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The big picture

? Guiding question(s)

- How are concepts of work, energy and power used to predict changes within a system?
- How can a consideration of energetics be used as a method to solve problems in kinematics?
- How can transfer of energy be used to do work?

Keep the guiding questions in mind as you learn the science in this subtopic. You will be ready to answer them at the end of this subtopic. The guiding questions require you to pull together your knowledge and skills from different sections, to see the bigger picture and to build your conceptual understanding.

Have you ever wondered what it feels like to accelerate from 0 to 200 $km\,h^{-1}$ in a few seconds? Visitors to the Six Flags Great Adventure amusement park in New Jersey, USA, who dare to ride the Kingda Ka, the tallest roller coaster in the world, are accelerated to 206 $km\,h^{-1}$ in just 3.5 seconds in order to climb 139 m up its steep track. Watch this video for a front-seat view of the Kingda Ka ride.

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Official Kingda Ka POV 2021 - 4k 60fps - Six Flags Great Adventure

Video 1. The Kingda Ka ride.

More information for video 1

The video provides a thrilling front-seat perspective of the Kingda Ka roller coaster, one of the fastest and tallest roller coasters in the world. It begins with the Kingda Ka logo set against a stark white background. The logo features a tiger's intense gaze, framed by three jagged claw marks that emphasize the ride's ferocity. The name "Kingda Ka" appears in a glowing yellow font, reinforcing the excitement and power associated with the ride.

As the scene transitions, the viewer is placed at the front of the roller coaster car, offering an immersive experience. The car slowly moves forward along the track. The towering main structure of the roller coaster looms ahead, its dark silhouette reaching into the bright blue sky. The roller coaster gradually approaches its launch position, and the camera captures a small white sign beside the track that reads: "ARMS DOWN HEAD BACK HOLD ON" in bold letters. This instruction serves as a crucial safety reminder, preparing riders for the intense acceleration that is about to take place. Suddenly, the train is launched forward by a high-powered mechanism, accelerating from 0 to 206 km/h in just 3.5 seconds. The video vividly captures this rapid acceleration as the track blurs past, emphasizing the immense forces at play.

As the coaster speeds toward the towering main structure, it ascends steeply, climbing 139 meters into the sky. The on-screen perspective tilts upward, revealing the vast blue sky above as the train reaches its peak. At this point, the ride momentarily slows before plunging into a near-vertical drop of 127 meters. The camera view shifts downward, displaying the dizzying descent as the ground rushes up at breathtaking speed. The surrounding amusement park, including other roller coaster tracks and a sprawling parking lot, flashes into view for a brief moment before the ride levels out.

The momentum from the descent propels the train forward along a twisting and curving track. The perspective shifts to capture the ride's remaining sections, where the coaster continues at high speed before gradually slowing to a stop. As the ride concludes, the screen transitions to black, and the Kingda Ka logo reappears, reinforcing the sheer intensity of the experience.

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In order to travel up and over the main tower, the roller coaster needs a great amount of energy. The Kingda Ka's launching mechanism uses 32 motors to transfer energy to the roller coaster, propelling it forward at the desired speed of 206 km h^{-1}. It is the high energy of the moving train that allows it to pass over Kingda Ka's tower.

After climbing to the top of the highest section in the track, the train drops 127 metres down and completes the ride in 28 seconds. Occasionally, the energy provided by the launching mechanism is not enough. What happens in this case? What do you think?

The roller coaster train experiences a rollback in which it descends back down the same side it was launched from. Retractable magnetic brakes are then set in action. These prevent the train from rolling back all the way into the station, where it could collide with another train about to be launched.

Figure 1. The Kingda Ka.

Source: 'Kingda Ka (https://commons.wikimedia.org/wiki/File:Kingda_Ka_(Full_Layout).JPG)' by Coasterman1234 is licensed under CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0/)

Student view

In this subtopic, you will develop your understanding of some of the key physics theories relating to energy conservation and energy transfers and be able to apply them to develop effective solutions to kinematic problems.

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Prior learning

Before you study this subtopic make sure that you understand the following:

- Vector components, area under a curve and the equations of motion (see subtopic A.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43128/)).
- Momentum, resistive forces and the equations for static and dynamic friction (see subtopic A.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43136/)).
- Elastic force of a spring (Hooke's law) (see subtopic A.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43136/)).

A. Space, time and motion / A.3 Work, energy and power

Work and energy

A.3.2: Work done by a force is equivalent to a transfer of energy A.3.4: Work done on a body by the component of a force
A.3.5: Work done and the change in energy of a system A.3.6: Mechanical energy
A.3.8: Transfer between different forms of mechanical energy

Learning outcomes

By the end of this section you should be able to:

- Identify key energy stores and describe energy transfers.
- Define work and use the equation for work to solve problems.
- Calculate the work done by a force as the area under a force—displacement curve.
- Describe that the work done by the resultant force on an object is equivalent to the change in energy of the object.
- Define kinetic energy, gravitational potential energy and elastic potential energy, and use the respective equations to solve problems.

Student view

The word *energy* comes from the Greek '*enérgeia*', and it comes from the combination of the preposition '*en*' (meaning 'in') and the noun '*ergon*' (meaning 'work'). Energy is often defined as the ability to do work. But what is work? Why is it related to energy? And can energy be defined without mentioning work?

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In this section, you will learn about energy, work, the relationship between work done and energy transferred, and how to calculate kinetic, gravitational potential and elastic potential energies. **Figure 1** shows the links between the different parts of the section.

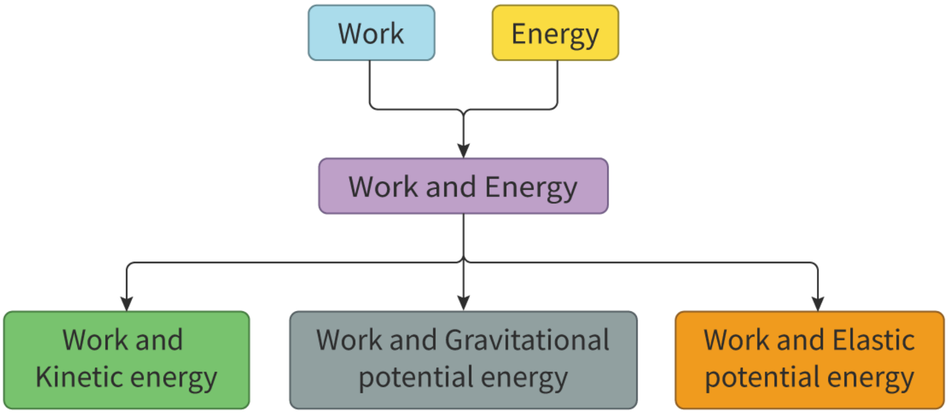

Figure 1. The links between the different parts of the section.

More information for figure 1

The flowchart starts with two cells at the top labeled "Work" and "Energy." Both these cells are connected by arrows to a single cell below labeled "Work and Energy." From this central cell, three branches emerge. The first branch leads to a cell labeled "Work and Kinetic Energy," the second branch goes to "Work and Gravitational Potential Energy," and the third branch connects to "Work and Elastic Potential Energy." This chart illustrates the relationships between different types of work and energy forms.

[Generated by AI]

Energy stores

Energy can be stored in a variety of forms. A car moving at 50 km h^{-1} stores kinetic energy. A stationary book on a shelf stores gravitational potential energy. A stretched rubber band stores elastic potential energy.

Table 1 lists some important stores of energy you should know about.

Table 1. Energy stores.

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Energy store	Description
Kinetic	Active energy of a mass in motion
Gravitational potential	Energy stored by a mass due to its position within a gravitational field
Elastic potential	Energy stored by an object that has been deformed
Thermal	Energy associated with molecular motion
Chemical potential	Energy associated with chemical bonds
Nuclear	Energy stored within the atomic nucleus
Electrical potential	Energy associated with a charge due to its position in an electric field

Work

In physics, the term work is associated with a transfer of energy. Work done and energy transferred are both measured in joules (J), and they are equivalent.

A force is said to do work when it acts on an object, and it transfers energy to it. The work done by a force is calculated by multiplying the displacement of the object upon which the force acts and the component of the force that is parallel to the object's displacement (**Figure 2**).

Table 2. Equation for work.

Equation	Symbols	Units
$W = Fs\cos\theta$	W = work	joules (J)
	F = force	newtons (N)
	s = displacement	metres (m)
	θ = angle between force and displacement	degrees (°)

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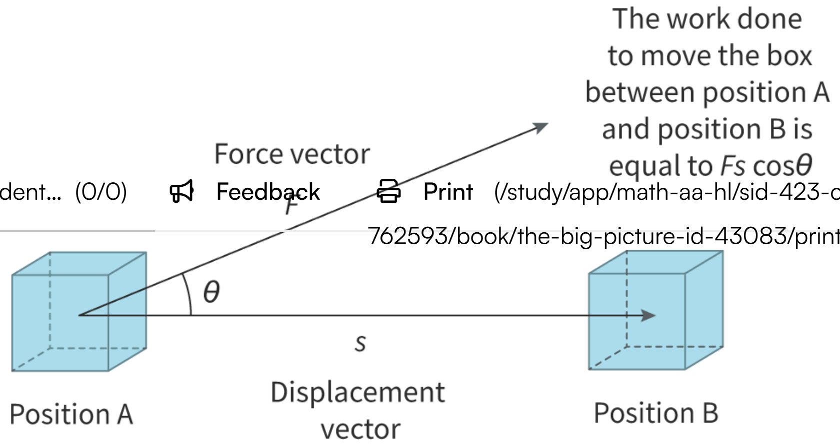

Figure 2. The work done by a force on an object.

More information for figure 2

The diagram illustrates the concept of work done by a force on an object, represented by two cuboids of the same size. The cuboid on the left is labeled as Position A, and the one on the right is labeled as Position B. A straight horizontal line, the displacement vector, connects the two cuboids and is labeled 's'. Below this line, it indicates that this is the displacement vector. Emerging from the left cuboid at Position A, there are two diverging lines creating an angle labeled 'θ'. Above these lines, a vector angled upwards represents the force vector, labeled 'F'. The text notes that the work done to move the box from position A to position B equals Fs cosθ. This implies that the work is calculated by the product of force, displacement, and the cosine of the angle between them, emphasizing the physics behind force and movement.

[Generated by AI]

Study skills

The equation for work is a rearranged version of $W = (F\cos\theta)s$. According to the definition of work and the diagram in **Figure 2**, in order to calculate work, you need to multiply the displacement s and the component of the force parallel to the displacement, which is $F\cos\theta$.

From the equation for work, you can see that:

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

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Worked example 1

A force of 48 N acts on an object and displaces it by 2.2 m. The angle between the force and the object's displacement is 45°. Calculate the work done by the force on the object.

Solution steps	Calculations
Step 1: recall the qualitative understanding of the physics	The work done by a force is the displacement of the object upon which the force acts multiplied by the component of the force that is parallel to the object's displacement.
Step 2: write out the values given in the question making sure to convert to SI units	$F = 48\text{ N}$ $s = 2.2\text{ m}$ $\theta = 45°$
Step 3: write out the equation	$W = Fs\cos\theta$
Step 4: substitute the values	$= 48\times 2.2\times \cos(45)$
Step 5: state the answer with appropriate units and the number of significant figures used in rounding	$= 75\text{ J (2 s.f.)}$
Step 6: does your answer make sense?	✓ Yes. The number of significant figures is the same as the smallest number of significant figures in the question data.

