HL IB Physics

Work, Energy & Power

Contents

Principle of Conservation of Energy

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**
- In physics, a **system** is defined as:
  An object or group of objects
- Defining the system in physics is a way of **narrowing** the parameters to **focus** only on what is relevant to the situation being observed
- When a system is in **equilibrium**, nothing changes and so nothing happens
- When there is a **change** in a system, things happen, and when things happen, **energy is transferred**

Types of Energy

Type of Energy	Description
Kinetic Energy	Energy of a moving object
Potential Energy	Stored energy due to an object's position or state
Thermal (Heat) Energy	Energy related to the temperature of an object due to the motion of its particles
Chemical Energy	Energy stored in chemical bonds (e.g., in food, fuel, batteries)
Electrical Energy	Energy of moving electric charges
Nuclear Energy	Energy stored in the nucleus of atoms, released during nuclear reactions
Light (Radiant) Energy	Energy carried by electromagnetic waves (e.g., sunlight, X-rays)
Sound Energy	Energy carried by sound waves through a medium
Elastic Energy	Stored energy in stretched or compressed objects (e.g., springs, rubber bands)
Gravitational Energy	Potential energy due to an object's height and gravity

- Kinetic energy, gravitational potential energy, and elastic potential energy are collectively known as **mechanical** energy types

Energy Dissipation

- No energy transfer is 100% efficient
- When energy is transformed from one form to another, some of the energy is **dissipated** to the surroundings
- Dissipated energy usually ends up as **thermal energy** transferred to the **surroundings** where it cannot be easily used for another purpose
- Therefore, dissipated energy is usually regarded as **wasted energy**

- A kettle transforms **electrical** energy into **thermal** energy
- The **thermal** energy in the **heating element** is transferred to **thermal** energy in the **water**
  - Some thermal energy is also transferred to the **plastic casing**
  - Some thermal energy is also **dissipated** to the surrounding air
- The energy transfers that are useful for heating the water are considered **useful** energy transfers
- The energy transfers that are not useful for heating the water are considered **wasted** energy transfers

Applications of Energy Conservation

- In mechanical systems, the **energy transferred** is equivalent to the **work done**
  - A falling object (in a vacuum, where no energy is not dissipated into the surroundings) transfers its gravitational potential energy into kinetic energy
  - Horizontal mass on a spring transfers its elastic potential energy into kinetic energy
  - A battery or cell transfers its chemical energy into electrical energy
  - A car transfers chemical energy from the fuel into kinetic energy of the car
  - A person bouncing on a trampoline is transferring energy from elastic potential to kinetic to gravitational potential

- 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

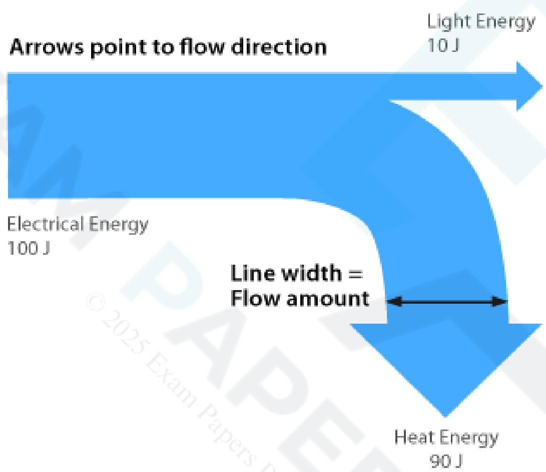
Spring Energy Conservation

- When a vertical spring oscillates, its energy is converted into other forms
- Although the total energy of the spring will remain constant, it will have changing amounts of:
  - **Elastic** potential energy (EPE)
  - **Kinetic** energy (KE)
  - **Gravitational** potential energy (GPE)
- At position **A:**
  - The spring has some EPE because it is slightly compressed
  - Its KE is **zero** because it is stationary
  - Its **GPE is at a maximum** because the mass is at its highest point
- At position **B:**
  - The spring has some EPE because it is slightly stretched
  - Its **KE is at a maximum** as it passes through the equilibrium position at its maximum speed
  - It has some GPE because the mass is still raised
- At position **C:**
  - The spring has its **maximum** EPE because the spring is at its maximum extension
  - Its KE is **zero** because it is stationary
  - Its **GPE is at a minimum** because the mass is at its lowest point
- For a **horizontal** mass on a spring system, you do not need to consider the gravitational potential energy because this does not change

