squashed or bent
Magnetic	Magnetic materials interacting with each other have energy in their magnetic store
Electrostatic	Objects with charge (like electrons and protons) interacting with one another have energy in their electrostatic store
Chemical	Chemical reactions transfer energy into or away from a substance's chemical store
Nuclear	Atomic nuclei release energy from their nuclear store during nuclear reactions
Thermal	All objects have energy in their thermal stores; the hotter the object, the more energy it has in this store

Energy transfers

- Energy is **transferred** between stores through different energy **transfer pathways**

Energy transfer pathways

- The energy transfer pathways are:
  - Mechanical
  - Electrical
  - Heating
  - Radiation

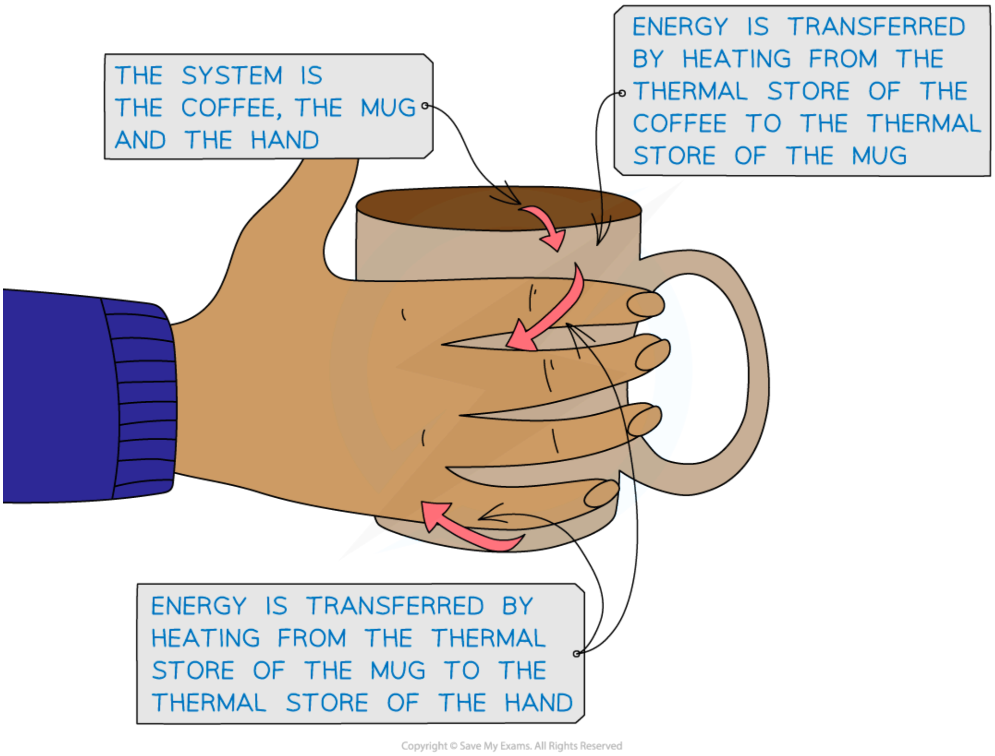
Table of energy transfer pathways

Your notes

Transfer Pathway	Description
Mechanical working	When a force acts on an object (e.g. pulling, pushing, stretching, squashing)
Electrical working	A charge moving through a potential difference (e.g. current)
Heating (by particles)	Energy is transferred from a hotter object to a colder one (e.g. conduction)
(Heating by) radiation	Energy transferred by electromagnetic waves (e.g. visible light)

- An example of an energy transfer by heating is a hot coffee heating up cold hands

Energy transfer by heating



Energy is transferred by heating from the hot coffee to the mug, to the cold hands

Worked Example

Describe the energy transfers in the following scenarios:

Your notes

a) A battery powering a torch

b) A falling object

Answer:

Part a)

Step 1: Determine the store that energy is being transferred away from, within the parameters described by the defined system

- For a battery powering a torch
- The system is defined as the battery and the torch
- Therefore, the energy began in the chemical store of the cells of the battery

Step 2: Determine the store that energy is transferred to, within the parameters described by the defined system

- When the circuit is closed, the bulb lights up
- Therefore, energy is transferred to the thermal store of the bulb
- Energy is then transferred from the bulb to the surroundings, but this is not described in the parameters of the system

Step 3: Determine the transfer pathway

- Energy is transferred by the flow of charge around the circuit
- Therefore, the transfer pathway is electrical

Step 4: State the energy transfer

- Energy is transferred **electrically** from the **chemical store** of the battery to the **thermal store** of the bulb

Part b)

Step 1: Determine the store that energy is being transferred away from, within the parameters described by the defined system

- For a falling object
- In order to fall, the object must have been raised to a height
- Therefore, it began with energy in its gravitational potential store

Step 2: Determine the store that energy is transferred to, within the parameters described by the defined system

- As the object falls, it is moving
- Therefore, energy is being transferred to its kinetic store

Step 3: Determine the transfer pathway

- For an object to fall, a resultant force must be acting on it, and that force is weight, and it acts over a distance (the height of the fall)
- Therefore, the transfer pathway is mechanical

Step 4: State the energy transfer

- Energy is transferred from the **gravitational store** to the **kinetic store** of the object via a **mechanical** transfer pathway

Your notes

Your notes

Examiner Tips and Tricks

Don't worry too much about the parameters of the system. They are there to help you keep your answers concise so you don't end up wasting time in your exam.

If you follow any process back far enough, you would get many energy transfers taking place. For example, an electric kettle heating water. The relevant energy transfer is from the thermal store of the kettle to the thermal store of the water, with some energy dissipated to the surroundings. But you could take it all the way back to how the electricity was generated in the first place. This is beyond the scope of the question. Defining the system gives you a starting point and a stopping point for the energy transfers you need to consider.