Despite being the product of two vectors (force and displacement), work is a scalar quantity (it has magnitude only).

Exercise 1

Click a question to answer

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view

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Calculating work from force—displacement graphs

You might be asked to calculate the work done by a force from a force–displacement graph. In this case,

work done = area under the line of a force–displacement graph

Making connections

The idea of work done as the area under the line of a force—displacement graph is analogous to the distance travelled being the area under a velocity—time graph, which you studied in subtopic A.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43128/). Distance travelled is equal to the product of average velocity and time taken. This is equivalent to the area under the line on a velocity—time graph. Work done is equal to the product of average force (more precisely, the component of the force parallel to the displacement) and displacement. This product is equivalent to the area under the line on a force—displacement graph.

Figure 3 and **Figure 4** show examples of force–displacement graphs, showing how the work done by the force is calculated in each case.

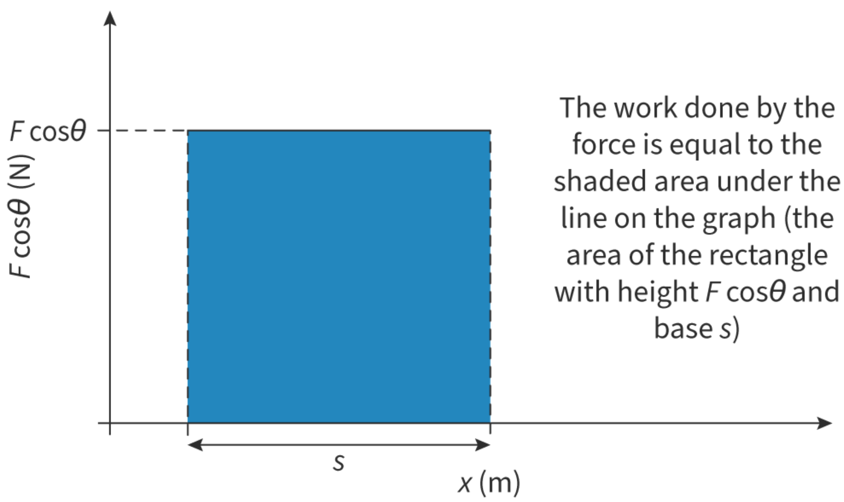

Figure 3. Force—displacement graph for a constant force.

More information for figure 3

Student view

The image is a graph illustrating a force-displacement relationship for a constant force. The X-axis represents displacement marked as 'x (m)' and the Y-axis represents force with the label 'F cosθ (N)'. There is a blue rectangle on the graph with its height denoted as 'F cosθ' and base as 's'. The text next to the graph states that the work done by the force is equivalent to the shaded area under the line, specifically the area of the rectangle with height 'F cosθ' and base 's'. This demonstrates how work is calculated as the product of force and displacement when the force is constant.

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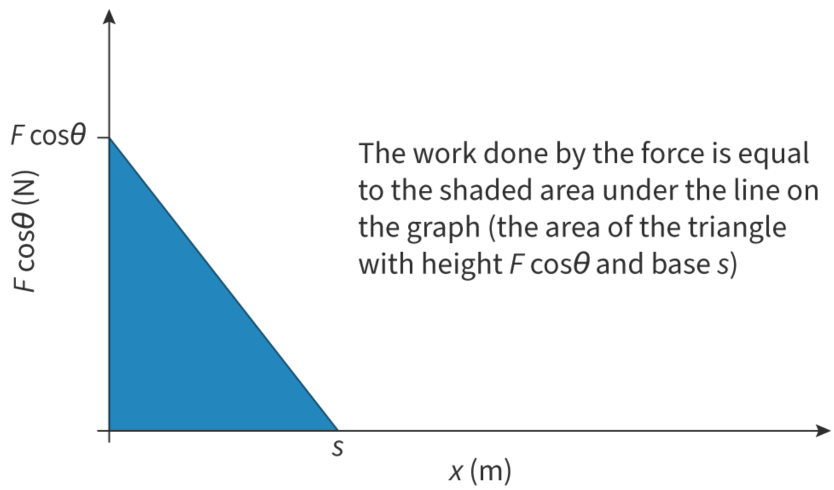

Figure 4. Force—displacement graph for a force changing constantly with displacement.

More information for figure 4

The image is a graph displaying a triangular area shaded blue, symbolizing work done by a constant force. The X-axis represents displacement labeled "x (m)," and the Y-axis represents force labeled "F cosθ (N)." The text on the image explains that "The work done by the force is equal to the shaded area under the line on the graph (the area of the triangle with height F cosθ and base s)." This indicates that the graph is used to visualize how work is calculated by multiplying force by displacement, corresponding to the area under the curve on a force-displacement graph.

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Worked example 2

Student view

Use **Figure 5** to calculate the work done by the force in moving the object.

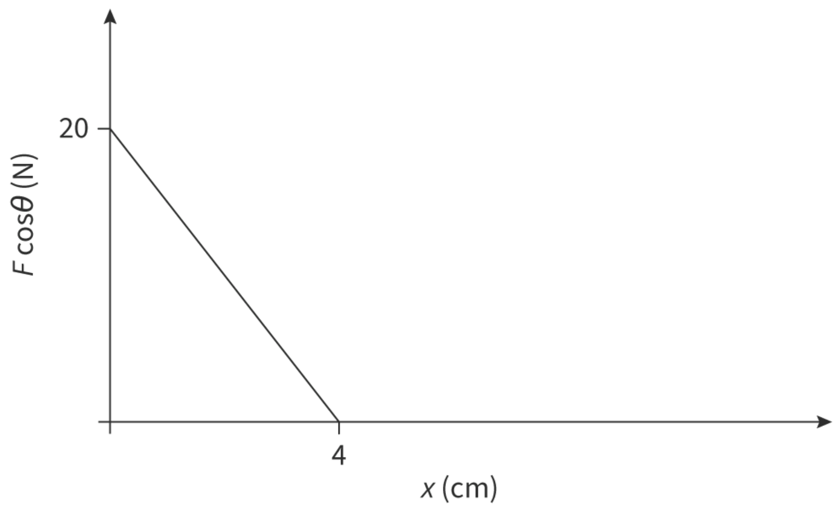

Figure 5. Force—displacement of a moving object.

More information for figure 5

The image is a graph showing a plotted line. The x-axis is labeled 'x (cm)' and runs from 0 to 4. The y-axis is labeled 'F cosθ (N)' and ranges from 0 to 20. A straight line connects a point at 4 on the x-axis with a point at 20 on the y-axis. This suggests a linear relationship where as x increases, the value of F cosθ decreases from 20 down to 0 as it approaches 4 on the x-axis. The graph represents the force related to displacement and can be used to calculate work done by the force.

[Generated by AI]

Solution steps	Calculations
Step 1: recall the qualitative understanding of the physics	The work done by the force in moving the object is equal t the area under the line on the graph (the area of the triangle).
Step 2: write out the values given in the question making sure to convert to SI units	$F = 20\ \text{N}$ $x = 0.04\ \text{m}$
Step 3: write out the equation	$W = \text{area of triangle} = \frac{1}{2}(bh)$

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Solution steps	Calculations
Step 4: substitute the values given with units	$= \frac{1}{2}\times 0.04\times 20$
Step 5: state the answer with appropriate units and the number of significant figures used in rounding	$= 0.4\text{ J (1 s.f.)}$
Step 6: does your answer make sense?	✓ Yes. The number of significant figures is the same as the smallest number of significant figures in the question data The units are dimensionally consistent with the equation.

Work and energy

Every time a force does work on an object, energy is transferred to the object. For example, when a car accelerates on a road, the thrust of the engine causes an increase in the kinetic energy of the car. So the work done by the resultant force on the car is equal to the change in energy of the car.

If the resultant force on the car is zero (because the forward thrust is balanced by the opposing combined action of friction and drag), the kinetic energy of the car will remain constant (since the car will travel at a constant velocity), and the change in energy will be equal to zero. The work done by the car’s engine goes into heat energy (either directly or through drag, friction and sound).

Work and kinetic energy

A Kingda Ka train travelling at high speed has a store of kinetic energy dependent on its mass (the combined mass of the passengers and the train) and its velocity. The equation for the kinetic energy of a moving object is given in **Table 3.**

Table 3. Equation for kinetic energy.

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Equation	Symbols	Units
$E_k = \frac{1}{2}mv^2$	E_k = kinetic energy	joules (J)
	m = mass	kilograms (kg)
	v = velocity	metres per second (m s^{-1})

You can see that, at constant velocity, kinetic energy is proportional to mass $(E_k \propto m)$, so that doubling the mass means doubling the kinetic energy.

For a constant mass, the kinetic energy is proportional to the square of the velocity $(E_k \propto v^2)$, so that doubling the velocity means increasing the kinetic energy by a factor of four.

You can also write an equation to relate the work done by the resultant force F on an object of mass m and speed v to the change in the kinetic energy of the object:

$$W = \Delta E_k = \frac{1}{2}m{v_f}^2 - \frac{1}{2}m{v_i}^2$$

Worked example 3

Object A has mass m and moves at a speed v. Object B has mass $m/2$ and velocity $2v$.

What is the ratio: $\frac{\text{kinetic energy of object A}}{\text{kinetic energy of object B}}$?

Solution steps	Calculations
Step 1: work out a strategy	You will need to write equations for the kinetic energies of objects A and B.
Step 2: write out the values given in the question	object A: mass $= m$; velocity $= v$ object B: mass $= m/2$; velocity $= 2v$

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Solution steps	Calculations
Step 3: write out the equations	The kinetic energy of object A is: $$E_{\text{kA}} = \frac{1}{2}mv^2$$ The kinetic energy of object B is: $$E_{\text{kB}} = \frac{1}{2}mv^2 = \frac{1}{2}\frac{m}{2}(2v)^2$$
Step 4: rearrange the equation for object B	$$E_{\text{kB}} = \frac{1}{2}\frac{m}{2}4(v)^2$$ $$E_{\text{kB}} = 2\frac{1}{2}m\,v^2$$
Step 5: state the answer	$E_{\text{kB}} = 2\text{E}_{\text{kA}}$ $$\frac{\text{kinetic energy of object A}}{\text{kinetic energy of object B}} = 0.5$$
Step 6: does your answer make sense?	✓ Yes. Notice that even though one of the variables is doubled and th other is halved, this does not cancel out because the velocity is squar and the mass is not.

Worked example 4

An object of mass 210 g moves at a speed of 8.0 m s^{-1}. Calculate its kinetic energy when moving at this speed.

Solution steps	Calculations
Step 1: recognise that the equation for kinetic energy will be required	The equation for the kinetic energy of an object is available in the DP physics data booklet.
Step 2: write out the values given in the question making sure to convert to SI units	$m = 0.21\ \text{kg}$ $v = 8.0\ \text{m s}^{-1}$

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Solution steps	Calculations
Step 3: write out the equation	$E_\mathrm{k} = \frac{1}{2}mv^2$
Step 4: substitute the values given	$= \frac{1}{2} \times 0.21 \times 8.0^2$
Step 5: state the answer with appropriate units and the number of significant figures used in rounding	$= 6.7\ \mathrm{J}\ (2\ \mathrm{s.f.})$
Step 6: does your answer make sense?	✓ Yes. The number of significant figures is the same as the smallest number of significant figures in the questic data. The units are dimensionally consistent with the equation.

