

THEME A · SPACE, TIME AND MOTION

SL & HL ≈ 30 min read

IB Physics A.3 Work, Energy and Power — Notes (SL & HL)

Written by Evan Kotronis for the IB Diploma Physics course (first assessment 2025). A.3 is identical for SL and HL — there is no additional HL content in this sub-topic.



SL A.3 questions



HL A.3 questions



Flashcards



Energy conservation simulation

What this page covers

- ✓ The principle of conservation of energy
- ✓ Work as a transfer of energy, and Sankey diagrams to show energy transfers
- ✓ Calculating the work done by a constant force at an angle to the displacement
- ✓ The link between the work done by the resultant force and the change in a system's energy
- ✓ Mechanical energy: kinetic, gravitational potential and elastic potential energy
- ✓ When mechanical energy is conserved, and how frictional and resistive forces change it
- ✓ Power as the rate of doing work, including $P = Fv$
- ✓ Efficiency in terms of energy or power
- ✓ Energy density of fuels

In one minute

- Energy is never created or destroyed — it is transferred between stores and between systems. **Work done = energy transferred.**
- $W = Fs \cos \theta$: only the component of the force along the displacement does work. A force perpendicular to the motion does no work.
- Work done by the **resultant** force = change in kinetic energy.
- Mechanical energy = $E_k + E_p + E_H$. With no friction or drag it stays constant; non-conservative forces change it by the work they do.
- Power is the rate of energy transfer: $P = \frac{\Delta W}{\Delta t} = Fv$.
- Efficiency = useful output ÷ total input (energy or power). Sankey diagrams show this to scale.
- Energy density is the energy released per unit volume of a fuel.

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What does the principle of conservation of energy say?

Energy cannot be created or destroyed. It can only be transferred from one store to another, or from one system to another, so the total energy of an isolated system is constant.

- A **system** is the part of the universe you choose to study (a ball, a car and its fuel, the Earth–ball pair). Everything else is the surroundings. Always be clear which system you mean.
- Energy is stored in different ways: kinetic, gravitational potential, elastic potential, chemical, nuclear, internal (thermal) energy of particles, and so on.
- Energy moves between stores by **doing work** (a force acting through a displacement), by electrical work, by heating (B.1) and by radiation and waves (C).
- In every real transfer some energy ends up as **thermal energy of the surroundings**. It is not destroyed, but it is spread out and much harder to use. We say it has been **dissipated**.

Conservation of energy is one of the most powerful problem-solving tools in physics: if you can account for every store at the start and at the end, you can find an unknown speed, height or force without knowing the details of the motion in between.

How do you calculate the work done by a force?

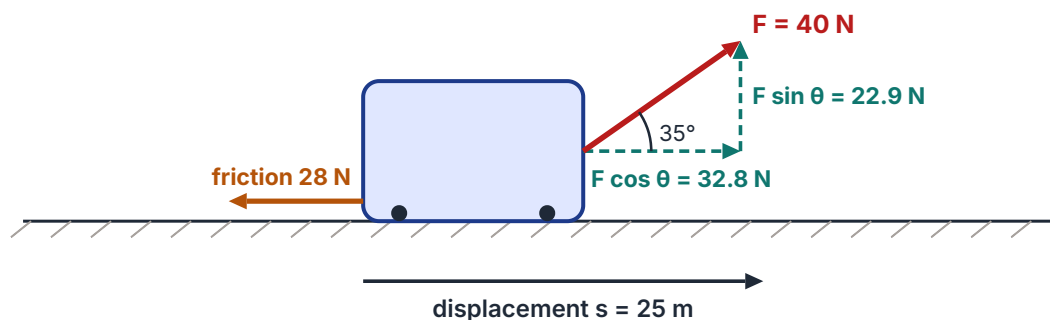
The work done by a constant force is the product of the force and the displacement of its point of application in the direction of the force: $W = F s \cos \theta$.

$$W = F s \cos \theta$$

- W = work done (J)
- F = magnitude of the constant force (N)
- s = magnitude of the displacement (m)
- θ = angle between the force and the displacement

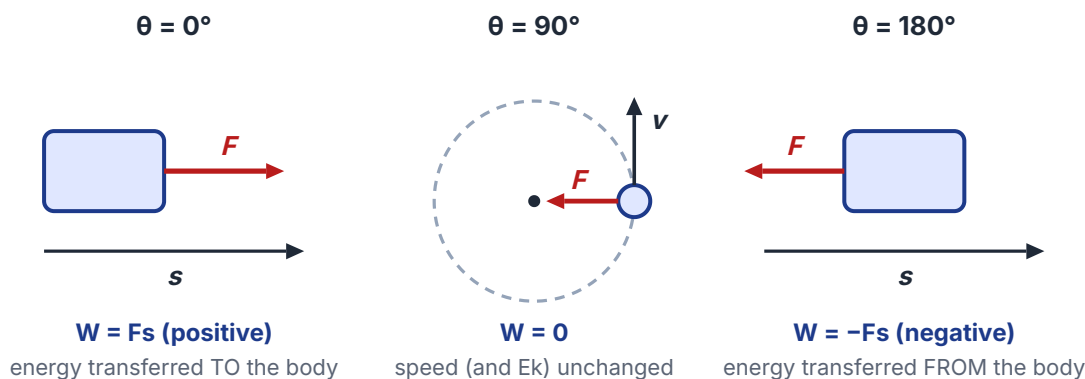
This equation is in the data booklet. Work is a **scalar**; its unit is the joule, $1 \text{ J} = 1 \text{ N m} = 1 \text{ kg m}^2 \text{ s}^{-2}$.

Only the component of F along the displacement does work: $W = Fs \cos \theta$



Only the horizontal component $F \cos \theta$ acts along the displacement, so only it does work. Forces drawn to scale. The weight and the normal force act vertically, at 90° to the displacement, so they do no work (not shown).