Kinetic energy

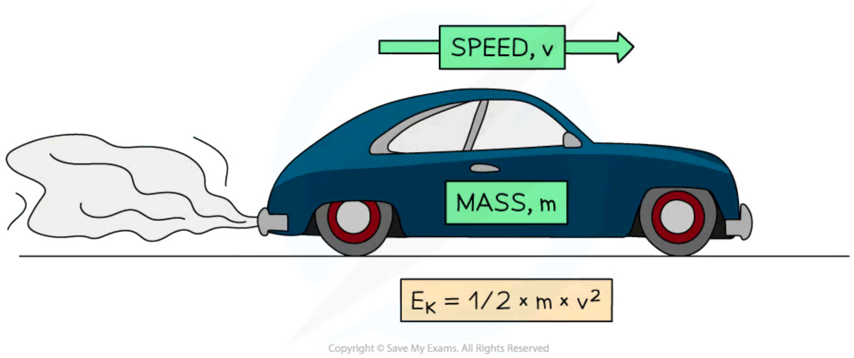
Extended tier only

- Energy in an object's kinetic store is defined as:

The amount of energy an object has as a result of its mass and speed

- This means that any object in **motion** has energy in its kinetic energy store
  - If an object **speeds up**, energy is **transferred to** its kinetic store
  - If an object **slows down**, energy is **transferred away** from its kinetic store

Kinetic energy of a moving object



A moving car has energy in its kinetic store

Kinetic energy equation

- The amount of energy in an object's kinetic store can be calculated using the equation:

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

- Where:
  - E_k = kinetic energy, measured in joules (J)
  - m = mass of the object, measured in kilograms (kg)
  - v = speed of the object, measured in metres per second (m/s)
- The kinetic energy equation demonstrates that if the mass of an object is doubled for a given speed, then its kinetic energy will double
  - This is because kinetic energy is **directly proportional** to mass

- $E_k \propto m$

- If the speed of the object is doubled for a given mass, it will have four times the kinetic energy
  - This is because kinetic energy is **directly proportional** to velocity squared
  - $E_k \propto v^2$

Your notes

Worked Example

Calculate the kinetic energy stored in a vehicle of mass 1200 kg moving at a speed of 27 m/s.

Answer:

Step 1: List the known quantities

- Mass of the vehicle, $m = 1200 \text{ kg}$
- Speed of the vehicle, $v = 27 \text{ m/s}$

Step 2: Write down the equation for kinetic energy

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

Step 3: Calculate the kinetic energy

$$E_k = \frac{1}{2} \times 1200 \times (27)^2$$

$$E_k = 437\,400 \text{ J}$$

Step 4: Round the final answer to 2 significant figures

$$E_k = 440\,000 \text{ J (2 s.f.)}$$

Examiner Tips and Tricks

When performing calculations using the kinetic energy equation, always double-check that you have squared the speed. Forgetting to do this is the most common mistake that students make.

You will most likely need to rearrange the kinetic energy equation in your IGCSE exam. The kinetic energy equation is one of the more difficult rearrangements at IGCSE, so make sure you are comfortable doing it before your exam!

Gravitational potential energy

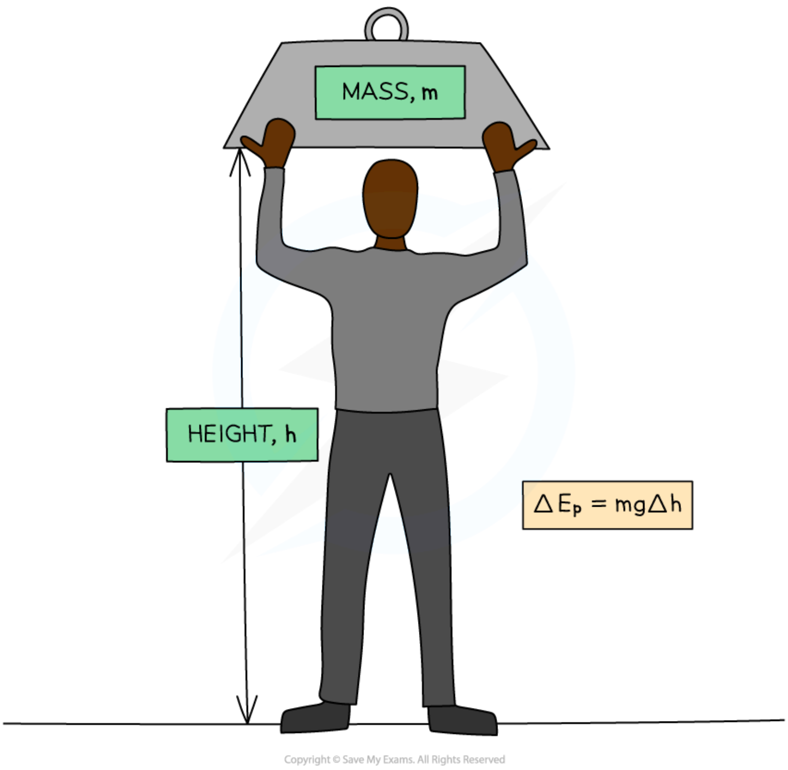
Extended tier only

- Energy in an object's gravitational potential energy store is defined as:

The energy an object has due to its height in a gravitational field

- **Work** is done against the **weight** force exerted on the object; therefore, energy is transferred
- This means that:
  - if an object is **lifted** up, energy will be transferred **to** its gravitational potential store
  - if an object is **lowered**, energy will be transferred **away from** its gravitational potential store

Gravitational potential energy of an object lifted through a gravitational field



Energy is transferred to the mass's gravitational store as it is lifted through the gravitational field

Gravitational potential energy equation

Your notes

- The change in energy in an object's gravitational potential energy store can be calculated using the equation:

$$\Delta E_p = mg\Delta h$$

- Where:
  - ΔE_p = change in gravitational potential energy, measured in joules (J)
  - m = mass, measured in kilograms (kg)
  - g = gravitational field strength, measured in newtons per kilogram (N/kg)
  - Δh = change in height, measured in metres (m)

Worked Example

A man climbs a flight of stairs that is, in total, 3.0 m higher than the floor. The man has a mass of 72 kg, and the gravitational field strength on Earth is approximately 9.8 N/kg.

Calculate the energy transferred to the man's gravitational potential energy store.

Answer:

Step 1: List the known quantities

- Mass of the man, $m = 72 \text{ kg}$
- Gravitational field strength, $g = 9.8 \text{ N/kg}$
- Change in height, $\Delta h = 3.0 \text{ m}$

Step 2: Write down the equation for gravitational potential energy

$$\Delta E_p = mg\Delta h$$

Step 3: Calculate the gravitational potential energy

$$\Delta E_p = 72 \times 9.8 \times 3.0$$

$$\Delta E_p = 2116.8 \text{ J}$$

Step 4: Round to an appropriate number of significant figures

- The input values are to 2 s.f. therefore, the output value must be to 2 s.f.

$$\Delta E_p = 2100 \text{ J (2 s.f.)}$$

Examiner Tips and Tricks

In your IGCSE exam, you will generally be expected to round your answers to an appropriate number of significant figures.

Your answer can only be as accurate as your least accurate input value. Therefore, your final answer should round to the lowest number of significant figures of all your input values.