For an object of mass m and velocity v, the kinetic energy equation can also be written in terms of the momentum p. Momentum is defined as the product of mass and velocity: $p = mv$. Can you derive the equation for kinetic energy in terms of momentum? Try it yourself, then click on solution below to check your working.

Step 1. Give the equation for kinetic energy:

$$E_\mathrm{k} = \frac{1}{2}mv^2$$

Step 2. Rearrange the equation for momentum:

$$p = mv \quad v = \frac{p}{m}$$

Step 3. Substitute this into the kinetic energy equation:

$$E_\mathrm{k} = \frac{1}{2}mv^2 = \frac{1}{2}m(\frac{p}{m})^2$$

Step 4. Simplify:

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

Work and gravitational potential energy

When the Kingda Ka train reaches the top of the tower element, it has an amount of gravitational potential energy. Consider how much energy is needed to move the train to the top of the tower. What changes could you make to the ride so it requires more energy to do this?

Increasing the mass (for example, adding more passengers) would increase this energy. Increasing the height of the tower would also increase the energy. And if you had the roller coaster on a planet with a stronger gravitational field, this would increase the energy required as well!

So the gravitational potential energy of an object is dependent on its mass, its height above the ground and the gravitational field strength.

Table 4 shows how the amount of gravitational potential energy stored in an object is calculated.

Table 4. Equation for change in gravitational potential energy.

Equation	Symbols	Units
$\Delta E_p = mg\Delta h$	ΔE_p = change in gravitational potential energy	joules (J)
	m = mass	kilograms (kg)
	g = gravitational field strength	newtons per kilogram ($N\,kg^{-1}$)
	Δh = change in height	metres (m)

You can also write an equation to relate the work done by the gravitational force on an object of mass m to the change in the gravitational potential energy of the object:

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

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Worked example 5

An object of mass 60 kg is moved vertically upwards by 2.09 m. Calculate the change in its gravitational potential energy.

Solution steps	Calculations
Step 1: recognise that the equation for gravitational potential energy will be required	The equation for the gravitational potential energy of a object is available in the DP physics data booklet.
Step 2: write out the values given in the question making sure to convert to SI units The value for *g* is in the DP physics data booklet	$m = 60\text{ kg}$ $\Delta h = 2.09\text{ m}$ $g = 9.8\text{ N kg}^{-1}$
Step 3: write out the equation	$\Delta E_\text{p} = mg\Delta h$
Step 4: substitute the values given	$= 60 \times 9.8 \times 2.09$
Step 5: state the answer with appropriate units and the number of significant figures used in rounding	$= 1200\text{ J (2 s.f.)}$
Step 6: does your answer make sense?	✓ Yes. The number of significant figures is the same as the smallest number of significant figures in the questic data. The units are dimensionally consistent with the equation.

Work and elastic potential energy

What happens when you stretch a spring? And what happens when you let it go? When you apply a force to stretch a spring, you are doing work, and the amount of work you do is equal to the elastic potential energy stored by the spring. When you let the spring go, removing the force you had applied initially, the elastic potential energy is transferred to

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kinetic energy of the spring (and anything attached to it), as the spring goes back to its original length. Eventually, due to friction and other interactions, all of this energy will be lost as heat to the surroundings.

The change in elastic potential energy of a spring is defined as the work done on the spring by the external force that is applied to it in order to change its length by a given amount (**Table 5**).

To calculate the work done on a spring, it is not possible to simply multiply the final displacement (extension) by the final applied force, because the applied force changes as the spring stretches. This can be seen in **Figure 6**, which shows a force–extension graph for a spring.

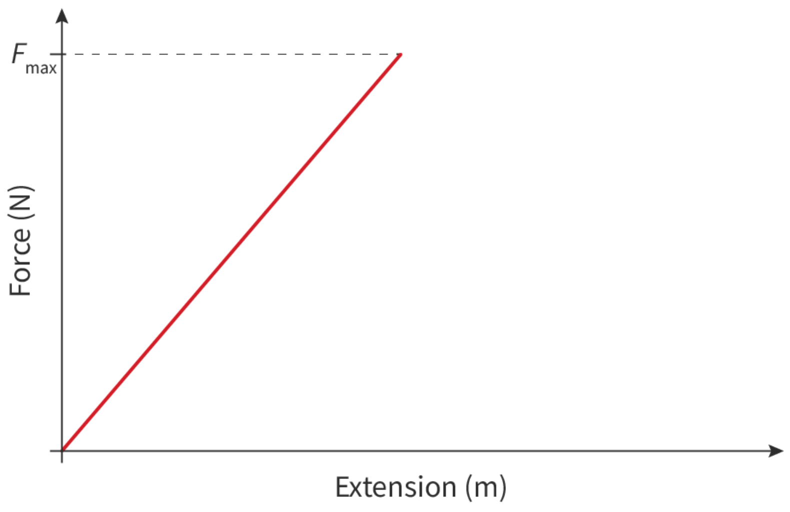

Figure 6. Force—extension graph for a spring.

More information for figure 6

The graph illustrates the relationship between force and extension for a spring. The X-axis represents the extension measured in meters (m), while the Y-axis represents the force measured in newtons (N). The graph displays a linear line starting from the origin (0,0) and ascending to the point where the maximum force (Fmax) is reached. The line reflects the linear increase of force as the spring extends, indicating Hooke's Law behavior where the force is directly proportional to the extension.

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From this graph you can see that the average force applied while extending a spring is half of the maximum applied force, F_{max}. Therefore the work done to extend the spring by x is

$$W = \frac{1}{2}F_{\max}x$$

which equals the area under the graph in **Figure 6**.

The amount of elastic potential energy stored in a stretched spring can also be expressed as shown in **Table 5**.

Table 5. Equation for change in elastic potential energy.

Equation	Symbols	Units
$\Delta E_{\mathrm{H}} = \frac{1}{2}k\Delta x^2$	ΔE_{H}= change in elastic potential energy	joules (J)
	k = spring constant	newtons per metre ($\mathrm{N\,m^{-1}}$)
	Δx= change in length	metres (m)

Can you use the equation $W = \frac{1}{2}F_{\max}x$ and Hooke's law (introduced in section A.2.4 (/study/app/math-aa-hl/sid-423-cid-762593/book/elastic-force-drag-buoyancy-id-44735/)) to derive the elastic potential energy equation in **Table 5**?

Hooke's law expresses the relationship between the elastic restoring force and the extension of a spring with spring constant k. If the extension is x when the final applied force is F_{max}, then

$$F_{\max} = -kx$$

Substituting this into the equation for work done on a spring (and ignoring the minus sign which indicates that the vector quantities F and x are in opposite directions) gives:

$$\begin{aligned} W &= \frac{1}{2}F_{\max}x \\ &= \frac{1}{2}(kx)x \\ &= \frac{1}{2}kx^2 \end{aligned}$$

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which matches the expression for elastic potential energy in **Table 5.**

Worked example 6

A bungee jumper jumps off a tall bridge. At the lowest point in their jump, the bungee jumper is momentarily stationary, upside down, with their feet tied to the elastic rope. At this point, the rope is stretched by 25 m. The spring constant of the rope is $50.0\,\text{N m}^{-1}$. Calculate the elastic potential energy stored in the stretched rope.

Solution steps	Calculations
Step 1: recognise that the equation for elastic potential energy will be required	The equation for the elastic potential energy of an objec is available in the DP physics data booklet.
Step 2: write out the values given in the question making sure to convert to SI units	$\Delta x = 25\text{ m}$ $k = 50.0\text{ N m}^{-1}$
Step 3: write out the equation	$\Delta E_{\text{H}} = \frac{1}{2}k\Delta x^2$
Step 4: substitute the values given	$= \frac{1}{2}\times 50.0\times 25^2$
Step 5: state the answer with appropriate units and the number of significant figures used in rounding	$= 16\,000\text{ J }(2\text{ s.f.})$
Step 6: does your answer make sense?	✓ Yes. The number of significant figures is the same as the smallest number of significant figures in the questio data. The units are dimensionally consistent with the equation.

Activity

- **Learner profile attribute:** Thinker

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- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time to complete activity:** 15 minutes
- **Activity type:** Individual activity

Complete the following tasks on your own during class or at home. The tasks make sure that you can work with the new learning in this section.

1. A trolley loaded with heavy boxes is pulled by a rope of length 1.0 m. The pulling force is 30 N. The direction along which the force acts is shown in **Figure 7.**

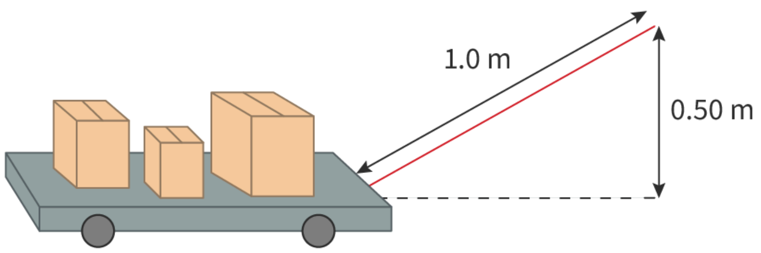

Figure 7. Pulling a trolley.

More information for figure 7

The image depicts a trolley loaded with multiple boxes. There is a red line representing a rope or pulling force that is 1.0 meters long. The rope is connected at one end to the trolley and extends at an angle upward. At the end of the rope line, there is a dashed line drawn downward perpendicular to the ground to show a vertical distance of 0.5 meters from the end of the rope to the ground. This illustrates the angle at which force is applied and provides measurements of the distance both horizontally and vertically.

[Generated by AI]

The vertical distance between the upper end of the rope and the ground is 0.5 m. The trolley's overall displacement is 12 m. Calculate the work done by the force.

To calculate the work done by the 30 N force, determine the angle θ that the force makes with the displacement vector (which is horizontal). Using trigonometry, this is given by:

Student view

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$$\theta = \sin^{-1}\left(\frac{0.5}{1.0}\right)$$
$$= 30^\circ$$

Now calculate the work F as:

$$W = Fs\cos\theta$$
$$= 30 \times 12 \times \cos(30)$$
$$\approx 311$$

The work done by the force is 310 J (2 s.f.).

2. A force acts on an object of mass 20 kg, making it accelerate. **Figure 8** shows the variation of the object's acceleration with displacement.

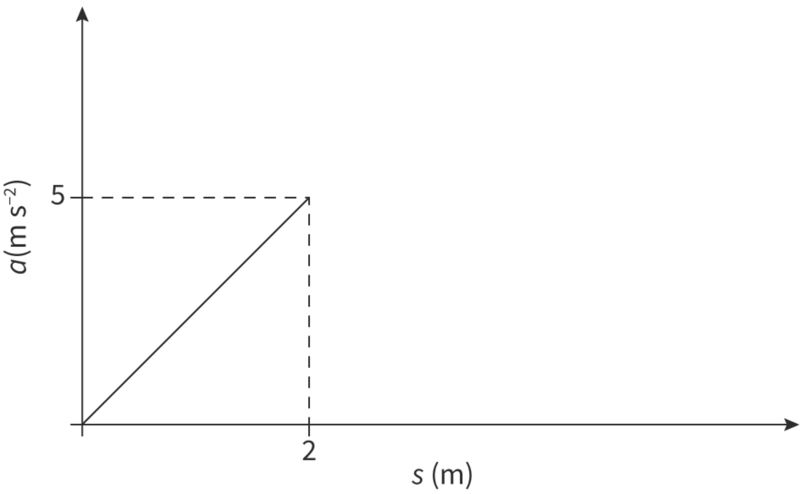

Figure 8. Acceleration v. displacement.