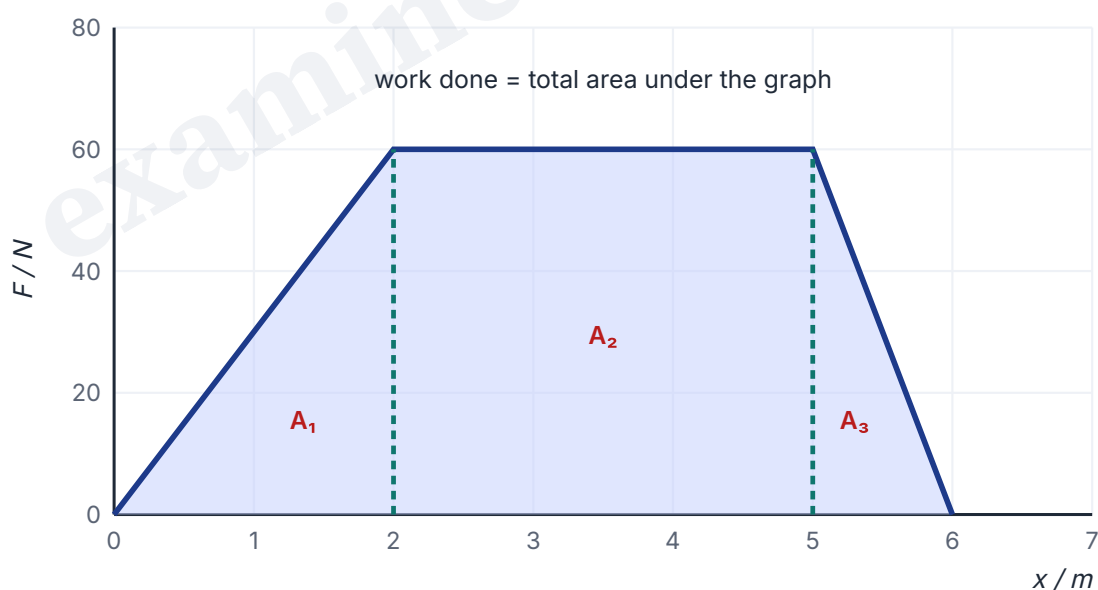
Angle θ	Work done	Example	What happens to the energy
0°	$W = Fs$ (maximum, positive)	engine force on a car moving forwards	energy transferred to the body
$0^\circ < \theta < 90^\circ$	positive, less than Fs	pulling a suitcase by a handle at an angle	energy transferred to the body
90°	zero	centripetal force in circular motion; normal force on a body sliding on a level floor	no transfer — speed unchanged by this force
180°	$W = -Fs$ (negative)	friction or braking force	energy transferred from the body



The sign of the work depends only on the angle between force and displacement. In uniform circular motion the centripetal force is always perpendicular to the velocity, so it does no work and the kinetic energy stays constant.

When the force is not constant: area under a force–displacement graph

$W = Fs \cos \theta$ needs a constant force. If the force varies, the work done is the **area under the force–displacement graph** (force component along the displacement plotted against displacement). Split the area into rectangles, triangles and trapezia, or count squares under a curve.



The force on a trolley varies with displacement. The work done is the total shaded area, $A_1 + A_2 + A_3$.

WORKED EXAMPLE 1 Easy · Calculate

A traveller pulls a 12 kg suitcase 25 m along level ground with a constant force of 40 N at 35° above the horizontal (see the first diagram above). A

constant friction force of 28 N acts on the suitcase. The suitcase starts from rest.

Calculate (a) the work done by the pulling force, (b) the work done by friction, (c) the work done by the weight of the suitcase and (d) the speed of the suitcase after 25 m.

(a) $W = Fs \cos \theta = 40 \times 25 \times \cos 35^\circ = 819 \text{ J} \approx 8.2 \times 10^2 \text{ J}$

(b) Friction is opposite to the displacement, $\theta = 180^\circ$: $W = 28 \times 25 \times \cos 180^\circ = -700 \text{ J}$

(c) The weight is vertical and the displacement horizontal, $\theta = 90^\circ$: **0 J** (the same is true for the normal force).

(d) Total work done on the suitcase = $819 - 700 = 119 \text{ J}$. This equals the gain in kinetic energy (see the next section):

$$\frac{1}{2}(12)v^2 = 119 \Rightarrow v = \sqrt{\frac{2 \times 119}{12}} = 4.5 \text{ m s}^{-1} (4.46 \text{ m s}^{-1})$$

WORKED EXAMPLE 2 Medium · Determine (graph)

A trolley of mass 15 kg is at rest on a horizontal frictionless track. A horizontal force acts on it, varying with displacement x as shown in the force–displacement graph above.

Determine (a) the work done on the trolley over the first 6.0 m and (b) the speed of the trolley at $x = 6.0 \text{ m}$.

(a) Work = area under the graph:

$$A_1 = \frac{1}{2}(2.0)(60) = 60 \text{ J}; A_2 = (3.0)(60) = 180 \text{ J}; A_3 = \frac{1}{2}(1.0)(60) = 30 \text{ J}$$

$$W = 60 + 180 + 30 = 270 \text{ J}$$

Treating the whole area as one trapezium gives the same in one step: $\frac{1}{2}(3.0 + 6.0)(60) = 270 \text{ J}$.

(b) The track is frictionless, so all 270 J becomes kinetic energy:

$$\frac{1}{2}(15)v^2 = 270 \Rightarrow v = \sqrt{36} = 6.0 \text{ m s}^{-1}$$

How is work linked to a change in energy?

Work done by a force is a transfer of energy. The work done by the resultant force on a body is equal to the change in its kinetic energy.

- When a force does **positive** work on a body, energy is transferred *to* it; when it does **negative** work, energy is transferred *from* it.
- More generally, the work done on a system by an external resultant force equals the change in the system's total energy.
- Work done *against* a force: lifting a box at constant speed, you do work $mg\Delta h$ against gravity, and that energy is stored as gravitational potential energy.

Where does $E_k = \frac{1}{2}mv^2$ come from?

A constant resultant force F accelerates a mass m from u to v over a displacement s . From A.2, $F = ma$, and from A.1, $v^2 = u^2 + 2as$, so $as = \frac{1}{2}(v^2 - u^2)$. Multiplying by m :

$$Fs = mas = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$$

The work done by the resultant force equals the change in $\frac{1}{2}mv^2$ — this quantity is the kinetic energy. This is exactly why energy methods can replace the equations of motion when you need a speed but not a time.

EXAM TIP — WHICH WORK?

Read the stem carefully: “work done **by the resultant (net) force**” equals the change in kinetic energy only. “Work done by the engine” or “work done against friction” is something different. If net work W is done on a body, its final kinetic energy is $E_{k,\text{initial}} + W$, whatever else happens — any work

done by gravity is already included inside W , so do not add or subtract a potential-energy change a second time.

What are kinetic, gravitational potential and elastic potential energy?

Mechanical energy is the sum of the kinetic energy, the gravitational potential energy and the elastic potential energy of a system.