Your notes

Conservation of energy

- The **principle of conservation of energy** states that:

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

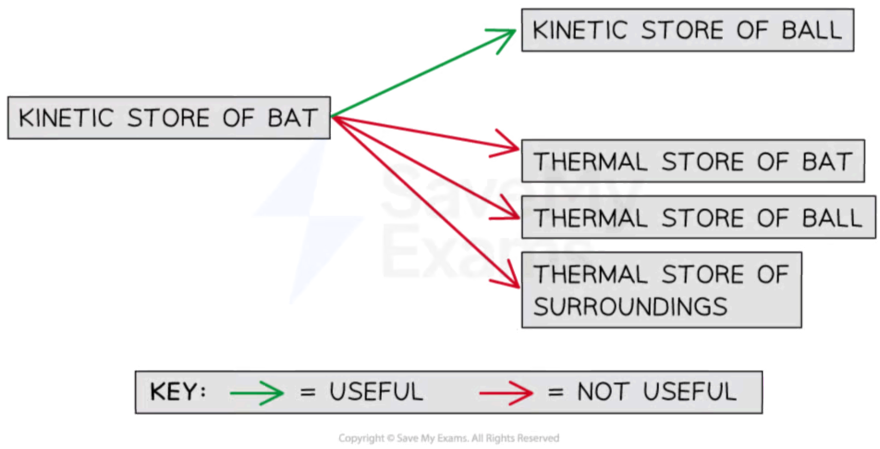
- The principle of conservation of energy means that for a closed system, the total amount of energy is **constant**
- The **total** amount of energy transferred **into** the system must be **equal** to the **total** amount of energy transferred **away** from the system
- Therefore, energy cannot be 'lost', but it can be transferred to the surroundings
  - Energy can be **dissipated** (spread out) to the surroundings by heating and radiation
  - Dissipated energy transfers are often not **useful**, in which case they can be described as **wasted** energy

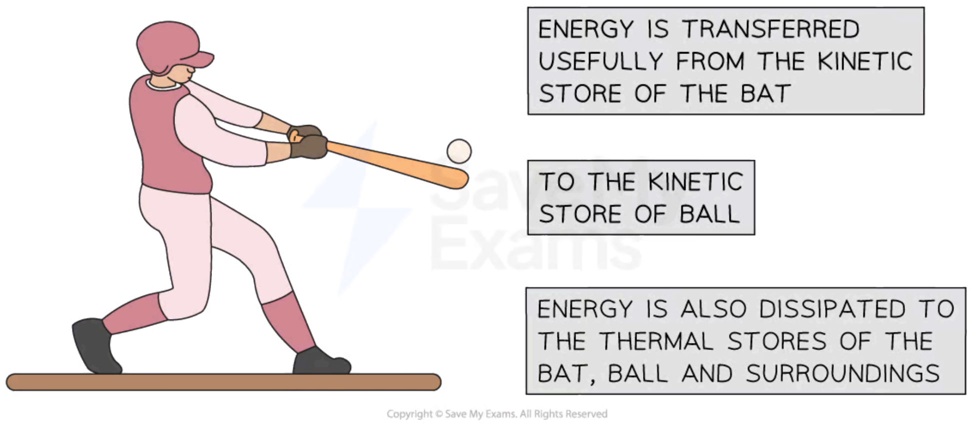
Examples of the principle of conservation of energy

Example 1: a bat hitting a ball

- The moving bat has energy in its **kinetic** store
- Some of that energy is transferred **usefully** to the **kinetic** store of the ball
- Some of that energy is transferred from the **kinetic** store of the bat to the **thermal** store of the ball **mechanically** due to the impact of the bat on the ball
  - This energy transfer is not useful; the energy is **wasted**
- Some of that energy is **dissipated** by **heating** to the **thermal** store of the bat, the ball, and the surroundings
  - This energy transfer is not useful; the energy is **wasted**
- The total amount of energy transferred into the system is equal to the total amount of energy transferred away from the system

Conservation of energy: a bat hitting a ball



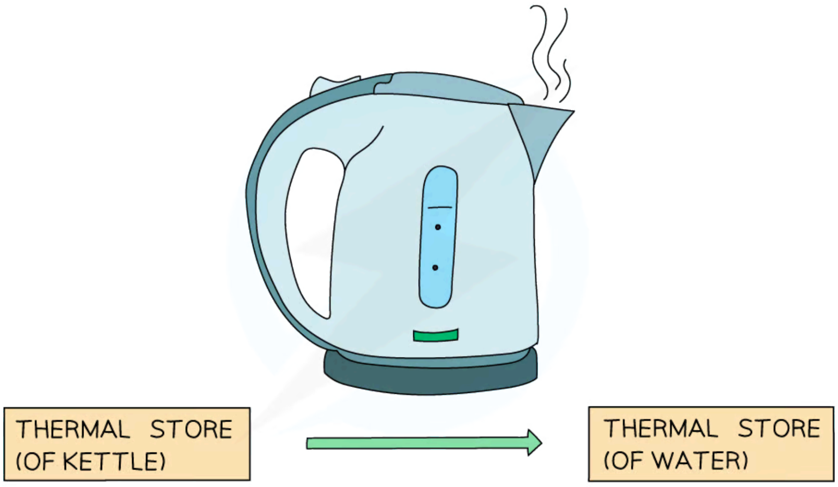


The principle of conservation of energy applied to a bat hitting a ball

Example 2: Boiling Water in a Kettle

- When an electric kettle boils water, **energy** is transferred **electrically** from the mains supply to the **thermal store** of the heating element inside the kettle
- As the heating element gets hotter, **energy** is transferred **by heating** to the **thermal store** of the water
- Some of the energy is transferred to the **thermal** store of the plastic kettle
  - This energy transfer is not useful; the energy is **wasted**
- And some energy is **dissipated** to the **thermal store** of the surroundings due to the air around the kettle being heated
  - This energy transfer is not useful; the energy is wasted
- The total amount of energy transferred into the system is equal to the total amount of energy transferred away from the system

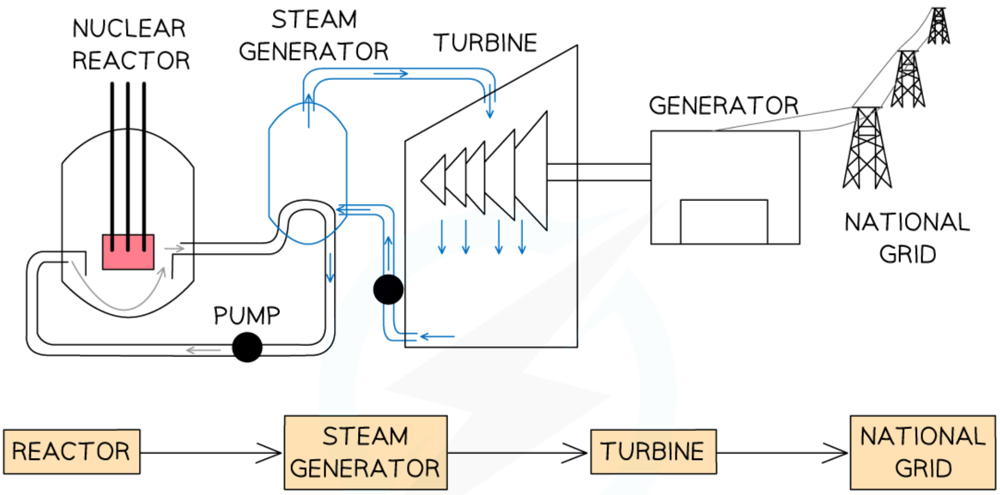
Conservation of energy: a kettle boiling water