More information for figure 8

The graph displays the relationship between acceleration and displacement. The x-axis represents displacement in meters (s), ranging from 0 to 2. The y-axis denotes acceleration in meters per second squared (ms^{-2}), with values ranging from 0 to 5. A single line is plotted, starting at the origin (0, 0) and ending at the point (2, 5), forming a linear relationship with a positive slope indicating that acceleration increases linearly with displacement.

[Generated by AI]

The acceleration and the displacement vectors point in the same direction. Determine the work done by the force on the object.

Student view

Since acceleration and displacement are in the same direction, the angle between the force and the displacement is $\theta = 0$. So the work done by the force is given by:

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$$W = Fs$$

Substituting Newton's second law for F, you can write:

$$W = mas$$

The product *as* is equal to the area under the line (the area of the triangle), hence:

$$\begin{aligned} W &= m \times \text{area of triangle} \\ &= 20 \times \frac{5 \times 2}{2} \\ &= 100 \end{aligned}$$

So the work done on the object is 100 J (1 s.f.).

3. **Figure 9** shows $F\cos\theta$ against displacement for a moving object.

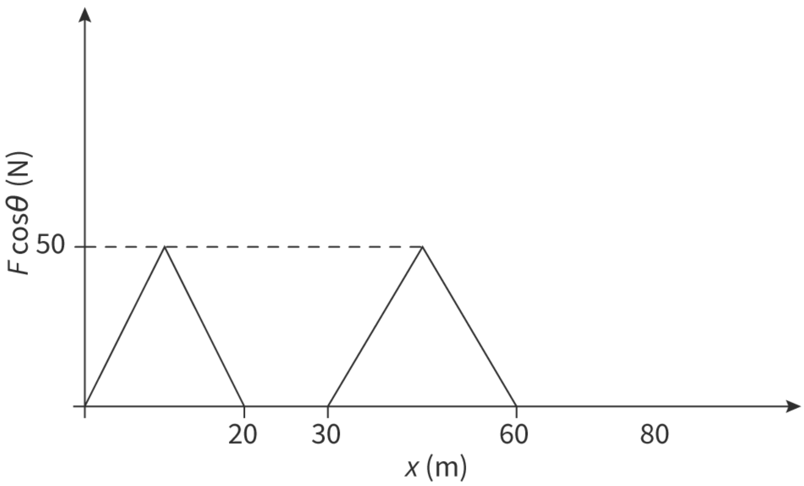

Figure 9. Force—displacement of a moving object.

More information for figure 9

The image is a graph depicting the relationship between displacement and force. The x-axis represents displacement (x) in meters, ranging from 0 to 80 meters. The y-axis represents force (F cosθ) in newtons, marked up to 50 N. The graph features two triangular peaks. The first triangle starts at 0 meters, peaks at 20 meters with a height of 50 N, and returns to the baseline at 20 meters. The second triangle starts at 30 meters, peaks at 50 N, and ends at 60 meters on the x-axis. This suggests a periodic force pattern applied during these specific intervals.

[Generated by AI]

The object's displacement is 80.0 m. The object's motion is opposed by a constant frictional force of 3.00 N. Calculate the kinetic energy of the object after 80.0 m.

Student view

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To calculate the amount of energy transferred to the kinetic energy of the object, first determine the work done on the object by force F.

The work done by force F is calculated as the total area under the line on the graph (the area of the two triangles):

$$\begin{aligned}\text{work done by } F &= \frac{20\times 50}{2} + \frac{(60-30)\times 50}{2} \\ &= 1250\end{aligned}$$

Some of that work, however, is being done against friction and does not go to increase the kinetic energy.

The work done against friction is the frictional force multiplied by the distance travelled:

$$\text{work done against friction} = 3.0\times 80 = 240$$

So, of the 1250 J of work done on the object, 240 J is done against friction (and so is lost as heat) and the rest is transferred to kinetic energy.

The kinetic energy of the object after 80 m is therefore:

$$1250 - 240 = 1010 \text{ J } (3 \text{ s.f.})$$

4. A box of mass 20 kg slides along a smooth horizontal surface at a constant speed of $4.0\,\mathrm{m\,s^{-1}}$. A constant resultant force is applied to the box. As a result, the box moves forward by 2.0 m and its speed becomes $8.0\,\mathrm{m\,s^{-1}}$. Determine the magnitude and direction of the force acting on the box.

The work done by the resultant force F is equal to the change in kinetic energy E_k of the object:

$$W = \Delta E_\mathrm{k}$$

Substituting the expressions for work done and change in kinetic energy:

$$Fs = \frac{1}{2}m(v^2 - u^2)$$

Rearranging the equation for F:

Student view

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$$F = \frac{1}{2}\frac{m(v^2 - u^2)}{s}$$
$$= \frac{1}{2}\times\frac{20\times(8.0^2 - 4.0^2)}{2.0}$$
$$= 240$$

So the magnitude of the resultant force acting on the box is 240 N (2 s.f.) and the direction is along the box's displacement (since the kinetic energy of the box has increased as a result of the force's action).

5. A ball of mass 2.0 kg is lifted from the floor to a table 1.5 m above the floor. The ball is then lifted from the table to a height of 2.0 m above the floor. From this position, the ball is released, and it falls freely to the floor. Calculate the change in gravitational potential energy for each of these three actions.

$$\begin{aligned} \Delta E_{\mathrm{p}_1} &= mg\Delta h_1 \\ &= 2.0\times9.8\times(1.5 - 0.0) \\ &= 29\ \mathrm{J}\ (2\ \mathrm{s.f.}) \end{aligned}$$

$$\begin{aligned} \Delta E_{\mathrm{p}_2} &= mg\Delta h_2 \\ &= 2.0\times9.8\times(2.0 - 1.5) \\ &= 9.8\ \mathrm{J}\ (2\ \mathrm{s.f.}) \end{aligned}$$

$$\begin{aligned} \Delta E_{\mathrm{p}_3} &= mg\Delta h_3 \\ &= 2.0\times9.8\times(0.0 - 2.0) \\ &= -39\ \mathrm{J}\ (2\ \mathrm{s.f.}) \end{aligned}$$

The negative result for the last change in gravitational potential energy indicates a decrease in E_p, which is associated with positive work done by the gravitational force. When the gravitational force does negative work, ΔE_p is positive ($E_\mathrm{p}$increases).

6. A horizontal spring is 10.0 cm long and has a spring constant of 3.50 N m^{-1}. The spring is extended to a length of 15.0 cm, then extended to 20.0 cm. Calculate the change in elastic potential energy of the spring between lengths 15.0 cm and 20.0 cm.

The spring is first extended by an amount $\Delta x_1 = (15.0 - 10.0)\ \mathrm{cm} = 5.00\ \mathrm{cm}$. The elastic potential energy of the spring due to this extension is:

Student view

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$$\begin{aligned}\Delta E_{\mathrm{H}_1} &= \frac{1}{2}k\Delta x_1^2 \\ &= \frac{1}{2}\times 3.50\times(5.00\times 10^{-2})^2 \\ &= 4.38\times 10^{-3}\ \mathrm{J}\end{aligned}$$

Then the spring is extended by a further $5.00\ \mathrm{cm}$, which means that the extension is now $\Delta x_2 = 5.00\ \mathrm{cm} + 5.00\ \mathrm{cm} = 10.0\ \mathrm{cm}$. This second extension changes the elastic potential energy of the spring to:

$$\begin{aligned}\Delta E_{\mathrm{H}_2} &= \frac{1}{2}k\Delta x_1^2 \\ &= \frac{1}{2}\times 3.50\times(10.0\times 10^{-2})^2 \\ &= 1.75\times 10^{-2}\ \mathrm{J}\end{aligned}$$

The change in elastic potential energy between extension 1 and extension 2 is given by the difference between the elastic potential energy after the second extension ΔE_{H_2} and the elastic potential energy after the first extension ΔE_{H_1}:

$$\begin{aligned}\Delta E_{\mathrm{H}} &= \Delta E_{\mathrm{H}_2} - \Delta \mathrm{E}_{\mathrm{H}_1} \\ &= (1.75\times 10^{-2}) - (4.38\times 10^{-3}) \\ &= 1.31\times 10^{-2}\ \mathrm{J}\ (3\ \mathrm{s.f.})\end{aligned}$$

5 section questions

Question 1

SL HL Difficulty:

A box is pulled a distance of 9.5 m to the right by a force of 45 N, acting at 30° to the horizontal. Calculate the work done by the force. Give your answer in joules (without writing the unit), to an appropriate number of significant figures.

370 J

Accepted answers

370 J, 370 joules, 0.37 kJ, 370

Also accepted

370.2, 370.23

Explanation

The work done by the force is given by:

Student view

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$$\begin{aligned} W &= Fs\cos\theta \\ &= 45\times 9.5\times \cos(30) \\ &= 370.226 \text{ J} \\ W &= 370 \text{ J } (2 \text{ s.f.}) \end{aligned}$$

Question 2

SL HL Difficulty:

A cyclist climbing a hill gains 15.0 kJ of gravitational potential energy. The combined mass of the cyclist and their bicycle is 110 kg. What is the height of the hill? Assume the cyclist starts from an initial height of zero. Include a unit of measurement in your answer.

14 m

Accepted answers

14 m, 14 meters, 14 metres, 13.9 m, 13.9 metres , 13.9 meters

Explanation

The gain in gravitational potential energy of the cyclist is:

$$\begin{aligned} \Delta E_{\text{p}} &= mg\Delta h \\ &= 15.0 \text{ kJ} \\ &= 15\,000 \text{ J} \end{aligned}$$

Rearranging for the change in height:

$$\begin{aligned} \Delta h &= \frac{\Delta E_{\text{p}}}{mg} \\ &= \frac{15\,000}{110\times 9.8} \\ &= 14m \end{aligned}$$

Since Δh = final height — initial height = final height — 0, the height of the hill is 14 m (2 s.f.).

Question 3

SL HL Difficulty:

An object moves in a straight line on a rough horizontal surface. The initial kinetic energy of the object is 50.0 J. A resultant force of 6.0 N opposes the object's motion. Determine the distance moved by the object before it comes to rest. Give your answer to an appropriate number of significant figures.

8.3 m

Accepted answers

8.3 m, 8.3 metres, 8.3 meters, 8.3, 8,3 m, 8,3 metres, 8,3 meters, 8,3

Explanation

Student view

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

The work done by the resultant force opposing the object's motion is equivalent to the initial kinetic energy of the object:

$$\begin{aligned} W &= Fs\cos\theta \\ &= -50 \text{ J} \end{aligned}$$

The object's displacement s and the resultant opposing force F are parallel to each other, but point in opposite directions, hence θ = 180°. Therefore:

$$-6.0 \times s = -50 \quad \text{as} \quad \cos(180) = -1$$

Rearranging for the displacement s:

$$\begin{aligned} s &= \frac{-50}{-6.0} \\ &= 8.3 \end{aligned}$$

So the distance moved by the object before coming to rest is 8.3 m (2 s.f.).