Store	Equation (data booklet)	Symbols and SI units	Notes
Kinetic energy (translational)	$E_k = \frac{1}{2}mv^2 = \frac{p^2}{2m}$	m mass (kg), v speed (m s^{-1}), p momentum (kg m s^{-1})	scalar, never negative; doubling v multiplies E_k by 4
Change in gravitational potential energy	$\Delta E_p = mg\Delta h$	$g = 9.8 \text{ m s}^{-2}$, Δh change in height (m)	only close to the Earth's surface, where g is constant; only <i>changes</i> matter, so choose any zero level
Elastic potential energy	$E_H = \frac{1}{2}k\Delta x^2$	k spring constant (N m^{-1}), Δx extension or compression (m)	only while Hooke's law ($F_H = -kx$, A.2) holds

Kinetic energy and momentum

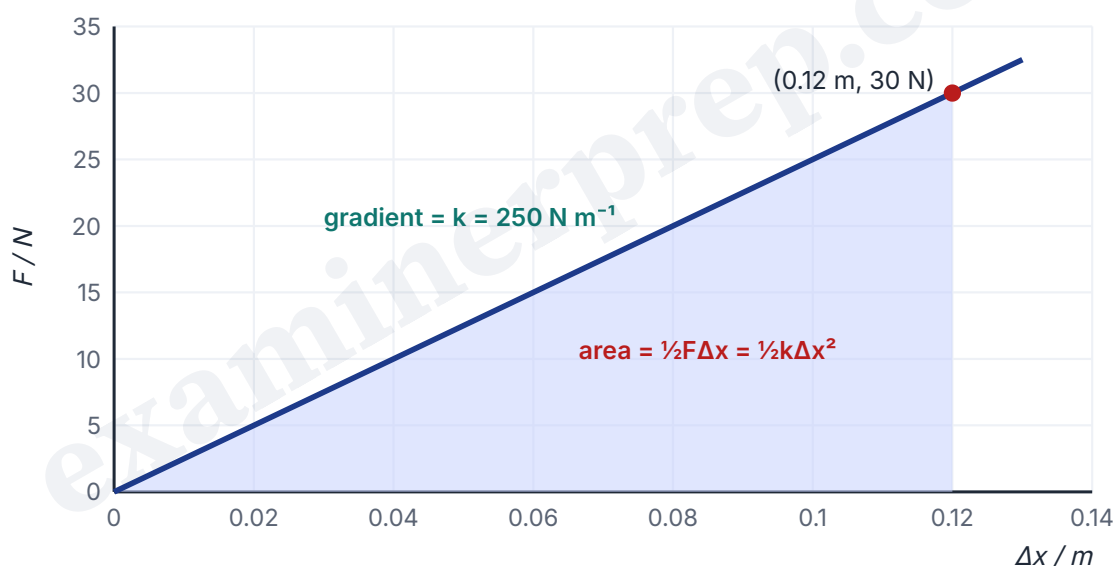
Since $p = mv$, $E_k = \frac{1}{2}mv^2 = \frac{(mv)^2}{2m} = \frac{p^2}{2m}$. This form is useful in collisions and explosions (A.2), where momentum is known: two bodies with the **same momentum** have kinetic energies in the inverse ratio of their masses, so the lighter body carries more kinetic energy.

Gravitational potential energy

Lifting a mass m through Δh at constant speed needs an upward force mg acting through Δh , so the work done against gravity is $mg\Delta h$. The work done by gravity depends only on the change in height, **not on the path**: sliding down a long gentle slope or falling vertically through the same height gives the same ΔE_p .

Elastic potential energy

For a spring obeying Hooke's law the force rises in proportion to the extension. The work done stretching it is the area of the triangle under the force–extension graph: $\frac{1}{2}F\Delta x = \frac{1}{2}(k\Delta x)\Delta x = \frac{1}{2}k\Delta x^2$.



Force–compression graph for the spring in worked example 3. The gradient is the spring constant; the shaded area is the elastic potential energy stored.

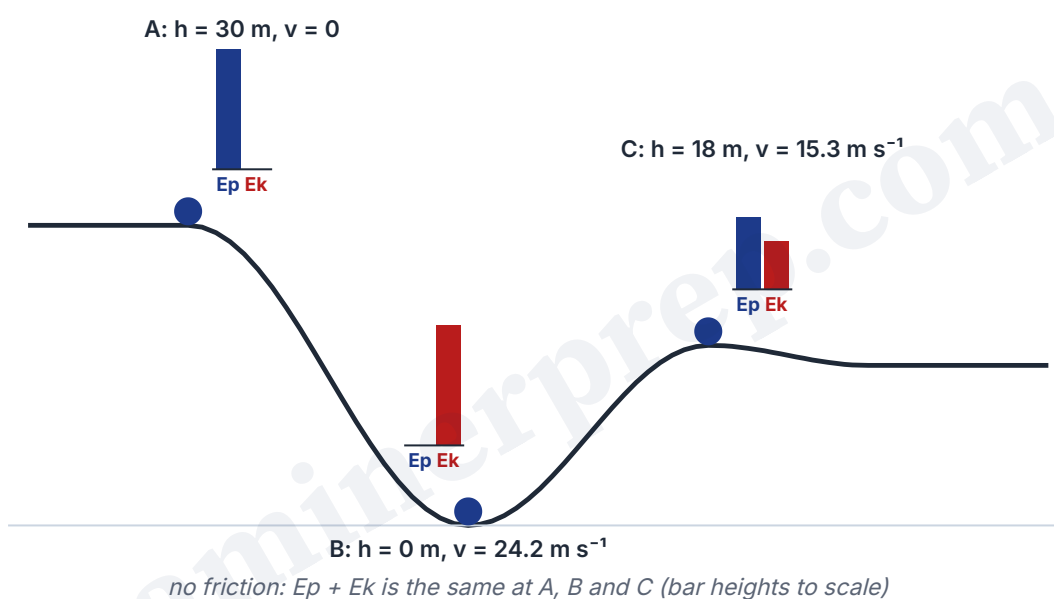
- E_H depends on Δx^2 : doubling the compression stores **four times** the energy.
- The same formula applies to compression and extension.

When is mechanical energy conserved?

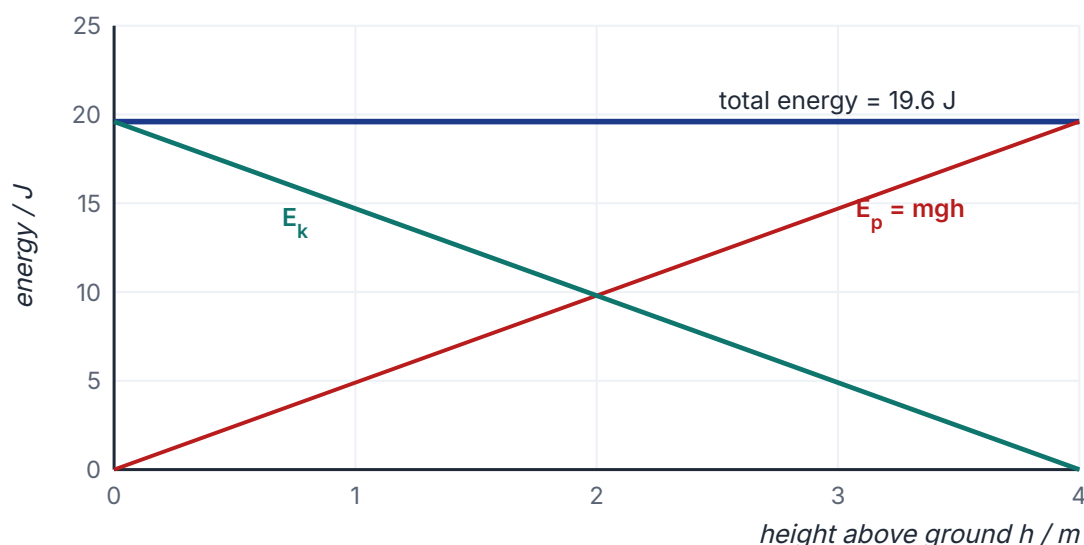
If no friction, drag or other resistive force acts, a system keeps the same total mechanical energy: work done only transforms energy between kinetic, gravitational potential and elastic potential energy.