Sankey Diagrams

Sankey Diagrams

- **Sankey diagrams** are used to represent energy transfers
- The arrow in a Sankey diagram represents the transfer of energy:
  - The end of the arrow pointing to the **right** represents the energy that ends up in the **desired** store (the **useful energy output**)
  - The end(s) that point(s) down represents the **wasted energy**



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 going to each store
- As a result of the conversation of energy:

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 downward, representing energy transferred by heating

Work Done

Work Done

- The **work done** by a force is equivalent to a **transfer of energy**
  - The units of work done are newton metres
  - 1 N m = 1 J
- The work done by a **resultant force** on a system is equal to the change in energy in that system

- Mechanical work is defined as

> **The transfer of energy when an external force causes an object to move over a certain distance**

- If a constant force is applied in the line of an object's displacement (i.e. parallel to it), the work done can be calculated using the equation:

$$W = Fs$$

- Where:
  - W = work done (J)
  - F = constant force applied (N)
  - s = 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

- When pushing a block, **work is done against friction** and energy is transferred from the man to the block
- The kinetic energy is transferred to other forms of energy such as heat and sound
- When plotting a graph of average force applied against displacement, the **area** under the graph is equal to the **work done**
- 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:

$$W = Fs\cos\theta$$

- Where ***θ*** is the angle, in degrees, between the direction of the force and the motion of the object
  - When ***θ*** is 0 (the force is in the direction of motion) then $\cos\theta = 1$ and $W = Fs$
- For **horizontal** motion, cos *θ* is used
- For **vertical** motion, sin *θ* is used
  - Always consider the horizontal and vertical components of the force
  - The component needed is the one that is **parallel to the displacement**

Kinetic Energy

Kinetic Energy

- Kinetic energy (E_k) is the energy an object has due to its **translational motion** (i.e. because it's moving)
  - The **faster** an object is moving, the **greater** its kinetic energy
- When an object is falling, it is **gaining** kinetic energy since it is **accelerating** under gravity
- This energy is transferred from the gravitational potential energy it is losing
- An object will **maintain** this kinetic energy unless its **speed** or **mass** changes
- Kinetic energy can be calculated using the following equation:

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

- Where:
  - E_k = kinetic energy (J)
  - m = mass (kg)
  - v = velocity (m s^{-1})
- Another quantity that also depends on mass m and velocity v is **momentum**
- Therefore, kinetic energy can be written in terms of momentum p, using the equation

$$E_k = \frac{p^2}{2m}$$

- Where:
  - p = momentum (kg m s^{-1})
- This form is very useful in particle physics, when comparing the momentum and kinetic energy of a particle

Gravitational Potential Energy

Gravitational Potential Energy

- Gravitational potential energy is the energy stored in a mass due to its position in a gravitational field
  - If a mass is **lifted** up, it will **gain** gravitational potential energy
  - If a mass **falls**, it will **lose** gravitational potential energy
- The equation for gravitational potential energy when **close** to the **surface** of the **Earth** is:

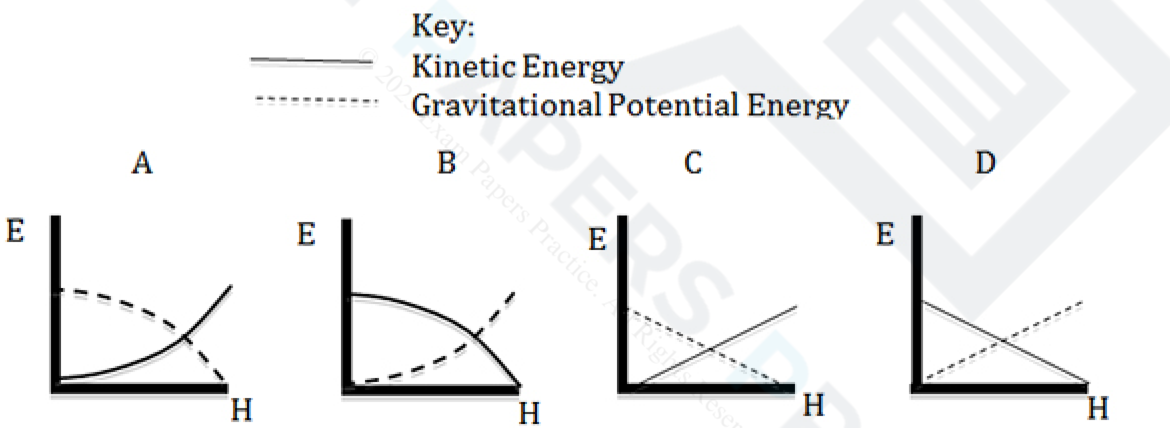
$$\Delta E_p = mg\Delta h$$

- Where:
  - ΔE_p = gravitational potential energy (J)
  - m = mass (kg)
  - g = gravitational field strength (9.8 N kg^{-1})
  - Δh = change in height (m)