Question 4

SL HL Difficulty:

Object A is in motion and has kinetic energy E_k. Object B has double the mass and half the speed of object A. What is the kinetic energy of object B?

1 $\frac{E_\text{k}}{2}$ ✓

2 $2E_\text{k}$

3 E_k

4 $\frac{E_\text{k}}{4}$

Explanation

The kinetic energy of object A is:

$$E_\text{k} = \frac{1}{2}mv^2$$

The kinetic energy of object B (with double the mass and half the speed) is:

Student view

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$$\begin{aligned}E_{\mathrm{k}} &= \frac{1}{2}\times 2m\left(\frac{v}{2}\right)^2\\ &= \frac{1}{2}\times 2m\frac{v^2}{4}\\ &= \frac{1}{2}m\frac{v^2}{2}\\ &= \frac{E_{\mathrm{k}}}{2}\end{aligned}$$

Question 5

SL HL Difficulty:

A 0.2 kg metal ball hangs at rest from the bottom of a vertical spring with negligible mass. The spring constant is 10 N m^{-1}. What is the elastic potential energy stored in the spring? Assume the gravitational field strength on Earth is 10 N kg^{-1}.

1 0.2 J ✓

2 0.002 J

3 0.02 J

4 2 J

Explanation

The metal ball hanging from the spring has a weight:

$$\begin{aligned}W &= mg\\ &= 0.2\times 10\\ &= 2\end{aligned}$$

Under this weight, the spring extends by an amount Δx equal to:

$$\begin{aligned}\Delta x &= \frac{W}{k}\\ &= \frac{2}{10}\\ &= 0.2\end{aligned}$$

The elastic potential energy of the spring is given by:

$$\begin{aligned}\Delta E_{\mathrm{H}} &= \frac{1}{2}k\Delta x^2\\ &= \frac{1}{2}\times 10\times 0.2^2\\ &= 0.2\end{aligned}$$

Student view

So the elastic potential energy stored by the spring is 0.2 J (1 s.f.).

A. Space, time and motion / A.3 Work, energy and power

Conservation of energy

A.3.1: The principle of the conservation of energy A.3.3: Energy transfers represented on Sankey diagrams

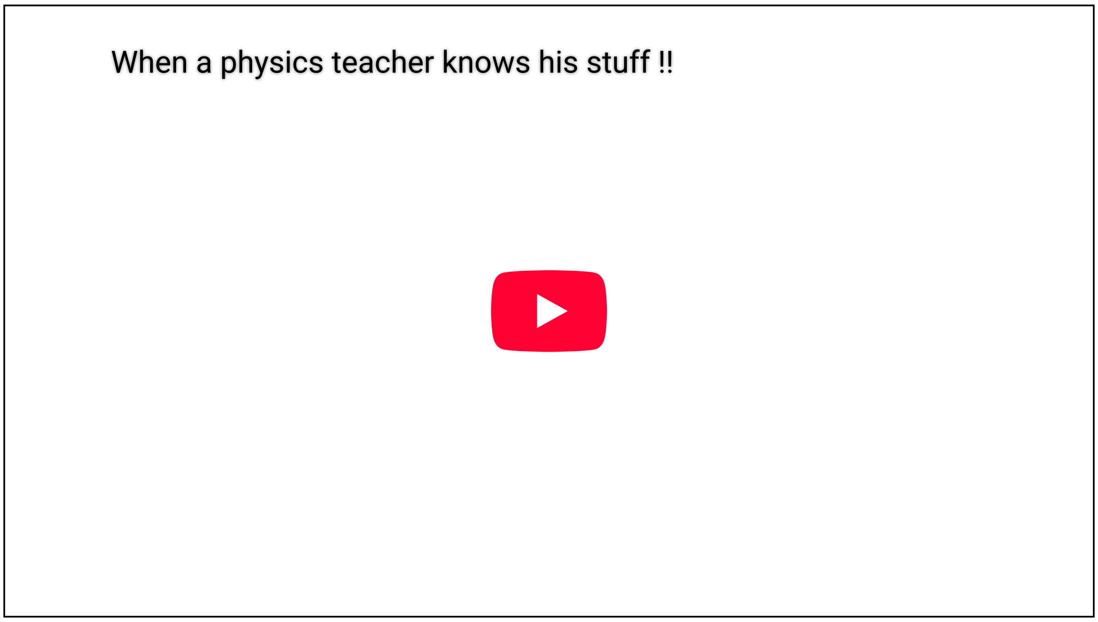
A.3.7: Conservation of mechanical energy

Learning outcomes

By the end of this section you should be able to:

- State the principle of conservation of energy and apply it to solve problems.
- Draw and interpret Sankey diagrams.

Look at **Video 1.** Why is the professor confident that the ball will not hit his face? And why is it important that he does not give the ball any initial velocity? What would happen if he failed and the ball did have some initial velocity?



Video 1. The importance of the principle of conservation of energy.

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

The principle of conservation of energy

Energy can be transferred from one store to another. When you turn on a table lamp, electrical energy is transferred to useful light energy and wasted thermal energy (since the light bulb heats up).

The principle of conservation of energy states that energy cannot be created or destroyed, but only transferred from one store to another. Hence, for an isolated system, the sum of the useful and wasted energy outputs will always be equal to the total energy input.

Nature of Science

Aspect: Models

In one of his lectures, world famous physicist Richard Feynman pointed out the abstract nature of the principle of conservation of energy, and he explained this fundamental law using a simple model. He asked his students to imagine a boy playing with 28 indivisible and identical blocks in his room. Even though the boy might be hiding some blocks under a rug or accidentally throwing some out of the window, the overall number of blocks will always be 28.

You can read the full lecture on Caltech's Division of Physics, Mathematics and Astronomy website (https://www.feynmanlectures.caltech.edu/I_04.html).

Sankey diagrams

Figure 1 shows Sankey diagrams for an energy efficient LED light bulb and for a filament light bulb.

Student view

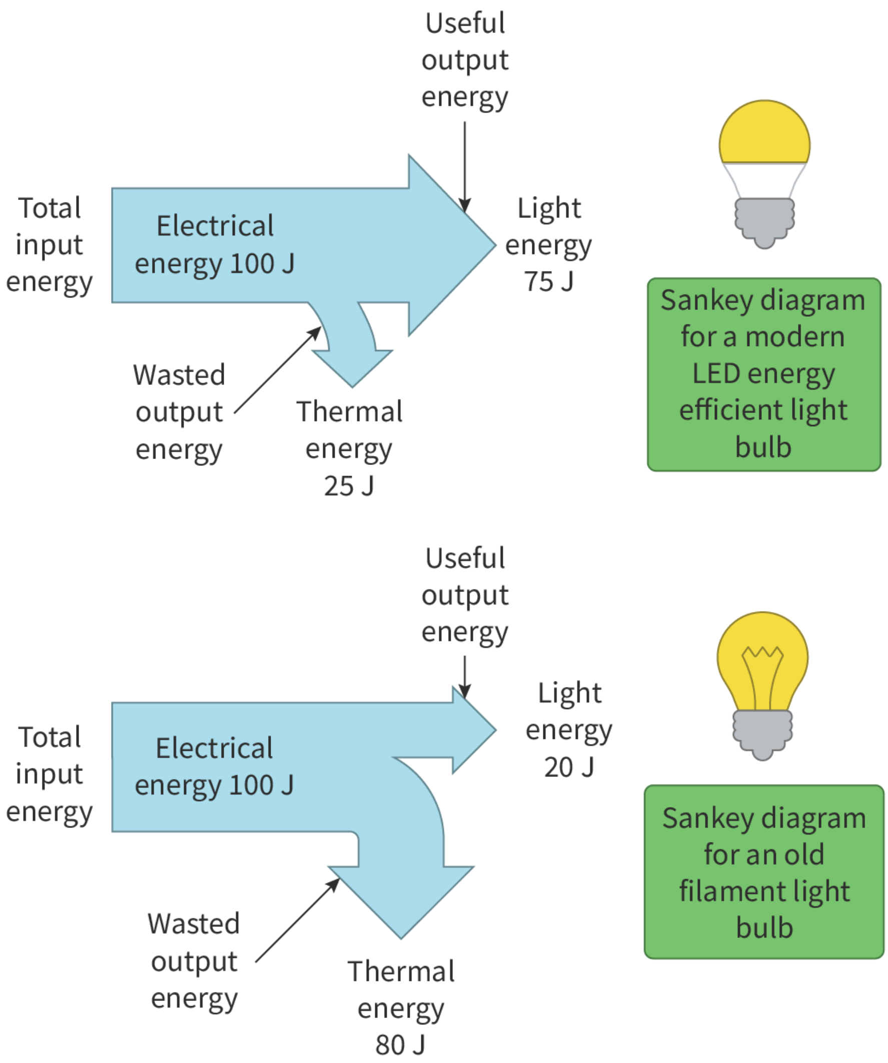


Figure 1. Sankey diagrams for an LED light bulb and a filament light bulb.

More information for figure 1

The image shows two Sankey diagrams side by side, comparing the energy distribution in a modern LED light bulb and an old filament bulb. Both diagrams begin with an input of electrical energy amounting to 100 Joules for each bulb. In the LED bulb diagram, 75 Joules are converted into useful light energy, while 25 Joules are wasted as thermal energy. The diagram is structured such that the width of the arrows is proportional to the energy amounts, visually representing the efficiency of energy conversion. On the other hand, the filament bulb diagram shows that only 20 Joules are converted into useful light energy, with a larger portion, 80 Joules, wasted as thermal energy. This contrasts the inefficiency of the filament bulb relative to the energy-efficient LED bulb. Text labels are present to distinguish between total input energy, useful output energy, and wasted output energy on both diagrams. Additionally, graphical representations of a LED and filament bulb are included next to their respective diagrams.