$$E_k + E_p + E_H = \text{constant} \quad (\text{no friction or drag})$$

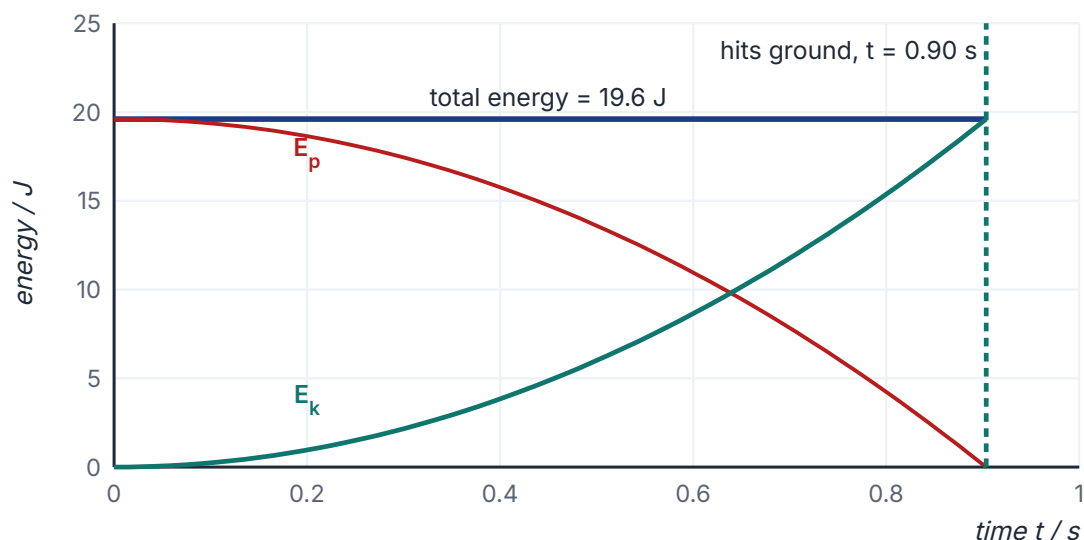
- A falling ball: $E_p \rightarrow E_k$. A pendulum: $E_p \leftrightarrow E_k$ twice per oscillation. A spring launcher: $E_H \rightarrow E_k \rightarrow E_p$.
- For a body falling from rest through h : $mgh = \frac{1}{2}mv^2 \Rightarrow v = \sqrt{2gh}$. The mass cancels.
- Energy gives speeds, heights and compressions — but never times or directions. For those you still need kinematics.



A roller-coaster car released from rest at A on a frictionless track. Gravitational potential energy (blue) becomes kinetic energy (red) and back; the total bar height is the same at every point. The speed depends only on the drop from A, not on the shape of the track.



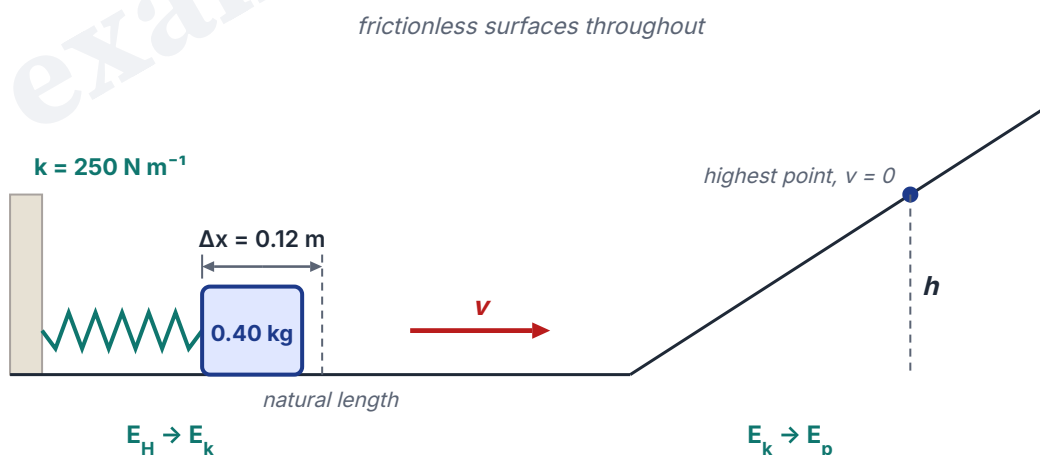
Energy against height for a 0.50 kg ball dropped from rest at 4.0 m, with no air resistance. Both graphs are straight lines because $\Delta E_p = mg\Delta h$.



The same ball plotted against time. The curves are parabolas, because the height fallen is $\frac{1}{2}gt^2$. The two energies cross at 0.64 s, not halfway through the time of fall (0.45 s), because the ball covers more distance per second as it speeds up.

TRY IT YOURSELF

A.3 Energy Conservation simulation: change the height, mass and friction and watch the kinetic, potential and thermal energy bars update — the total never changes.



Worked example 3: the spring's elastic potential energy becomes kinetic energy, which becomes gravitational potential energy on the ramp.

WORKED EXAMPLE 3 Medium · Show that / Calculate

A block of mass 0.40 kg is pushed against a spring of spring constant 250 N m⁻¹, compressing it by 0.12 m. The block is released, leaves the spring and

slides along a horizontal surface and then up a ramp. All surfaces are frictionless.

(a) Show that the block leaves the spring with a speed of about 3 m s^{-1} . (b) Calculate the maximum height h the block reaches on the ramp. (c) Calculate the momentum of the block as it leaves the spring and use it to confirm the kinetic energy.

(a) $E_H = \frac{1}{2}k\Delta x^2 = \frac{1}{2}(250)(0.12)^2 = 1.80 \text{ J}.$

All of it becomes kinetic energy: $\frac{1}{2}(0.40)v^2 = 1.80 \Rightarrow v = \sqrt{\frac{2 \times 1.80}{0.40}} =$
 $3.00 \text{ m s}^{-1} \approx 3 \text{ m s}^{-1}$

(b) At the highest point the block is momentarily at rest, so $mgh = 1.80$:
 $h = \frac{1.80}{0.40 \times 9.8} = \textbf{0.46 m}$ (0.459 m)

(c) $p = mv = 0.40 \times 3.00 = \textbf{1.2 kg m s}^{-1}$; $E_k = \frac{p^2}{2m} = \frac{1.2^2}{2 \times 0.40} = 1.8 \text{ J}$
✓

Note that the height does not depend on the angle of the ramp — only on the energy available.