- The potential energy on the Earth's surface at ground level is usually taken to be equal to zero
  - However, any position can be taken as zero if you are calculating the change in gravitational potential energy
- This equation is only relevant for energy changes in a **uniform gravitational field** (such as near the Earth's surface)
- A different potential energy is used in the gravitational fields topic, because the field is no longer uniform outside of the Earth's surface

Gravitational Potential Energy vs Height

- The two graphs below show how the gravitational potential energy changes with height for a ball being thrown up in the air and then falling down (ignoring air resistance)



- Since the graphs are straight lines, gravitational potential energy and height are said to have a **linear** relationship
  - These graphs would be identical for gravitational potential energy against time instead of height

Elastic Potential Energy

Elastic Potential Energy

- Elastic potential energy is defined as

  The energy stored within a material (e.g. in a spring) when it is stretched or compressed

- Therefore, for a material obeying Hooke's Law, elastic potential energy is equal to:

$$E_H = \frac{1}{2}k\Delta x^2$$

- Where:
  - k = spring constant of the spring (N m^{-1})
  - Δx = extension of the spring (m)
- This can also be written as:

$$E_H = \frac{1}{2}F\Delta x$$

- Where:
  - F = restoring force (N)
- This force is the same restoring force as in Hooke's law: $F = k\Delta x$

- It is very dangerous if a wire under large stress suddenly breaks
- This is because the elastic potential energy of the strained wire is **converted** into kinetic energy

$$E_H = E_K$$

$$\frac{1}{2}k\Delta x^2 = \frac{1}{2}mv^2$$

$$v \propto \Delta x$$

- This equation shows
  - The greater the **extension** of a wire Δx the greater the **speed** v it will have when it breaks

Worked example

A car's shock absorbers make a ride more comfortable by using a spring that absorbs energy when the car goes over a bump. One of these springs, with a spring constant of 50 kN m^{-1} is fixed next to a wheel and compressed a distance of 10 cm.

Calculate the energy stored by the compressed spring.

Answer:

Step 1: List the known values

- Spring constant, $k = 50$ kN m^{-1} = 50×10^3 N m^{-1}
- Compression, $x = 10$ cm = 10×10^{-2} m

Step 2: Substitute the values into the elastic potential energy equation

$$E_H = \frac{1}{2} \times (50 \times 10^3) \times (10 \times 10^{-2})^2 = 250 \text{ J}$$

Conservation of Mechanical Energy

Mechanical Energy

- Mechanical energy is the **sum** of kinetic energy, gravitational potential energy and elastic potential energy

$$\text{Mechanical energy} = E_k + \Delta E_p + E_H$$

- An example of a system that has mechanical energy is a spring and mass system
- The **change** in the total mechanical energy of a system should be interpreted in terms of the **work done** on the system by any non-conservative force
  - A non-conservative force is one that dissipates energy away from the system, such as friction
- When a vertical spring is extended and contracted, its energy is converted into other forms
- Although the total energy of the spring will remain constant, it will have changing amounts of:
  - **Elastic** potential energy (E_H or EPE)
  - **Kinetic** energy (E_k or KPE)
  - **Gravitational** potential energy (E_p or GPE)
- When a vertical mass is hanging on a spring and it moves up and down, its energy will convert between the three in various amounts

Position	GPE	KE	EPE
A	Maximum	Zero	Some
B	Some	Maximum	Some
C	Minimum	Zero	Maximum

- For a **horizontal** mass on a spring system, there is no gravitational potential energy to consider because this is constant
  - The spring would only convert between kinetic and elastic potential energy

Conservation of Mechanical Energy

- In the absence of frictional, resistive forces, the total **mechanical** energy of a system is **conserved**
  - This means the total kinetic, gravitational potential and elastic potential energy is the same throughout the motion of the system
  - Because the total energy of a system is always conserved
- 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 that involve falling, such as skiing and skydiving
- Using the principle of conservation of energy, and taking any drag forces as negligible:

Loss in gravitational potential energy = Gain in kinetic energy

- Another example is if a ball on a spring oscillates vertically
- In this case:

Loss in gravitational potential energy = Gain in elastic potential energy

- The change in energy is the **work done** on the system. The types of changes depend on the system

Energy & Power

Energy & Power

- The power of a mechanical process is the **rate at which energy is transferred**
- This energy transferred is the **work done**
- Therefore, power is:

The rate of work done (energy transfer)

- **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 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**
- Power can be calculated using the equation:

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

- Where:
  - P = power (W)
  - ΔW = change in work done (J)
  - Δt = time interval (s)
  - F = force (N)
  - v = velocity (m s^{-1})

- The equation with F and v 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

- Power is also used in electricity
- Appliances are given a power rating, for example, 1000 W

- The power ratings indicate the amount of energy transferred per second to the appliance

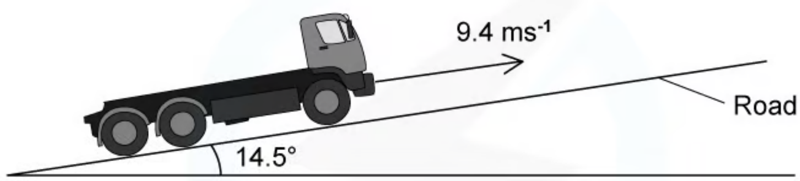
The Watt

- Power is measured in **watts (W)**
- 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 1 joule of energy in 1 second

Worked example

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



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: List the known quantities

- Angle of slope, $\theta = 14.5°$
- Mass, $m = 3500$ kg
- Speed, $v = 9.4$ m s^{-1}

Step 2: Write out the equation for the power of a constant force at a constant speed

$$P = Fv$$

Step 3: Calculate the constant force

- The force needed to move the lorry up the slope is that which overcomes the component of the weight force pulling it down the slope

$$F = mg\sin\theta$$

$$F = 3500 \times 9.81 \times \sin(14.5)$$

$$F = 8596.8 \text{ N}$$

Step 4: Determine the power

$$P = 8596.8 \times 9.4$$

$$P = 80\,810 \text{ W} = 81\,000 \text{ W (2 s.f.)}$$

Efficiency Formula

Efficiency Formula

- 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 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 energy is transferred from the thermal store of a kettle's heating element to the thermal store of the water, this is **useful** energy
  - When energy is transferred to the plastic or metal casing of the kettle and to the surrounding air, this energy is **wasted**

- Efficiency is represented as a fraction, and can be calculated using the equation:

$$\eta = \frac{E\,(output)}{E\,(input)} = \frac{P\,(output)}{P\,(input)}$$

- Where:
  - η = efficiency (the greek letter "eta")
  - E = energy (J)
  - P = power (W)
- To turn this equation into a percentage, just × 100 %
- It can also be written in words as:

$$\eta = \frac{\text{useful work out}}{\text{total work in}} = \frac{\text{useful power out}}{\text{total power in}}$$

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 (as a percentage)

$$\eta = \frac{useful\ power\ out}{useful\ power\ in} \times 100\%$$

Step 2: Rearrange equation for the useful power in

$$useful\ power\ in = \frac{userful\ power\ out \times 100\%}{\eta}$$

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 = $\frac{353.16}{3}$ = 117.72 W

Step 4: Substitute values into power input equation

$$useful\ power\ in = \frac{117.72 \times 100}{35} = 336\ W$$

Energy Density

Energy Density

- A fuel is anything that can be burned to produce heat, which can be used for an engine to work
- The energy that an amount of fuel can provide is an important consideration for the modern world
  - When this is compared by **volume** of fuel, it is known as **energy density**
- Energy density is a measure of the amount of **energy per unit volume** of a fuel
  - Energy density is measured in J m^{-3}
- Different fuels contain different amounts of energy, which make them suitable for certain uses e.g. petrol for running vehicles
- Some examples are:

Energy Density Table

Fuel	Energy density / MJ L^{-1}
coal	38
liquid hydrogen	9
methane (natural gas)	0.3
diesel	39
biodiesel	33
vegetable oil	30
wood	3

- 1 L (litre) is 0.001 m^3
- This means that we can get **more** energy per unit volume of coal than we can wood
- Fuels are chosen for specific uses based on a number of factors, including energy density, safety of use and pollutants released in combustion