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Overview
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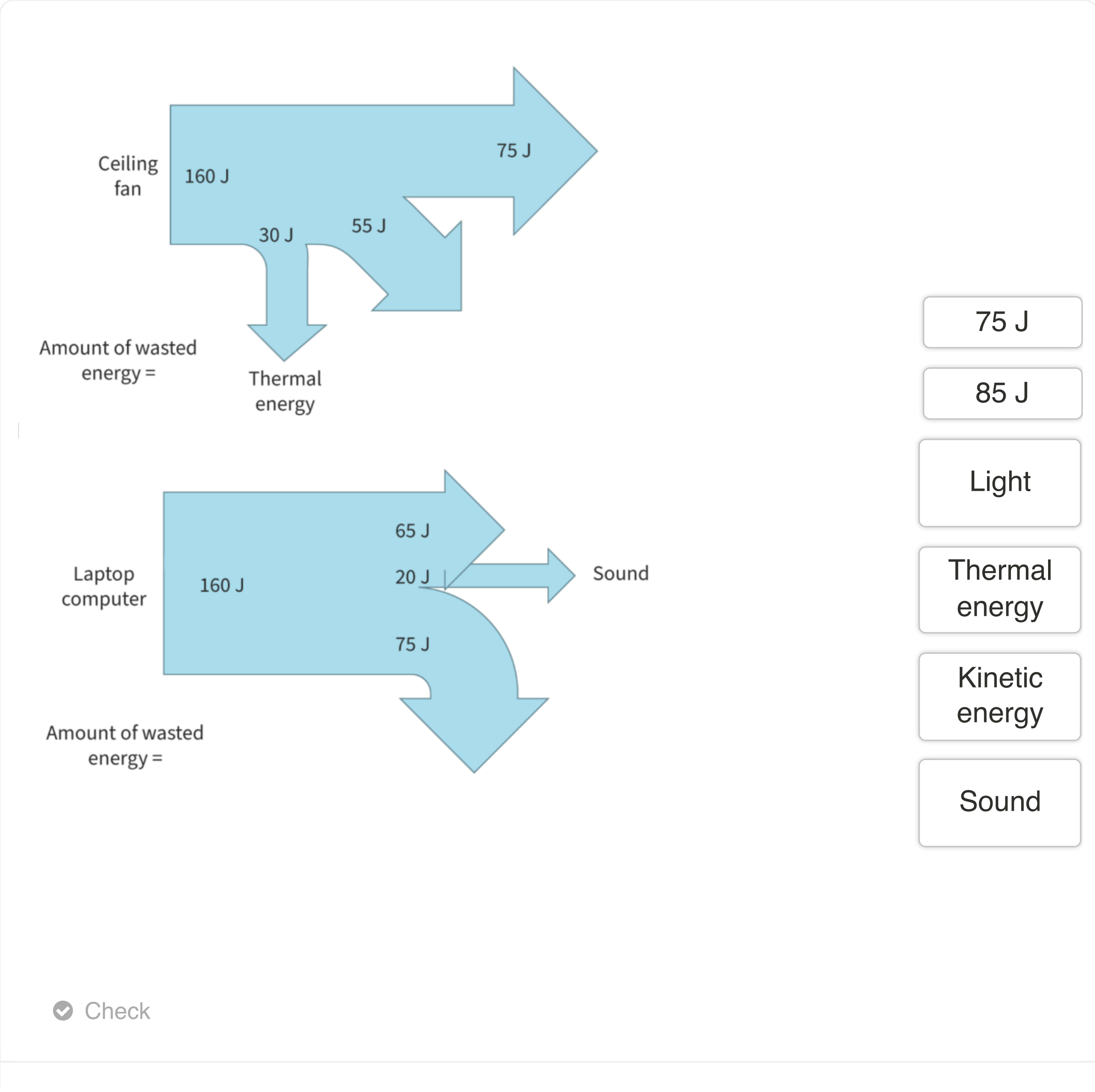
Sankey diagrams can be used to represent energy transfers. The thickness of each arrow is proportional to the amount of energy in each store.

Sankey diagrams give a visual representation of the efficiency of an energy transfer. The concept of efficiency will be discussed in more detail in section A.3.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/power-and-efficiency-id-43086/).

To check your understanding, drag the labels onto the correct places to label the two Sankey diagrams in **Interactive 1**.



Interactive 1. Sankey Diagrams Highlight Efficiency in Energy Transfers.

More information for interactive 1

Student view

Overview
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This interactive activity presents two Sankey diagrams, one for a ceiling fan and one for a laptop computer. The interactive is designed to help users understand how energy is transferred and wasted in different devices. Each diagram begins with a total energy input of 160 J, which is then split into various useful and wasted energy outputs, represented by arrows of different sizes. The goal is for the user to identify and label each form of energy output and the corresponding amount of wasted energy. Wasted energy is unwanted and unusable output energy that is released into the environment and cannot be retrieved for productive purposes.

On the right side of the screen are six draggable labels: "75 J", "85 J", "Light", "Thermal energy", "Kinetic energy", and "Sound". Drag these labels into the blank boxes on the diagrams. In the ceiling fan diagram at the top, the 160 J of total energy is split into 30 J of thermal energy, 55 J of an unknown form, and 75 J of useful energy, which needs to be labeled. Below this, there is a box for the amount of wasted energy, which must be calculated based on the known values.

The bottom diagram shows a laptop computer also starting with 160 J of input energy, distributed as 65 J, 20 J (labeled as Sound), and 75 J. There is a blank label to identify what kind of energy the 65 J represents. The total wasted energy must also be determined and labeled in the box below the diagram.

The user must drag and place the correct energy forms, such as "Kinetic energy", "Light", "Thermal energy", and the correct numerical energy values such as, "85 J" and "75 J", into the appropriate positions. By analyzing the diagram and applying energy conservation principles, users engage in critical thinking to correctly label both the types and amounts of energy. Once all labels are placed, the user can press the Check button to verify their answers.

Solution:

Ceiling fan diagram (top):

The arrow labeled 75 J represents Kinetic energy.

The arrow labeled 55 J should be labeled as Sound.

The amount of wasted energy is the sum of energy not converted to useful kinetic energy, which is the difference between input energy and output useful kinetic energy. That is, $\text{Amount of wasted energy} = 160\text{ J} - 75\text{ J} = 85\text{ J}$

So, 85 J is placed in the box below "Amount of wasted energy".

Laptop computer diagram (bottom):

The 65 J arrow should be labeled as Light.

The 75 J arrow going downward should be labeled as Thermal energy.

The amount of wasted energy is the difference between input energy and output useful energy. That is,

$\text{Amount of wasted energy} = 160\text{ J} - (65\text{ J} + 20\text{ J}) = 75\text{ J}$

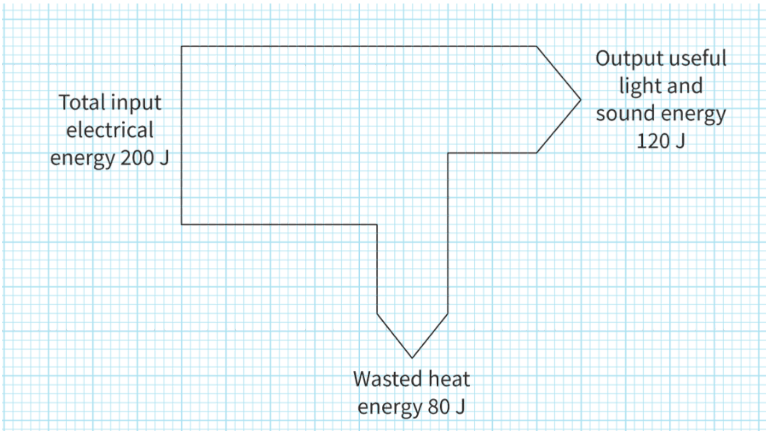
So, 75 J is placed in the box below "Amount of wasted energy".

Worked example 1

A modern television transfers 200 J of electrical energy to 120 J of light and sound energy. The rest of the energy is wasted as heat. Draw a Sankey diagram for the television.

Student view

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

Solution steps	Calculations
Step 1: recall the qualitative understanding of the physics	In a Sankey diagram, the thickness of each arrow is proportional to the amount of energy in each store.
Step 2: write out the values given in the question	total input energy = 200 J useful energy output (light and sound) = 120 J
Step 3: calculate the wasted energy	wasted energy output (heat) = 200 J − 120 J = 80 J
Step 4: draw the diagram	 Sankey diagram for a television.
Step 5: does your answer make sense?	✓ Yes. The amount of wasted and useful energy add up to equal the total input energy. The thickness of the arrows is proportional to their magnitudes.

Creativity, activity, service

Strand: Activity
Learning outcome: Demonstrate how to initiate and plan a CAS experience

Student view

Overview
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Wasted energy is unwanted and unusable output energy that is transferred to the surroundings and cannot be recovered to do useful work. Therefore, the lower the amount of energy wasted, the better.

You could set up a CAS project to raise awareness of energy wasted as a result of poor behaviour by consumers, and to inform the school community of energy-saving behaviours that could be adopted in everyday life.

Activities could include:

- creating a monthly leaflet to be sent via email to all students and teachers
- organising talks and inviting external speakers
- creating visuals to be displayed around the school.

Applications of the principle of conservation of energy

Many problems in physics can be solved by applying the principle of conservation of energy.

When a roller coaster train moves along the track, its energy transfers continuously between kinetic energy and gravitational potential energy, assuming no energy is wasted. The total amount (kinetic + gravitational potential) will stay the same throughout the ride. So the amount of kinetic energy the train has soon after launch is the same as the amount of gravitational potential energy the train has when it is momentarily stationary at the top of the main tower element, just before it starts falling back down.

You can investigate the energy transfers in a roller coaster in **Interactive 2**. To get the train moving press 'Start' and observe the energy transfers in the chart. You can press 'Reset' to replay or 'Randomise Track' to change the track contour and see the effect on the relative amounts of energy. In this interactive, it is assumed that no thermal energy is transferred to the surroundings due to friction. The size of the circle does not change throughout the movement along the track showing the conservation of energy.

Student
view

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Interactive 2. Energy transfers in a roller coaster.

More information for interactive 2

An interactive simulation titled, Energy Transfers in a Roller Coaster, illustrates the transfer of energy in a roller coaster system by showing how kinetic and gravitational potential energy change as a coaster moves along a track. The total energy of the system remains constant throughout, as there is no energy loss due to friction or air resistance. The coaster moves along a track with varying heights, and the interactive provides a real-time graphical representation of the relative amounts of kinetic and potential energy at each point.

The track includes peaks and valleys, allowing users to observe how energy is transferred between different forms. When the coaster is at the highest point of the track, it has maximum gravitational potential energy and minimal kinetic energy. As it descends, the potential energy converts into kinetic energy, causing the coaster to accelerate. When the coaster reaches the lowest part of the track, its speed is at a maximum, meaning kinetic energy is at its peak while gravitational potential energy is at its lowest. This cycle repeats as the coaster continues along the track.

Student view

Overview
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Users can press "Start" to begin the simulation and watch the energy transfers in action. The "Reset" button allows them to replay the scenario with the same track, while "Randomise Track" changes the track's shape, altering the distribution of energy. The interactive ensures that the total energy remains constant by keeping the total energy pie chart size unchanged throughout. The speed of the coaster is displayed.

Sample calculation:

Suppose a roller coaster car has a mass of 500 kilograms and starts from rest at a height of 50 meters. The gravitational potential energy at this height is given by the formula:

$$U = mgh$$

$$U = (500)(9.81)(50)$$

$$U = 245,250 \text{ Joules}$$

At the lowest point of the track, all of this potential energy is converted into kinetic energy, which is given by the equation:

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

$$245,\ 250 \text{ Joules} = \frac{1}{2}(500 \text{ kg})v^2$$

$$v^2 = \frac{245,\ 250 \times 2}{500}$$

$$v = \sqrt{490.5}$$

$$v \approx 22.14 \text{ m/s}$$

This calculation demonstrates how the energy conversion determines the coaster's velocity at different points in its path. The interactive visually represents these changes, allowing users to explore energy conservation and transformation in an engaging and intuitive way.

Student view

Worked example 2

A toy rocket is launched vertically upward with an initial speed of 14 m s^{-1} (**Figure 2**).

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Figure 2. Motion of a toy rocket.