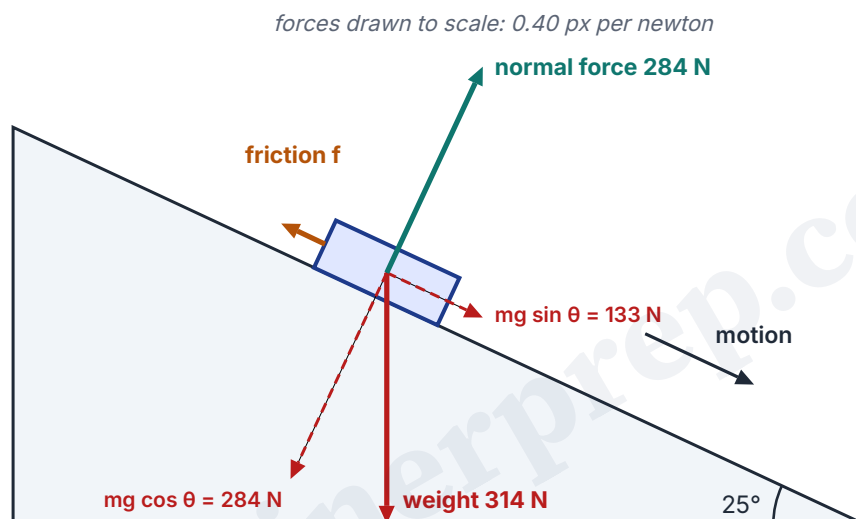
How do friction and other non-conservative forces change mechanical energy?

Non-conservative forces change a system's total mechanical energy by exactly the work they do on it. Examples are friction, drag and the driving force of an engine or a person.

$$\Delta E_{\text{mech}} = W_{\text{non-conservative}}$$

- **Conservative forces** (gravity, the elastic force of a spring) only move energy between mechanical stores; the work they do does not depend on the path.

- **Friction and drag** always act against the motion, so they do negative work: mechanical energy decreases, and the same amount appears as **internal (thermal) energy** of the surfaces, the body and the air. Total energy is still conserved.
- A **driving force** (engine, motor, muscle) can do positive work and *increase* mechanical energy, using energy from another store (chemical, electrical).
- For friction of constant size f over a path length d : energy dissipated $= fd$.



Forces on the sledge in worked example 4, drawn to scale. The normal force is perpendicular to the motion and does no work; friction does negative work and dissipates mechanical energy.

WORKED EXAMPLE 4 Medium · Determine

A child on a sledge, total mass 32 kg, starts from rest at the top of a straight snowy slope 18 m long, inclined at 25° to the horizontal. At the bottom the speed is 9.0 m s^{-1} .

Determine (a) the loss of gravitational potential energy, (b) the gain in kinetic energy and (c) the average friction force on the sledge.

(a) Vertical drop $\Delta h = 18 \sin 25^\circ = 7.61 \text{ m}$.

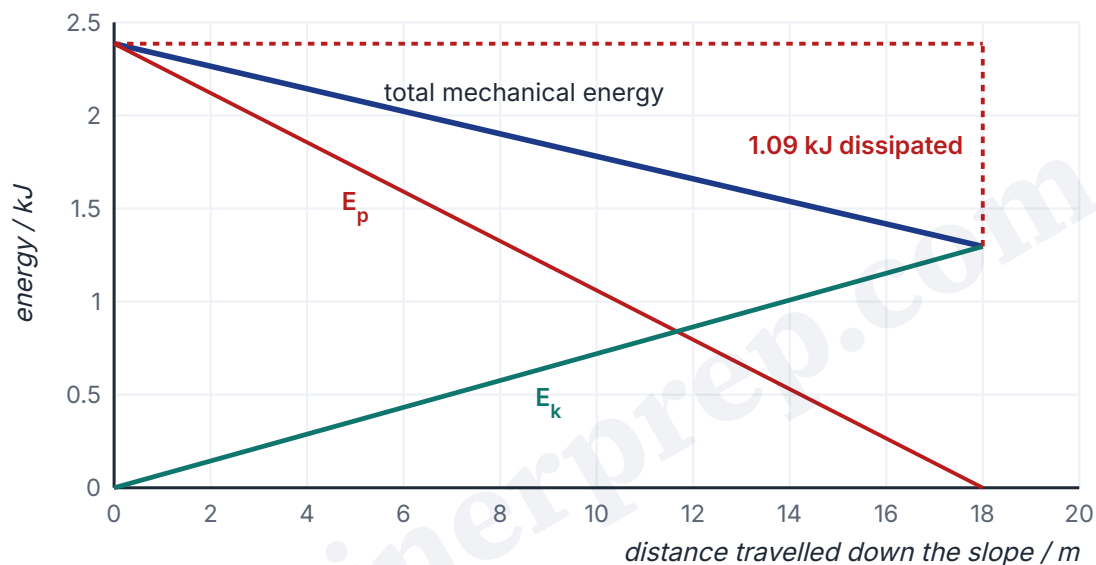
$$\Delta E_p = mg\Delta h = 32 \times 9.8 \times 7.61 = 2.39 \times 10^3 \text{ J}$$

(b) $\Delta E_k = \frac{1}{2}(32)(9.0)^2 = 1.30 \times 10^3 \text{ J}$

(c) Mechanical energy dissipated = $2386 - 1296 = 1090 \text{ J}$. This equals the work done against friction over the 18 m slope:

$$f \times 18 = 1090 \Rightarrow f = \mathbf{61 \text{ N}} \text{ (60.5 N using unrounded values; accept 60–61 N)}$$

Check: without friction the sledge would reach $\sqrt{2 \times 9.8 \times 7.61} = 12.2 \text{ m s}^{-1}$ — friction has cost it almost half of its potential energy.



Energy of the sledge in worked example 4 against distance travelled. Potential energy falls and kinetic energy rises, but their sum (blue) falls steadily: the gap is the energy dissipated by friction.

What is power and how do you use $P = Fv$?