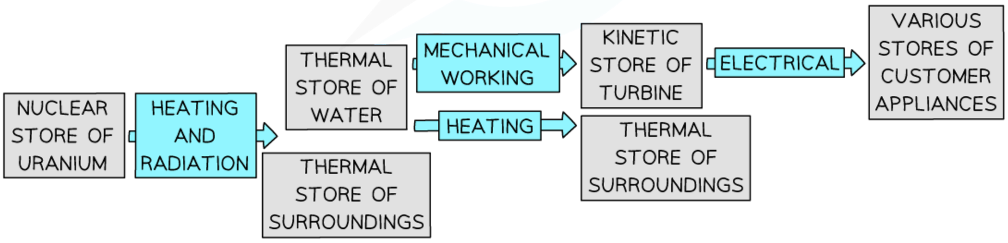


The principle of conservation of energy applied to a kettle boiling water

Energy flow diagrams

- Energy stores and transfers can be represented using a flow diagram
  - This shows both the stores and the transfers taking place within a system





Energy flow diagram showing energy stores and transfers in a nuclear power plant.

Note the colour difference of the labels (stores) and the arrows (transfer pathways)

Your notes

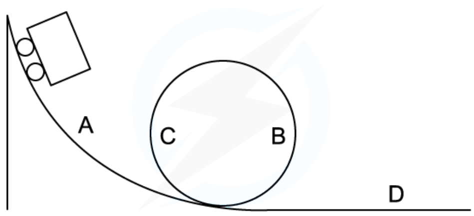
- In an energy flow diagram, energy is always **conserved**

total energy in = total energy out

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. $E_K \rightarrow \Delta E_P \rightarrow \Delta E_P \rightarrow E_K$

B. $E_K \rightarrow \Delta E_P \rightarrow E_K \rightarrow \Delta E_P$

C. $\Delta E_P \rightarrow E_K \rightarrow E_K \rightarrow \Delta E_P$

D. $\Delta E_P \rightarrow E_K \rightarrow \Delta E_P \rightarrow E_K$

Answer: D

- **At point A:**
  - The rollercoaster is raised above the ground, therefore it has energy in its **gravitational potential store**
  - As it travels down the track, energy is transferred **mechanically** to its **kinetic store**

- **At point B:**
  - Energy is transferred **mechanically** from the kinetic store to the **gravitational potential store**
  - As the kinetic energy store **empties**, the gravitational potential energy store **fills**

- **At point C:**
  - Energy is transferred **mechanically** from the gravitational potential store to the **kinetic store**
- **At point D:**
  - The flat terrain means there is no change in the amount of energy in its gravitational potential store, the rollercoaster only has energy in its **kinetic store**
  - The kinetic energy store is full
  - In reality, some energy will also be transferred to the thermal energy store of the tracks due to **friction**, and to the thermal energy store of the surroundings due to **sound**
  - We say this energy is **dissipated to the surroundings**
    - The total amount of energy in the system will be constant
    - Total energy in = total energy out

Examiner Tips and Tricks

It is helpful to think of energy stores as beakers and the total energy in the system as water. The water can be poured from one beaker into another, back and forth, as energy is transferred between stores.

You may not always be given the energy transfers happening in the system in your IGCSE exam questions.

By familiarising yourself with the energy stores and transfer pathways, you should be able to relate these to the situation presented in the question. For example, a ball rolling down a hill transfers energy from the ball's gravitational potential energy store to its kinetic energy store mechanically, while a spring transfers energy from its elastic potential energy store to its kinetic energy store mechanically.

Sankey diagrams

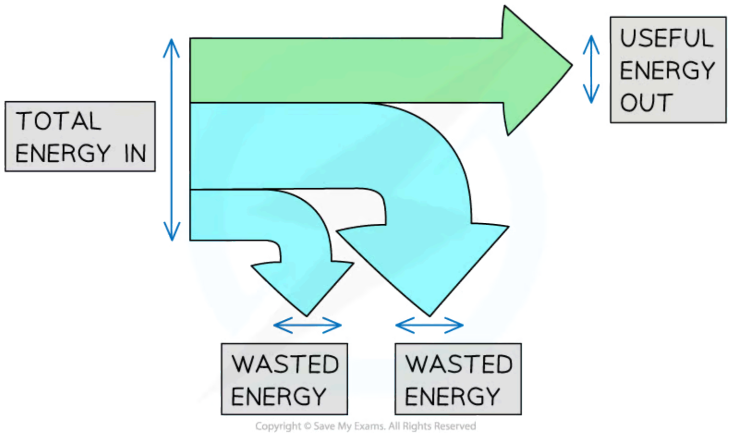
Extended tier only

- **Sankey diagrams** can be used to represent energy transfers
  - Sankey diagrams are characterised by arrows that split to show the proportions of the energy transfers taking place
- The different parts of the arrow in a Sankey diagram represent the different energy transfers:
  - The left-hand side of the arrow (the flat end) represents the energy transferred **into** the system

Your notes

- The straight arrow pointing to the right represents the energy that ends up in the desired store; this is the **useful energy output**
- The arrows that bend away represent the **wasted energy**

Features of a Sankey diagram



Total energy in, wasted energy and useful energy out shown on a Sankey diagram

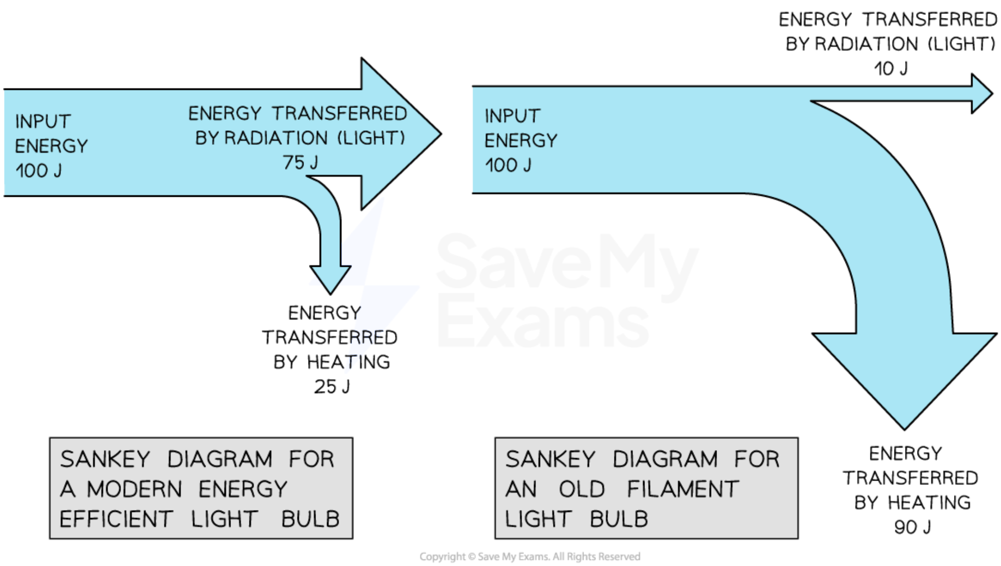
- The width of each arrow is **proportional** to the amount of energy being transferred
- As a result of the conversation of energy:

total energy in = total energy out

total energy in = useful energy out + wasted energy

- A Sankey diagram for a modern efficient light bulb will look very different from that for an old filament light bulb
- A more efficient light bulb has **less** wasted energy
  - This is shown by the smaller arrow downwards representing the heat energy

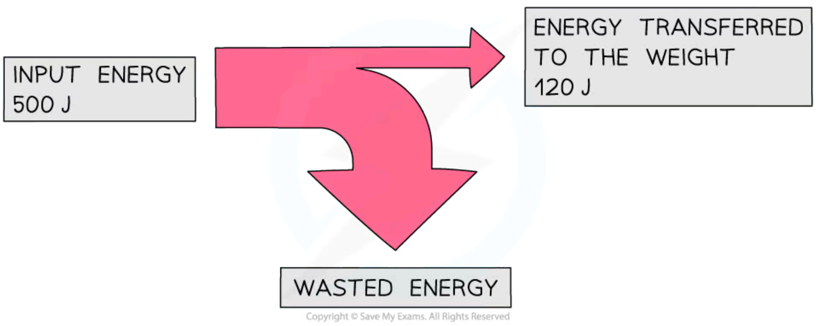
Sankey diagrams for an energy efficient bulb and a filament bulb



Filament bulbs have a much greater proportion of wasted energy than modern energy efficient bulbs

Worked Example

An electric motor is used to lift a weight. The diagram represents the energy transfers in the system.



Calculate the amount of wasted energy.

Answer:

Step 1: State the conservation of energy

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

$$\text{total energy in} = \text{useful energy out} + \text{wasted energy}$$

Step 2: Rearrange the equation for the wasted energy

$$\text{wasted energy} = \text{total energy in} - \text{useful energy out}$$

Step 3: Substitute the values from the diagram

$$\text{wasted energy} = 500 - 120$$

$$\text{wasted energy} = 380 \text{ J}$$

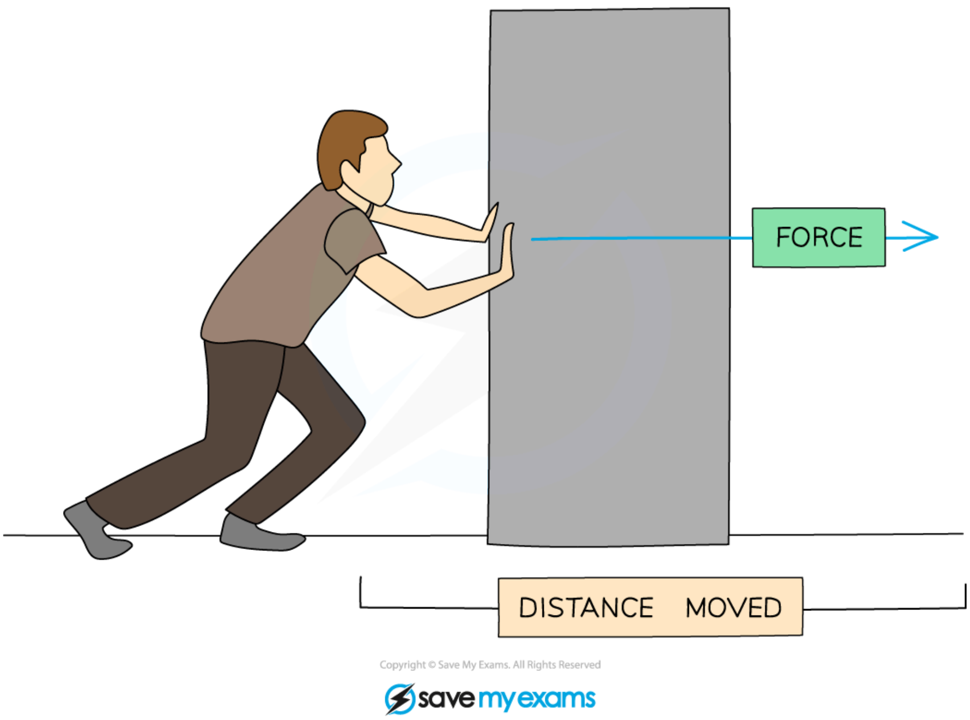
Your notes

Your notes

Work done & energy transfers

- **Mechanical work** is done when an object is moved over a **distance** by a **force** applied in the **direction** of its displacement
  - It is said that the **force does work** on the object
  - If a force is applied to an object but doesn't result in any movement, no work is done
- When **work** is done, **energy** is transferred
- Work done and energy transferred are **equivalent** quantities

Work done pushing a box



Work is done when a force is used to move an object over a distance, and energy is transferred from the person to the box

Work done equation

- The formula for work done is:

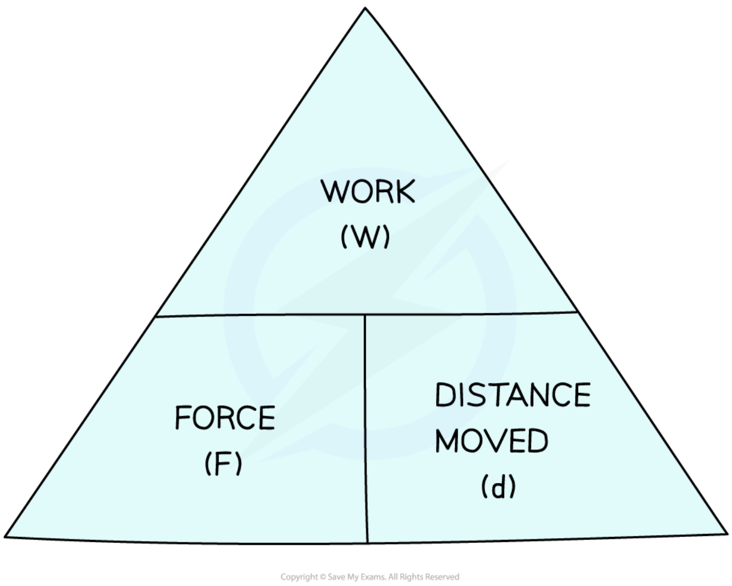
$$W = Fd = \Delta E$$

- Where:

- W = work done, measured in newton-metres (N m)
- F = force applied, measured in newtons (N)
- d = distance in metres (m)
- ΔE = energy transferred, measured in joules (J)

Your notes

Formula triangle for work done, force and distance



To use a formula triangle, simply cover up the quantity you wish calculate and the structure of the equation is revealed

- Using formula triangles is covered in more detail in the revision note on Speed & velocity
- Mechanical work done and electrical work done are equivalent to energy transferred

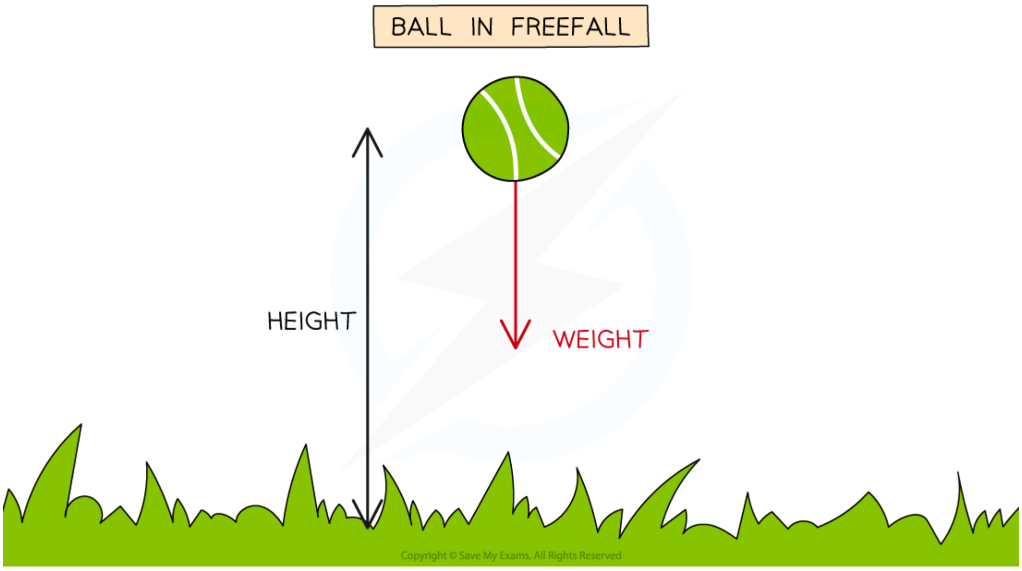
$$\text{work done} = \text{energy transferred}$$

- Therefore:

$$1 \text{ N m} = 1 \text{ J}$$

Examples of work done

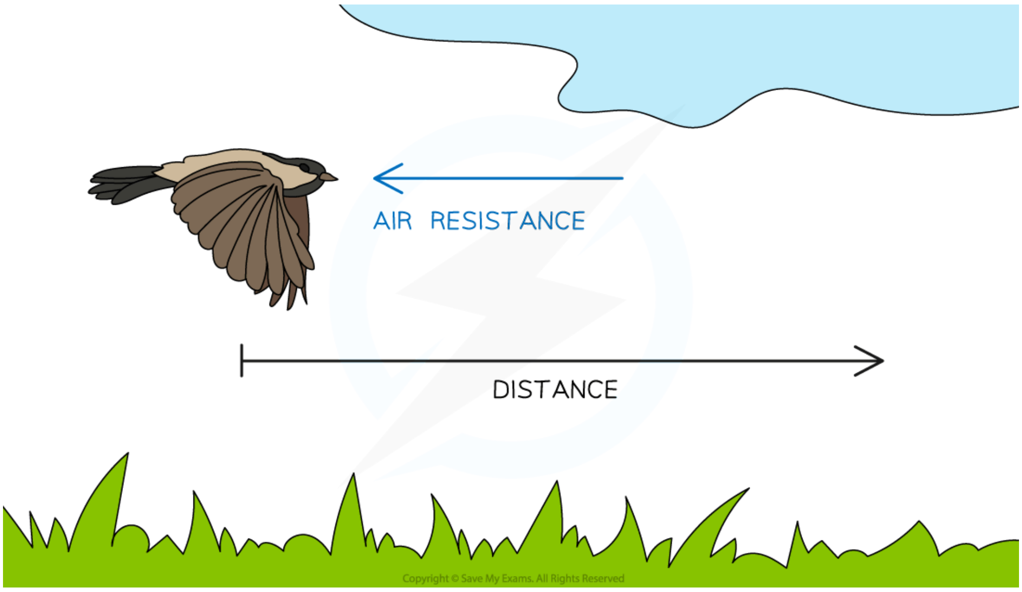
- Work is done on a ball when it is lifted to a height:
  - A force is required to lift the ball
  - Work is done against the weight force to lift the ball through the gravitational field
  - Energy is transferred as work in done



The weight on the ball produced by the gravitational field does work on the ball over a distance

- Work is done when a bird flies through the air
  - A force is required to overcome the drag force
  - Work is done against the drag force as the bird flies over a distance
  - Energy is transferred as work is done

Work done by a bird



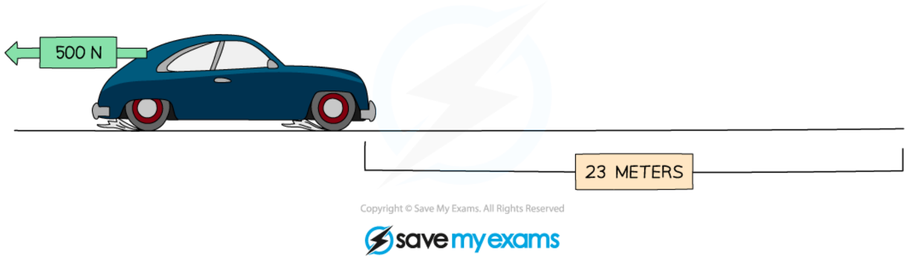
The bird does work against air resistance (drag) as it flies through the air

Your notes

Your notes

Worked Example

A car moving at speed begins to apply the brakes. The brakes of the car apply a force of 500 N, which brings it to a stop after 23 m.



Calculate the work done by the brakes in stopping the car.