More information for figure 2

The image depicts the motion of a toy rocket in three stages. The bottom rocket shows thrust with flames indicating maximum kinetic energy as it lifts off. The middle rocket is unlabeled and shown without any annotations as it continues upward. The top rocket is labeled "Maximum gravitational potential energy," indicating the point where it has reached its peak height before descending. Arrows next to each rocket illustrate the upward motion. This diagram visually represents the transition of energy types during the rocket's flight.

[Generated by AI]

Calculate the maximum height it can reach. Assume no wasted energy.

Solution steps	Calculations
Step 1: recall the qualitative understanding of the physics	At the start, the rocket has an initial amou of kinetic energy. When the rocket reache its maximum height, all its kinetic energy i transferred to gravitational potential energ

Student
view

Overview
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Solution steps	Calculations
Step 2: write out the values given in the question making sure to convert to SI units The value for g is in section 1.6.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/fundamental-constants-id-45155/)of the DP physics data booklet	$\Delta v = 14 \text{ m s}^{-1}$ $g = 9.8 \text{ N kg}^{-1}$
Step 3: write out the equation	kinetic energy = gravitational potential energy $\frac{1}{2}m\Delta v^2 = mg\Delta h$
Step 4: simplify for the mass	$\frac{1}{2}\Delta v^2 = g\Delta h$
Step 5: rearrange to calculate the change in height Δh	$\Delta h = \frac{\Delta v^2}{2g}$
Step 6: substitute the values	$= \frac{14^2}{2\times 9.8}$
Step 7: state the answer with appropriate units and the number of significant figures used in rounding	$= 10 \text{ m } (2 \text{ s.f.})$ Assuming the rocket starts from ground level $(h_\text{i} = 0)$, the maximum height it can reach is 10 m.
Step 8: does your answer make sense?	✓ Yes. The units are dimensionally consistent with the equation.

If resistive forces do act and cannot be neglected, the work they do must be taken into account. For example, consider an object with a certain initial speed travelling up a rough inclined ramp.

1. The object has an initial amount of kinetic energy dependent on its mass and initial speed.
2. As the object moves up the ramp, the initial kinetic energy decreases and the object gains gravitational potential energy. At the same time, some thermal energy is transferred to the surroundings due to friction.

Student view

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3. At a given point along the ramp:

$$\textit{final (kinetic energy + gravitational potential energy) +}$$
$$\textit{thermal energy = initial kinetic energy}$$

The principle of conservation of energy is still valid, although, in this case, it is not the mechanical energy that is being conserved, but the overall energy of the system (made up of the sliding object and the ramp) (**Figure 3**).

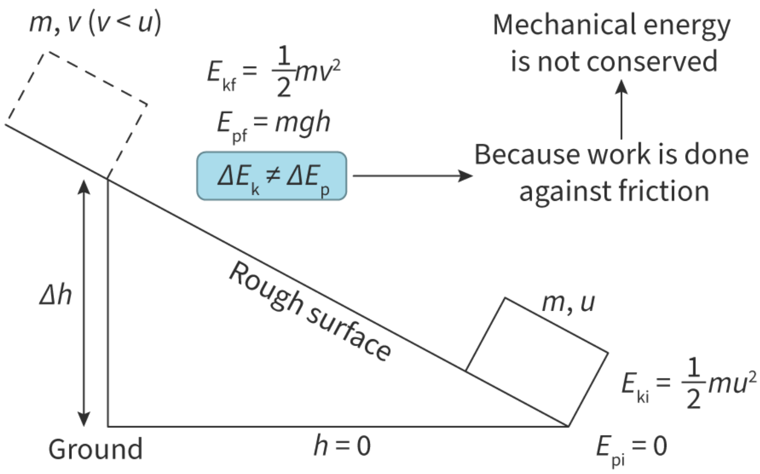

Figure 3. Mechanical energy is not conserved for an object sliding up the rough surface of a ramp.

More information for figure 3

The image is a diagram depicting a rough ramp with an object sliding up it. The diagram shows an object with mass 'm' initially moving with velocity 'u' at the bottom of the ramp, where its initial kinetic energy, denoted as E_ki, is given as (1/2)mu^2 and its potential energy E_pi is 0 because it starts at ground level. As the object ascends the ramp, its height increases by Δh. At the top of the ramp, the object's velocity becomes 'v', which is less than 'u' (v<u), indicating that some energy is lost to friction. The final kinetic energy E_kf is given as (1/2)mv^2, and the potential energy E_pf is mgh. There is a callout in the diagram that states "ΔE_k ≠ ΔE_p," highlighting that mechanical energy is not conserved. Text within the diagram also clearly notes "Because work is done against friction, mechanical energy is not conserved." Other labels include "Rough surface" on the ramp, with arrows indicating directions of motion and change in height (Δh). This diagram illustrates that while mechanical energy is not conserved, the total energy of the system might still be conserved.

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Worked example 3

A wooden block slides along a rough horizontal surface with an initial speed of 2.0 m s^{-1}. The coefficient of dynamic friction between the block and the surface is $\mu_{\mathrm{d}} = 0.15$. After moving a certain distance along the surface, the block comes to rest. Calculate the distance travelled by the block before coming to rest.

Solution steps	Calculations
Step 1: recall the qualitative understanding of the physics The equation for frictional force is given in the DP physics data booklet	The wooden block has an initial amount of kinetic energy. As th block slides along the rough surface, work is done by friction to reduce the speed. The magnitude of the frictional force F_f is given by the product of the coefficient of dynamic friction and the normal reaction force F_{N} $F_{\mathrm{f}} = \mu_d F_{\mathrm{N}}$
Step 2: determine the expression for the resistive force	Since the block is moving along a horizontal surface, the norm reaction force F_{N} and the block's weight $W = mg$ are equal. Therefore, the expression for the magnitude of the resistive for becomes: $F_{\mathrm{f}} = \mu_{\mathrm{d}} mg$
Step 3: relate force to work done	If s is the displacement of the wooden block before it comes to rest, the total work done by friction is: $W = -F_{\mathrm{f}} s = -\mu_{\mathrm{d}} mgs$ The minus sign in the equation is due to the fact that the angle between the frictional force F_f and the block's displacement s is $\theta = 180°$, hence $\cos\theta = -1$. The amount of work done by friction is equal to the change in the kinetic energy of the wooden block (with final kinetic energ equal to zero since the block comes to rest): $-\mu_{\mathrm{d}} mgs = 0 - \frac{1}{2}mv^2$
Step 4: write out the values given in the question making sure to convert to SI units The value for *g* is in the DP physics data booklet	$v = 2.0 \text{ m s}^{-1}$ $\mu_{\mathrm{d}} = 0.15$ $g = 9.8 \text{ N kg}^{-1}$

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Solution steps	Calculations
Step 5: rearrange for the displacement *s* and simplify for the mass *m*:	$s = \dfrac{v^2}{2\mu_d g}$
Step 6: substitute the values	$= \dfrac{2.0^2}{2\times0.15\times9.8}$
Step 7: state the answer with appropriate units and the number of significant figures used in rounding	$= 1.36$ So the block travels a distance of 1.4 m (2 s.f.) before coming tc rest.
Step 8: does your answer make sense?	✓ Yes. The number of significant figures is the same as the smallest number of significant figures in the question data. The units are dimensionally consistent with the equation.

Try the activity in the next section (/study/app/math-aa-hl/sid-423-cid-762593/book/activity-conservation-of-energy-id-43247/) to check your understanding of the principle of conservation of energy.

5 section questions

Question 1

SL HL Difficulty:

A skateboarder is at rest on one side of a half-pipe, waiting to slide down. Friction between the ramp's surface and the skateboard's wheels cannot be neglected. Which of the statements is correct?

1 The change in gravitational potential energy of the skateboarder is equal to the sum of the change in their kinetic energy and the thermal energy transferred to the surroundings. ✓

2 The initial kinetic energy of the skateboarder is transferred to gravitational potential energy and thermal energy.

3 The initial gravitational potential energy of the skateboarder is equal to their kinetic energy at the lowest point of their journey.

4 The thermal energy transferred to the ramp's surface is an example of mechanical energy.

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Explanation

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Since resistive forces are not negligible (there is friction between the ramp's surface and the skateboard's wheels), mechanical energy is not conserved. Therefore, at any point along the half-pipe, the change in gravitational potential energy of the skateboarder (the energy they start with) is equal to the sum of the change in their kinetic energy (useful output) and the thermal energy (wasted output) transferred to the surroundings due to the work done by friction.

Question 2

SL HL Difficulty:

A child sits at the top of a smooth slide, 1.5 m above the ground. What is the child's speed at the bottom of the slide? Assume no mechanical energy is lost.

1 5.4 m s^{-1} ✓

2 29 m s^{-1}

3 15 m s^{-1}

4 3.8 m s^{-1}

Explanation

Since no resistive forces act on the child, mechanical energy is conserved. This means that all the initial gravitational potential energy of the child when they are sitting at the top of the slide is equal to the final kinetic energy they have when they reach the bottom of the slide.

$$\frac{1}{2}m\Delta v^2 = mg\Delta h$$

Simplifying for the mass m:

$$\frac{1}{2}\Delta v^2 = g\Delta h$$

Rearranging for the speed:

$$\begin{aligned} v &= \sqrt{2g\Delta h} \\ &= \sqrt{2\times 9.8\times 1.5} \\ &= 5.4\ \mathrm{m\ s^{-1}}\ (2\ \mathrm{s.f.}) \end{aligned}$$

Question 3

SL HL Difficulty:

Student view

A projectile with a mass of 12 g is launched vertically upward from the ground by a spring release mechanism. The spring has a constant k = 15 N m^{-1}. The maximum height reached by the projectile is 2.4 m above the ground. Determine how much the spring is compressed just

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before the projectile is launched. Assume no mechanical energy is lost. Give your answer to two significant figures.

0.19 m ✓

Accepted answers

0.19 m, 0.19 metres, 0.19 meters, 0.19m

Also accepted

19 cm, 19 centimetres, 19 centimeters, 19cm

Explanation

Since no resistive forces act, the mechanical energy of the spring—projectile system is conserved. This means that all the initial elastic potential energy stored by the spring is equal to the sum of the final gravitational potential energy and kinetic energy of the projectile at its maximum height. Notice that the kinetic energy at the highest point is zero (since the projectile stops before falling back down). Hence:

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

Rearranging for the change in length of the spring:

$$\begin{aligned}\Delta x &= \sqrt{\frac{2mg\Delta h}{k}}\\ &= \sqrt{\frac{2\times0.012\times9.8\times2.4}{15}}\\ &= 0.19\text{ m (2 s.f.)}\end{aligned}$$

Question 4

SL HL Difficulty:

An object of mass 15 kg moves along a smooth horizontal surface until it hits the end of a large spring attached to a wall. The spring is compressed by 120 cm and the object comes to rest. The spring constant is 2500 N m^{-1}. What is the speed at which the object is moving before coming into contact with the spring? Assume no mechanical energy is lost. Give your answer to two significant figures.

The speed of the object is 1 15 ✓ m s^{-1}.