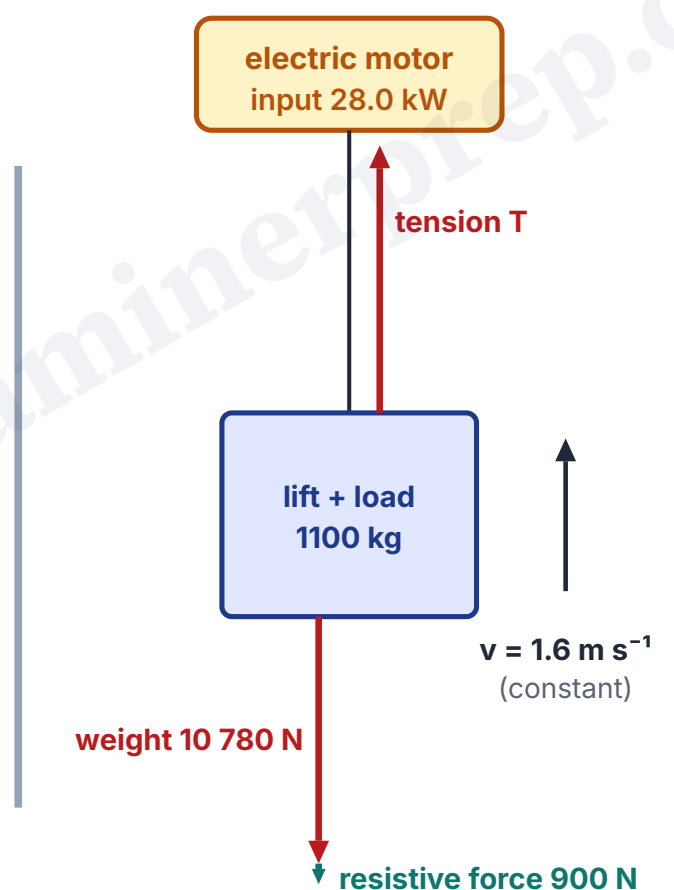
Power is the rate of doing work, or the rate of energy transfer.

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

- P = power (W, where $1 \text{ W} = 1 \text{ J s}^{-1}$)
- ΔW = work done, or energy transferred (J), in time Δt (s)
- F = force doing the work, acting along the velocity (N)
- v = speed of the point where the force acts (m s^{-1})

Both forms are in the data booklet. $P = Fv$ follows from $\Delta W = F\Delta s$: dividing by Δt gives $P = F \frac{\Delta s}{\Delta t} = Fv$.

- **Constant velocity:** the resultant force is zero (A.2), so the driving force equals the total resistive force (plus $mg \sin \theta$ on a slope). Use *that* driving force in $P = Fv$.
- **Maximum speed:** on level ground, a vehicle reaches its top speed when its maximum power output is all used against resistive forces: $v_{\max} = P_{\max} / F_{\text{resistive}}$.
- The kilowatt-hour (kWh) is a unit of *energy*, not power: $1 \text{ kWh} = 1000 \times 3600 = 3.60 \times 10^6 \text{ J}$ (this conversion is in the data booklet).



forces on the lift drawn to scale; $T = \text{weight} + \text{resistive force}$

Worked example 5: a lift rising at constant velocity. The cable tension balances the weight plus the resistive force, so the resultant force is zero.

How do you calculate efficiency and draw a Sankey diagram?

Efficiency is the ratio of the useful energy (or power) output to the total energy (or power) input.

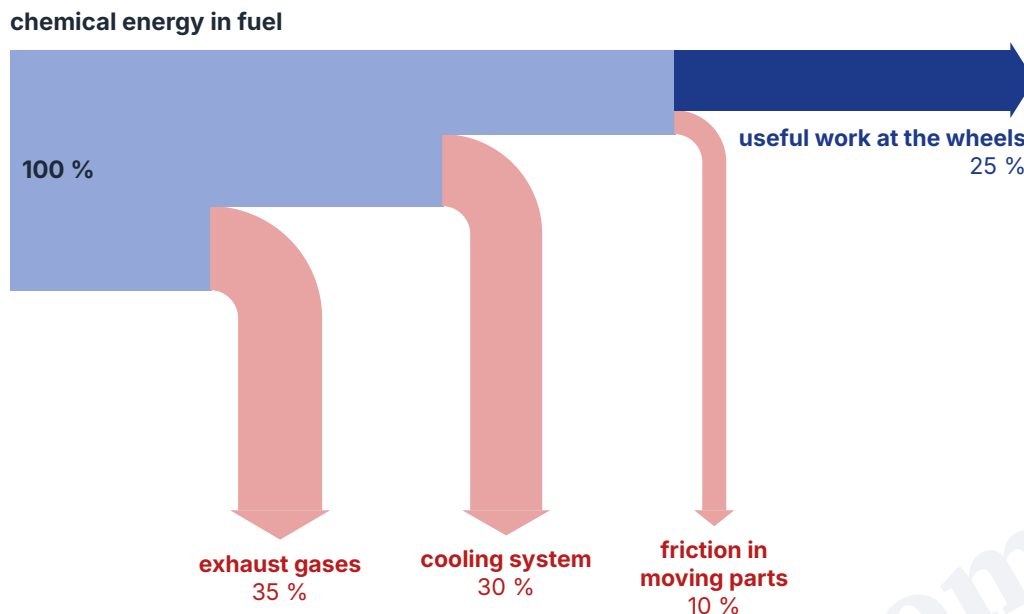
$$\eta = \frac{E_{\text{output}}}{E_{\text{input}}} = \frac{P_{\text{output}}}{P_{\text{input}}}$$

- η has no unit. Give it as a decimal (0.25) or a percentage (25 %); it is always less than 1 for a real device.
- The data booklet writes it as useful work out $\div$ total work in = useful power out $\div$ total power in.
- Wasted energy = input – useful output. It is almost always dissipated as thermal energy of the surroundings.

Sankey diagrams

A Sankey diagram shows every energy transfer in a device as an arrow whose **width is proportional to the energy (or power)**.

- The input arrow enters from the left; the useful output continues straight on; wasted energy branches off (usually downwards).
- Energy is conserved, so the width of the input equals the sum of the widths of all the outputs.
- Label each arrow with the form of energy and its value or percentage.
Efficiency = useful width $\div$ input width.



arrow widths drawn to scale: width $\propto$ energy (or power)

Sankey diagram, drawn to scale, for a typical petrol car engine (rounded typical values). Only about a quarter of the chemical energy in the fuel does useful work; the rest is transferred to the surroundings as thermal energy.

WORKED EXAMPLE 5 Hard · Determine

A lift and its passengers have a total mass of 1100 kg. The lift rises at a constant speed of 1.6 m s^{-1} . A constant resistive force of 900 N acts on it. The electric motor takes an input power of 28.0 kW.

Determine (a) the rate at which the gravitational potential energy of the lift increases, (b) the tension in the cable and the output power of the motor, (c) the overall efficiency of the system and (d) the energy wasted while the lift rises 24 m. Draw a Sankey diagram for the system.