Answer:

Step 1: List the known quantities

- Distance, $d = 23 \text{ m}$
- Force, $F = 500 \text{ N}$

Step 2: Write out the work done equation

$$W = Fd$$

Step 3: Calculate the work done on the car by the brakes

$$W = 500 \times 23$$

$$W = 11\,500 \text{ J}$$

Step 4: Round to an appropriate number of significant figures

- The lowest number of significant figures in the input values in 1 s.f. (500 N)
- Therefore, the final answer must be rounded to 1 s.f.

$$W = 10\,000 \text{ N} \left(1 \text{ s.f.}\right)$$

Examiner Tips and Tricks

Remember to always convert the distance into **metres** and force into n**ewtons** so that the work done is in **joules** or **newton-metres**

Power

- Power is defined as:

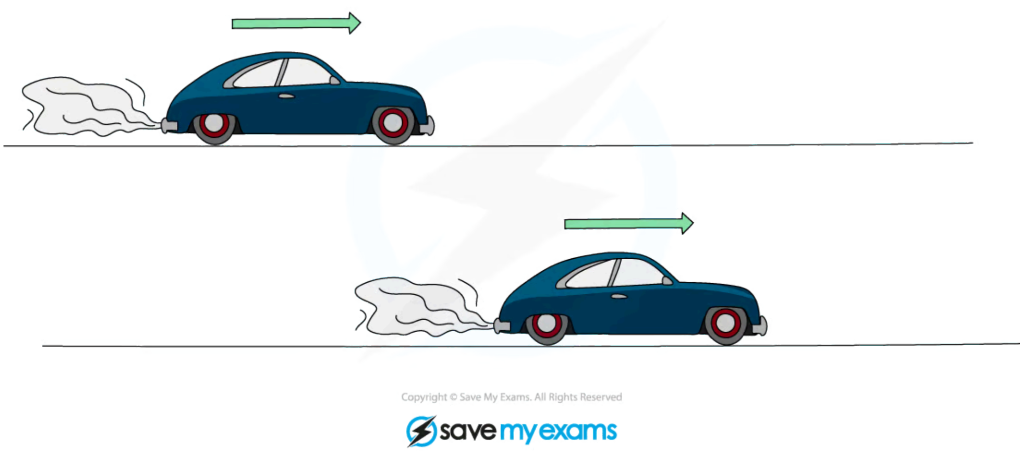
Work done per unit time

- Since work done is equal to energy transferred, **power** is also defined as:

Energy transferred per unit time

- Machines, such as car engines, transfer energy from one energy store to another constantly over a period of **time**
    - The **rate** of this energy transfer, or the rate of work done, is **power**
- **Time** is an important consideration when it comes to **power**
- Two cars transfer the **same amount of energy**, or do the **same amount of work** to accelerate over a distance
- If one car has **more power**, it will transfer that energy, or do that work, in a **shorter amount of time**

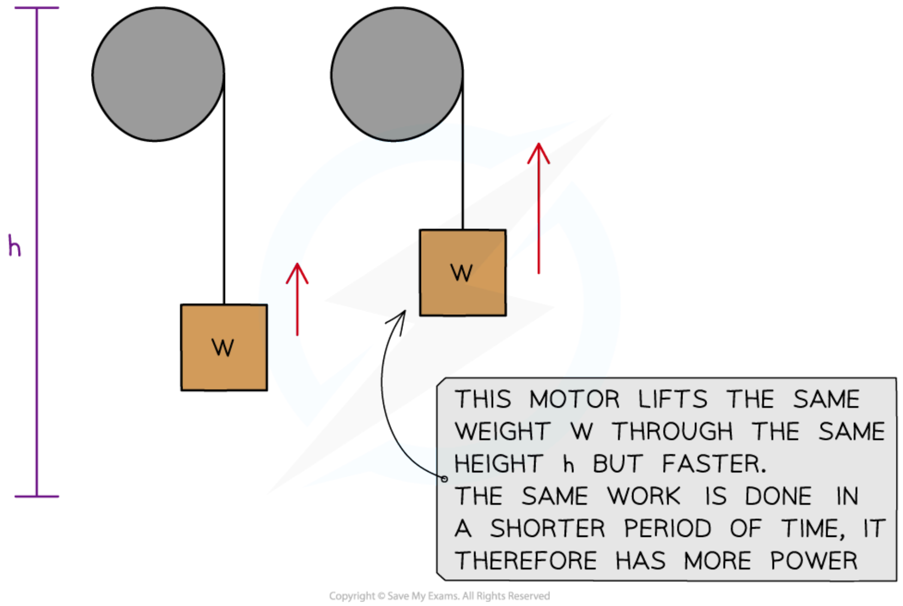
Two cars with different power ratings doing the same amount of work



Two cars accelerate to the same final speed, but the one with the most power will reach that speed sooner

- Two electric motors:
    - lift the same weight
    - by the same height

- but one motor lifts it **faster** than the other
- The motor that lifts the weight faster has more **power**



Two motors with different powers

Power ratings

- **Power ratings** are given to appliances to show the amount of energy transferred per unit time
- Common power ratings are shown in the table below:

Power ratings table

Appliance	Power rating
A torch	1 W
An electric light bulb	100 W
An electric oven	10 000 W = 10 kW
A train	1 000 000 W = 1 MW
Saturn V space rocket	100 MW
Large power station	10 000 MW
Global power demand	100 000 000 MW

Your notes

A star like the Sun	100 000 000 000 000 000 000 MW

- 1 kW = 1000 W (1 kilowatt = 1000 watts)
- 1 MW = 1 000 000 W (1 megawatt = 1 million watts)

Calculating Power

The power equations

- There are two equivalent forms of the power equation
- Power can be expressed in terms of work done W:

$$P = \frac{W}{t}$$

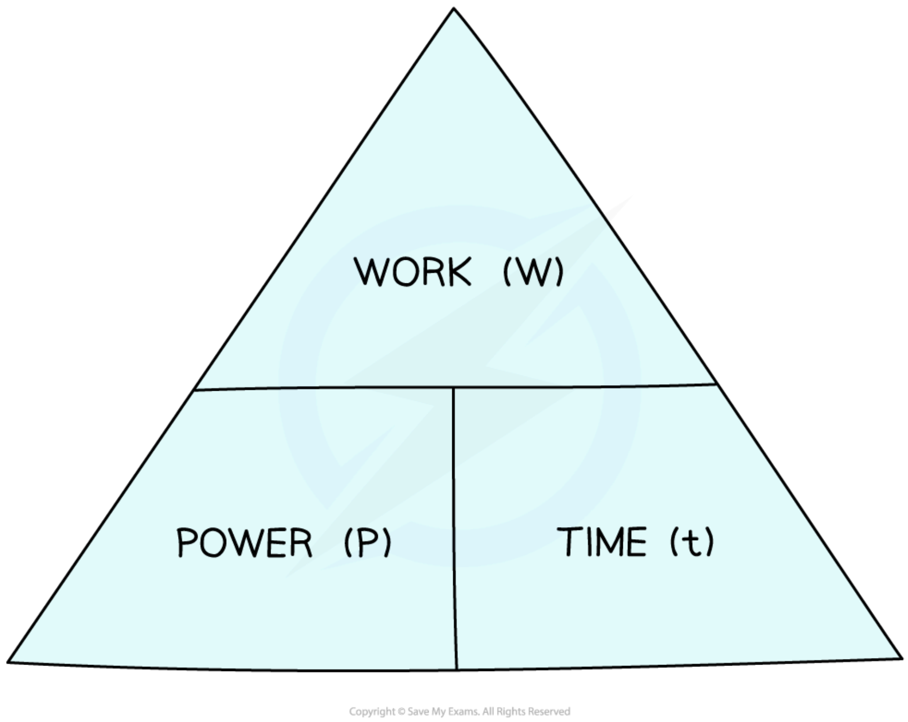
- Or, power can be expressed in terms of energy transferred ΔE:

$$P = \frac{\Delta E}{t}$$

- Where:
  - P = power measured in watts (W)
  - W = work done, measured in newton metres (N m)
  - t = time measured in seconds (s)
  - ΔE = energy transferred, measured in joules (J)
- Note that these two equations may be written slightly differently, but they represent the same thing
  - A transfer of energy (work done) over time

Power equation triangle

Your notes



To use a formula triangle, simply cover up the quantity you wish to calculate and the structure of the equation is revealed

- Using an equation triangle is covered in more depth in the revision note Speed & velocity

Worked Example

Calculate the energy transferred when an iron with a power rating of 2000 W is used for 5 minutes.

Answer:

Step 1: List the known values

- Power, $P = 2000 \text{ W}$
- Time, $t = 5 \text{ minutes}$

Step 2: Convert minutes into seconds

- $1 \text{ min} = 60 \text{ s}$

$$5 \text{ min} \times 60 \text{ s} = 300 \text{ s}$$

Step 3: Write down the power equation in terms of energy

$$P = \frac{\Delta E}{t}$$

Your notes

Your notes

Step 4: Rearrange to make energy transferred, *ΔE, the subject*

$$\Delta E = Pt$$

Step 5: Substitute in the known values

$$\Delta E = 2000 \times 300$$

$$\Delta E = 600\,000 \text{ J}$$

Examiner Tips and Tricks

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

In your IGCSE exam, you will be expected to use both equations and to be able to rearrange them. You may be required to calculate the energy transferred in a previous question part, so always check back through the question if you seem to be missing a value!

Your notes

Efficiency of energy transfer

- The **efficiency** of a system is a measure of the amount of **useful** and **wasted energy** in an energy transfer
- Efficiency is defined as:

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

Calculating efficiency

Extended tier only

- Efficiency is represented as a percentage and can be calculated using two equations
- Efficiency in terms of **energy**:

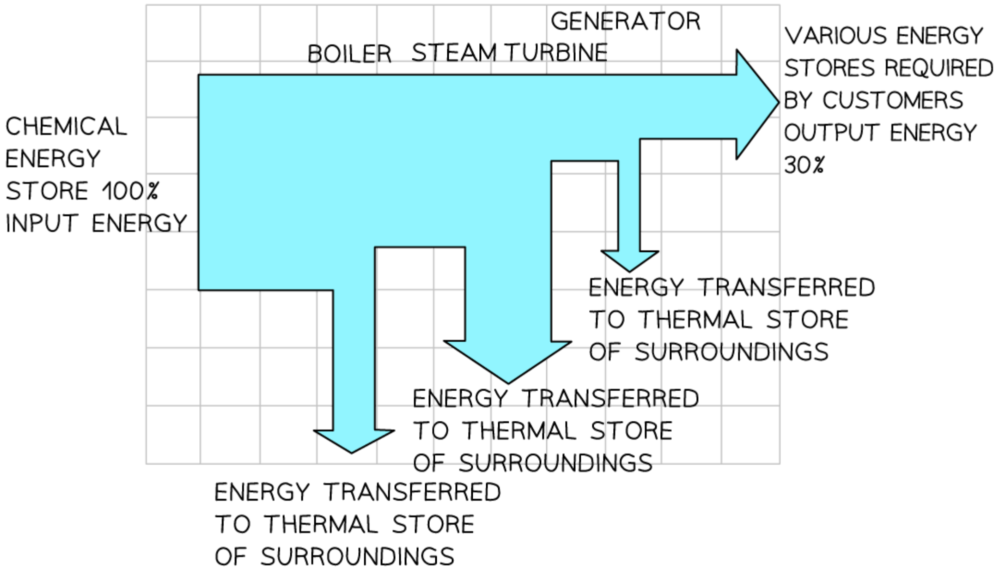
$$\text{efficiency} = \frac{\text{useful energy output}}{\text{total energy input}} (\times 100\%)$$

- Efficiency in terms of **power**:

$$\text{efficiency} = \frac{\text{useful power output}}{\text{total power input}} (\times 100\%)$$

- In the production of electricity:
  - Energy is used to heat water to produce steam
  - The steam turns a turbine
  - The turbine turns a generator
  - The generator produces electricity
    - At each stage of this process, energy is dissipated to the surroundings
- The overall efficiency of a typical thermal power station is approximately 30%
  - This means that 70% of the energy transferred from the power station to the National Grid is **wasted energy**

Sankey diagram of electricity production



Sankey diagram showing the energy transfers involved in generating electricity in a gas-fired power station

Your notes

Worked Example

An electric motor lifts a 7.2 kg load through a height of 5.0 m in 3 seconds. The efficiency of the motor is 35%.

Calculate the power supplied to the motor.

Answer:

Step 1: List the known quantities

- Mass of load, m = 7.2 kg
- Change in height, h = 5.0 m
- Acceleration of free fall, g = 9.8 m/s^2
- Time, t = 3 s
- Efficiency = 35% or 0.35

Step 2: Calculate the power output of the motor

- The power supplied by the motor is the work done, or energy transferred, to lift the load

$$\text{power output} = \frac{\Delta E}{t}$$

- ΔE is equal to the change in gravitational potential energy as the load is lifted

$$\Delta E_P = mg\Delta h$$

$$\Delta E_p = 7.2 \times 9.8 \times 5.0 = 352.8 \text{ J}$$

- Therefore:

$$\text{power output} = \frac{352.8}{3} = 117.6 \text{ W}$$

Step 3: Write down the efficiency equation in terms of power

$$\text{efficiency} = \frac{\text{useful power output}}{\text{total power input}}$$

Step 4: Rearrange to make power input the subject

$$\text{power input} = \frac{\text{power output}}{\text{efficiency}}$$

Step 5: Substitute the values into the power input equation

$$\text{power input} = \frac{117.6}{0.35}$$

$$\text{power input} = 336 \text{ W}$$

Examiner Tips and Tricks

Efficiency can be given 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**

Your notes