(a) Rate of gain of $E_p = mgv = 1100 \times 9.8 \times 1.6 = 1.72 \times 10^4 \text{ W (17.2 kW)}$

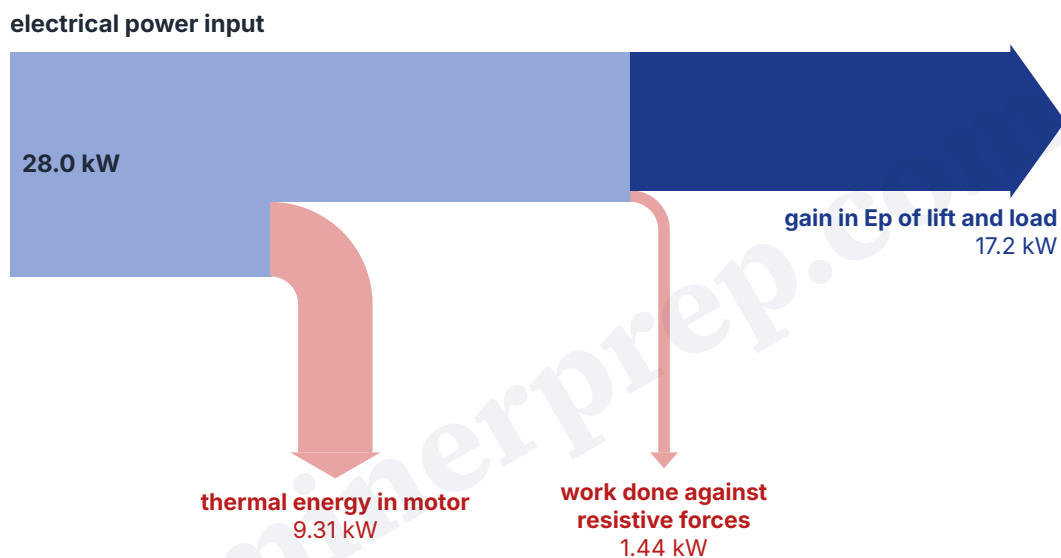
(b) Constant velocity, so resultant force = 0: $T = mg + f = 10\,780 + 900 = 1.17 \times 10^4 \text{ N}$

Motor output power = $Tv = 11\,680 \times 1.6 = 18.7 \text{ kW}$

(c) Useful output = gain in E_p : $\eta = \frac{17\,248}{28\,000} = 0.616 \approx 0.62 \text{ (62 \%)}$

(d) Time to rise 24 m = $24/1.6 = 15$ s. Energy input = $28.0 \times 10^3 \times 15 = 4.20 \times 10^5$ J; useful = $mg\Delta h = 1100 \times 9.8 \times 24 = 2.59 \times 10^5$ J.
 Energy wasted = $4.20 \times 10^5 - 2.59 \times 10^5 = 1.6 \times 10^5$ J (1.61×10^5 J)

Sankey diagram: input 28.0 kW splits into 17.2 kW useful (gain in E_p),
 $fv = 900 \times 1.6 = 1.44$ kW against resistive forces and $28.0 - 18.7 = 9.31$ kW dissipated in the motor.



arrow widths drawn to scale: width $\propto$ energy (or power)

Sankey diagram for the lift in worked example 5, drawn to scale. The three output widths add up to the input width: $17.2 + 1.44 + 9.31 = 28.0$ kW.

What is the energy density of a fuel?

The energy density of a fuel is the energy that can be released per unit volume of the fuel. Its unit is J m^{-3} .

$$\text{energy density} = \frac{E}{V}$$

- Not in the data booklet — learn it. Some sources quote energy released **per unit mass** (J kg^{-1}), often called specific energy. Read the unit in the question: to convert, multiply the per-kilogram value by the density of the fuel.

- A high energy density matters wherever space is limited — vehicle fuel tanks, aircraft, portable devices.
- The energy actually *usable* also depends on the efficiency of the device that burns or uses the fuel.

Energy source	Approximate energy per unit mass / MJ kg ⁻¹	Approximate energy density / J m ⁻³
Natural gas (at atmospheric pressure)	55	4×10^7
Lithium-ion battery	0.8	2×10^9
Hydrogen (compressed to 700 bar)	120	5×10^9
Wood (dry)	16	1×10^{10}
Ethanol	27	2.1×10^{10}
Petrol (gasoline)	46	3.4×10^{10}
Diesel	45	3.7×10^{10}
Coal	29	4×10^{10}
Uranium-235 (complete fission, E.4)	8×10^7	2×10^{18}

Values are typical, rounded figures; real fuels vary. Notice that hydrogen has a very large energy per kilogram but a small energy per cubic metre, because even highly compressed hydrogen gas has a low density — which is why fuel-tank size is a challenge for hydrogen vehicles. Nuclear fuel releases about a million times more energy per kilogram than fossil fuels, and tens of millions of times more per unit volume.

WORKED EXAMPLE 6 Hard · Show that / Determine

A car of mass 1400 kg climbs a straight road inclined at 4.0° to the horizontal at a constant speed of 22 m s^{-1} . The total resistive force on the

car is 650 N. The engine's efficiency is 28 % and petrol has an energy density of $3.4 \times 10^{10} \text{ J m}^{-3}$.

(a) Show that the useful power output of the engine is about 35 kW. (b) Determine the volume of petrol, in litres, used per kilometre of the climb.

(a) Constant velocity, so driving force = component of weight down the slope + resistive force:

$$F = mg \sin \theta + 650 = 1400 \times 9.8 \times \sin 4.0^\circ + 650 = 957 + 650 = 1607 \text{ N}$$

$$P = Fv = 1607 \times 22 = \mathbf{3.54 \times 10^4 \text{ W} \approx 35 \text{ kW}}$$

(b) Useful work per km = $Fs = 1607 \times 1000 = 1.607 \times 10^6 \text{ J}$.

$$\text{Energy from fuel} = \frac{1.607 \times 10^6}{0.28} = 5.74 \times 10^6 \text{ J}.$$

$$\text{Volume} = \frac{5.74 \times 10^6}{3.4 \times 10^{10}} = 1.69 \times 10^{-4} \text{ m}^3 = \mathbf{0.17 \text{ L per km}} \text{ (about 17 L per 100 km)}$$

On a level road only the 650 N resistive force must be overcome, and the same calculation gives about 6.8 L per 100 km — the slope more than doubles the fuel use.

Exam tips for A.3

EXAM TIP 1 — SAY "THERMAL ENERGY", NOT "HEAT"

When friction or drag does work, the energy goes into the **internal (thermal) energy** of the surfaces and surroundings. Do not write that it is "lost as heat": in IB physics "heat" means energy transferred because of a temperature difference (B.1), and mark schemes regularly refuse it in this context.

EXAM TIP 2 — θ IS THE ANGLE BETWEEN **F** AND **S**

In $W = Fs \cos \theta$, θ is the angle between the force and the **displacement**, not the angle of a slope or of the string to the vertical. Sketch both vectors

before you substitute. For gravity, skip the angle altogether: the work done is $mg\Delta h$ whatever the path.

EXAM TIP 3 — STATE YOUR ENERGY ASSUMPTION

When you use conservation of mechanical energy, say so and give the assumption: "no friction or air resistance, so loss in E_p = gain in E_k ". In a "show that" question, write the energy equation, show the substitution and give the answer to at least one more significant figure than the stated value (3.0 m s^{-1} or 3.00 m s^{-1} , not " 3 m s^{-1} ").

EXAM TIP 4 — $P = Fv$ AT CONSTANT VELOCITY

At constant velocity the resultant force is zero, so do not put the resultant force into $P = Fv$. Use the **driving force**, which equals the total opposing force (resistive forces plus $mg \sin \theta$ on a slope).

EXAM TIP 5 — SANKEY DIAGRAMS ARE DRAWN TO SCALE

Three things earn the marks: arrow widths proportional to the energies, the input width equal to the sum of the output widths, and every arrow labelled with its form of energy and value. Use a ruler and choose a simple scale such as 1 mm per 1 %.

Common misconceptions

Misconception	Why it is wrong	Correct idea
Energy is "used up" or "lost" in a machine.	Energy cannot be destroyed.	Energy is transferred; the wasted part is dissipated as thermal energy of the surroundings.
Carrying a bag along a level corridor at constant speed does work on it against gravity.	Your upward force is perpendicular to the horizontal displacement.	$W = Fs \cos 90^\circ = 0$; no energy is transferred to the bag.
The work done by the resultant force equals the gain in potential energy.	Gravity is one of the forces making up the resultant.	Work done by the resultant force = change in <i>kinetic</i> energy.
Doubling the speed doubles the kinetic energy.	$E_k \propto v^2$.	Doubling the speed multiplies E_k by four (and doubling momentum does the same).
A car moving at constant velocity needs no power.	Resistive forces do negative work all the time.	The engine must supply $P = F_{\text{resistive}} v$ just to keep the speed constant.
Efficiency is measured in joules or watts, and can reach 100 %.	It is a ratio of two energies (or powers).	η has no unit and is always less than 1 for a real device.

How this topic connects

Power and other rates of change across the course

Power is the rate of change of energy, just as velocity is the rate of change of displacement and acceleration the rate of change of velocity (A.1), force the rate of change of momentum (A.2), and current the rate of flow of charge (B.5). The same graph skills apply everywhere: on an energy–time graph the gradient is the power, and on a power–time graph the area is the energy transferred.

The limits of $mg\Delta h$: when constant g stops being a good assumption

The equation assumes the gravitational force mg is constant throughout the change in height. That is only true when Δh is tiny compared with the Earth's radius (about 6400 km). Further away, g decreases with distance ($g = GM/r^2$, D.1). HL students then use gravitational potential energy $E_p = -GMm/r$ (D.1, HL), which places the zero of potential energy at infinite separation rather than at the ground.

Energy conservation beyond mechanics: circuits, oscillators, fields and orbits

Conservation of energy is a law built from a vast body of experimental evidence, and it is never found to fail. It reappears in electric circuits (B.5), in simple harmonic motion (C.1), in the motion of charges in fields (D.3), as the first law of thermodynamics and in orbits and escape speed (B.4 and D.1, HL) and in mass–energy equivalence in nuclear reactions (E.3). Momentum (A.2), angular momentum (A.4, HL) and charge are also conserved — conservation laws let physicists predict outcomes without knowing every detail of the process.

Tools & inquiry — measuring energy transfers in the lab

- **Efficiency of a small motor:** lift a known mass through a measured height. Input energy = VIt (from a voltmeter, ammeter and stopwatch, or a joulemeter); useful output = $mg\Delta h$. Repeat for different loads and plot efficiency against load.
- **Elastic potential energy:** record force–extension data for a spring or rubber band; the energy stored is the area under the graph. For a rubber band the loading and unloading curves differ, and the area between them is the energy dissipated.
- **Mechanical energy:** use light gates or video analysis to measure the speed of a trolley at the bottom of a ramp. Compare $\frac{1}{2}mv^2$ with $mg\Delta h$; the shortfall estimates the work done against friction.
- Fractional uncertainties combine: in $E_k = \frac{1}{2}mv^2$, the fractional uncertainty in v counts twice.

Key equations

Equation	Use	In data booklet?
$W = Fs \cos \theta$	work done by a constant force	yes
$W_{\text{resultant}} = \Delta E_k$	work done by the resultant force	no — learn it
$E_k = \frac{1}{2}mv^2 = \frac{p^2}{2m}$	kinetic energy	yes
$\Delta E_p = mg\Delta h$	change in gravitational potential energy near the Earth's surface	yes
$E_H = \frac{1}{2}k\Delta x^2$	elastic potential energy (Hooke's law region)	yes
$\Delta E_{\text{mech}} = W_{\text{non-conservative}}$	effect of friction, drag or a driving force	no — learn it
$P = \frac{\Delta W}{\Delta t} = Fv$	power	yes
$\eta = \frac{E_{\text{output}}}{E_{\text{input}}} = \frac{P_{\text{output}}}{P_{\text{input}}}$	efficiency	yes
energy density = $\frac{E}{V}$	energy released per unit volume of fuel	no — learn it

Check your understanding

1. A ball on a string moves in a horizontal circle at constant speed. How much work does the tension do in one revolution? Explain.

None. The tension acts towards the centre, perpendicular to the velocity at every instant, so $W = Fs \cos 90^\circ = 0$. The kinetic energy, and therefore the speed, does not change.

2. The momentum of a body is doubled. By what factor does its kinetic energy change?

$$E_k = \frac{p^2}{2m}, \text{ so doubling } p \text{ multiplies } E_k \text{ by } 2^2 = 4.$$

3. A 62 kg student runs up a flight of stairs with a vertical height of 3.6 m in 4.5 s. Estimate the useful power developed.

$$P = \frac{mg\Delta h}{\Delta t} = \frac{62 \times 9.8 \times 3.6}{4.5} = 490 \text{ W (486 W).}$$

The total power developed by the student's muscles is greater, because much of the energy is dissipated as thermal energy in the body.

4. A 60 W filament lamp emits 3.0 W of visible light. Calculate its efficiency and describe its Sankey diagram.

$$\eta = \frac{3.0}{60} = 0.050 \text{ (5.0 \%)}.$$

The 60 W input arrow splits into a thin 3.0 W "light" arrow continuing straight on and a wide 57 W arrow for thermal energy transferred to the surroundings — 19 times wider than the useful arrow.

5. Petrol has an energy density of $3.4 \times 10^{10} \text{ J m}^{-3}$. What volume of petrol stores 1.0 GJ?

$$V = \frac{E}{\text{energy density}} = \frac{1.0 \times 10^9}{3.4 \times 10^{10}} = 0.029 \text{ m}^3, \text{ about 29 litres.}$$

Practise A.3 with exam-style questions

Original Paper 1A, 1B and 2 questions on work, energy and power, with full mark schemes. Tick the questions you want and print them as your own test.

SL A.3 questions

HL A.3 questions

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[← Previous: A.2 Forces and momentum](#) · [Next: A.4 Rigid body mechanics \(HL only\)](#) →

SL students: A.4 and A.5 are HL only. Continue with [B.1 Thermal energy transfers](#) → (and the [SL B.1 questions](#)).

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