Accepted answers and explanation

#1 15

General explanation

Since no resistive forces act, the mechanical energy of the object—spring system is conserved. This means that all the initial kinetic energy stored by the moving object is equal to the final elastic potential energy stored by the spring when it is compressed by an amount $\Delta x = 120\text{ cm} = 1.2\text{ m}$. Hence:

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

Simplifying and rearranging for the change in speed of the object:

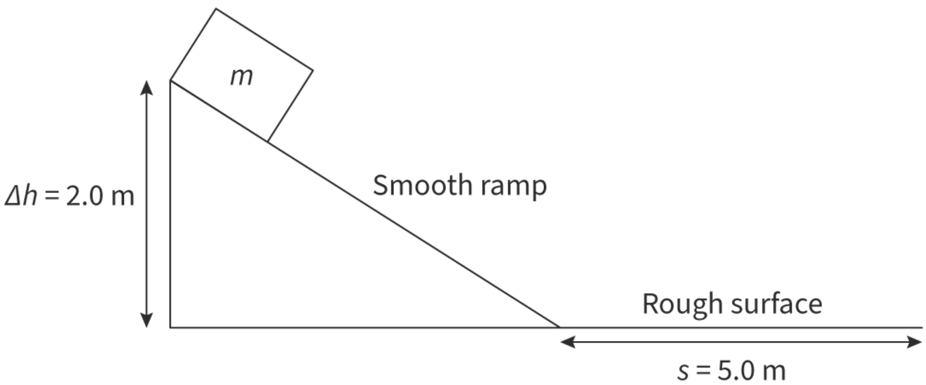
$$\Delta v = \sqrt{\frac{k\Delta x^2}{m}}$$
$$= \sqrt{\frac{2500\times1.2^2}{15}}$$
$$= 15 \text{ m s}^{-1} \text{ (2 s.f.)}$$

Since the object comes to rest, the speed of the object before coming into contact with the spring is 15 m s^{-1}.

Question 5

SL HL Difficulty:

A block is released from the top of a smooth ramp of height 2.0 m. The block slides down the ramp and then moves 5.0 m along a rough horizontal surface before coming to rest.



More information

What is the coefficient of dynamic friction between the block and the horizontal surface?

1 0.40 ✓

2 2.5

3 0.50

4 0.30

Student view

Explanation

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Consider the journey of the block down the smooth ramp. The change in gravitational potential energy of the block is equal to the change in its kinetic energy when it reaches the bottom of the ramp:

$$mg\Delta h = \frac{1}{2}m\Delta v^2$$

Now consider the journey of the block along the rough horizontal surface. The change in the kinetic energy of the block is equal to the work done by friction F (recall that the final kinetic energy is zero since the block stops in a distance s):

$$-\frac{1}{2}m\Delta v^2 = -Fs$$

Using the previous equivalence between the changes in gravitational potential energy and kinetic energy:

$$-mg\Delta h = -Fs$$

Substituting $F = \mu_d mg$ for friction:

$$mg\Delta h = \mu_d mgs$$

Simplifying for the product of mass and gravitational field strength mg and rearranging for the coefficient of dynamic friction μ_d:

$$\begin{aligned}\mu_d &= \frac{\Delta h}{s}\\ &= \frac{2}{5}\\ &= 0.40 \text{ (2 s.f.)}\end{aligned}$$

A. Space, time and motion / A.3 Work, energy and power

Activity: Conservation of energy

A.3.1: The principle of the conservation of energy A.3.7: Conservation of mechanical energy

Student view

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Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/work-and-energy-id-43084/print/) Assign

Activity

- **IB learner profile attribute:**
  - Thinker
  - Communicator
- **Approaches to learning:**
  - Thinking skills — Applying key ideas and facts in new contexts
  - Social skills — Working collaboratively to achieve a common goal
- **Time to complete activity:** 20—30 minutes
- **Activity type:** Pair activity

This activity consolidates your understanding of the principle of conservation of energy.

Instructions

Part 1

Start by selecting 'Intro' on the 'Energy Skate Park' simulation.

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On the top right corner of the screen, tick the 'Grid' and 'Speed' boxes. A speedometer should appear. Each small division on the speedometer is equal to 1 m s^{-1}.

At the bottom of the screen, in the centre, enable the 'Slow motion'.

1. Place the skateboarder at a height of 6 m on either side of the track. Record this in a table.
2. Press play to release the skateboarder, and pause when it reaches the bottom of the track. Record the skateboarder's speed on the table.
3. Repeat steps 1 and 2 for heights of 5 m, 4 m, 3 m, 2 m and 1 m. Record all heights and speeds in the table.

The mass of the skateboarder is 40 kg. Calculate the initial gravitational potential energy of the skateboarder for each height and the final kinetic energy when they reach the bottom of the track. Compare these values. What do you notice? Discuss this with your partner.

Part 2

At the bottom of the screen, select the 'Friction' scenario. Click the 'Grid' and 'Speed' boxes again. Then select 'Slow motion' and repeat steps 1—3 from Part 1. Then, assuming the skateboarder mass is still 40 kg, calculate the initial gravitational potential energy of the skateboarder for each height and the final kinetic energy when they reach the bottom of the track. Compare these values. What do you notice? How do your results differ from the ones you obtained in the 'Intro' scenario in Part 1? Discuss this with your partner.

A. Space, time and motion / A.3 Work, energy and power

Power and efficiency

A.3.9: Power A.3.10: Efficiency in terms of energy transfer or power

Learning outcomes

By the end of this section you should be able to:

- Define power and use the equation for power to solve problems.
- Define efficiency in terms of energy and power.

The concepts of energy and work are often connected to the concepts of power and efficiency .

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Machines were invented and built because they could help humans transfer energy in less time, or in other words, they could do work faster. A modern smartphone can perform approximately 11 trillion operations per second and is about 5000 times faster than a supercomputer from the 1980s. Would you say that modern smartphones are more powerful than the first supercomputers? What does it mean for one machine to be more powerful than another?

Theory of Knowledge

Interpretation

The term *power* is often related to authority and influence. This is very different to the meaning the word power has in physics.

Why do scientists need to have explicitly defined terms? How do scientists use language differently from other disciplines?

In addition to developing more powerful machines, scientists and engineers are concerned with improving the efficiency of machines. A modern LED light bulb is much more efficient than an old filament light bulb, as explained in section A3.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/conservation-of-energy-id-43085/). The efficiency of solar panels (**Figure 1**) has increased from about 15% to over 20%. But what is efficiency? And how can the efficiency of a machine be determined?

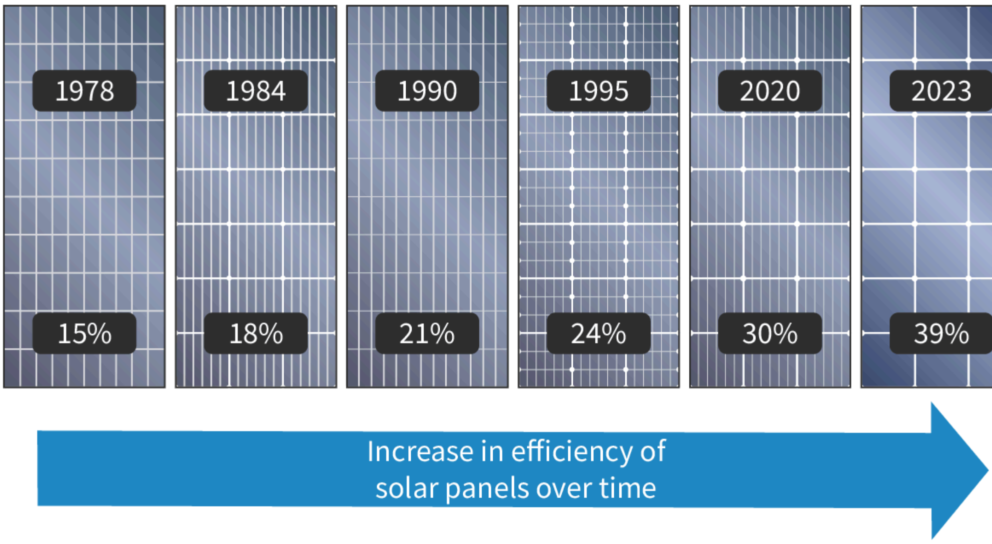

Figure 1. Increasing efficiency of solar panels.

More information for figure 1

Student view

The graphic illustrates the increase in solar panel efficiency over several decades. It displays six solar panels arranged sequentially from left to right, each marked with a year and efficiency percentage. The first panel on the left is labeled "1978" with an efficiency of 15%. The second panel is labeled "1984" with 18% efficiency. The third panel shows "1990" with 21% efficiency. The fourth is labeled "1995" with 24% efficiency. The fifth panel is marked "2020" with 30% efficiency, and the panel on the far right is labeled "2023" with an efficiency of 39%. An arrow underneath the panels indicates the timeline, titled "Increase in efficiency of solar panels over time."

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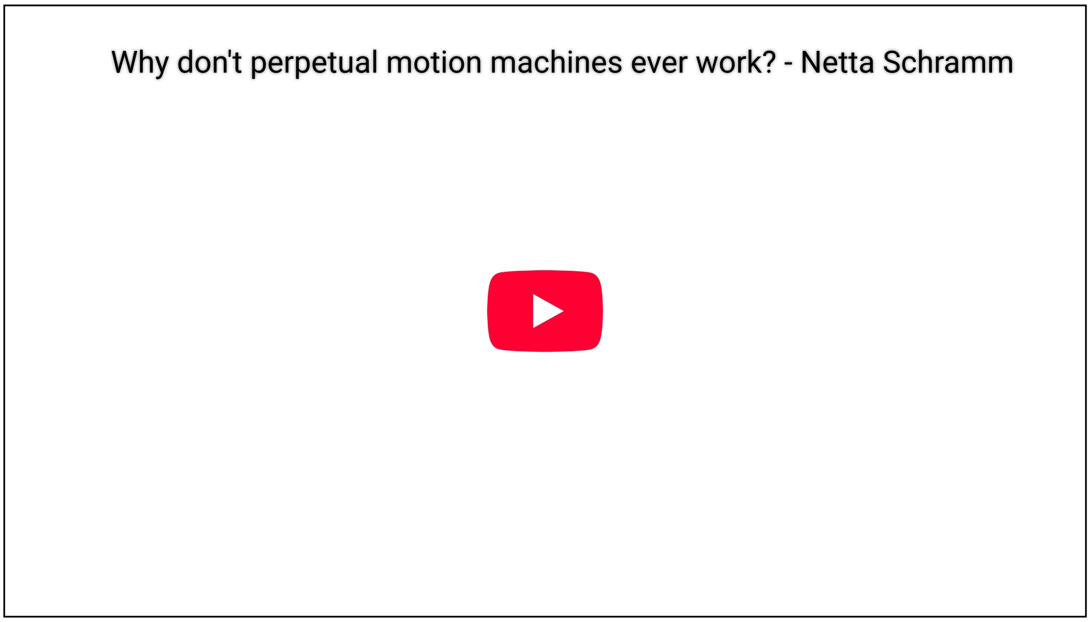
Nature of Science

Aspect: Theories

Humans have long been fascinated with the idea of perpetual machines. Such machines can transfer energy from one store to another infinitely, without any loss of energy. A perpetual machine would therefore have a useful energy output with a zero energy input. We now know that perpetual machines cannot exist as they violate several laws of physics.

This video explains why perpetual machines will never work.



Video 1. Why don't perpetual motion machines ever work?

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Power

Power is defined as the rate of work done or the rate of energy transfer. **Table 1** shows how it is calculated.

Making connections

The word **rate** in physics is used to indicate the measure of the change of a quantity as a function of time. Lots of physical quantities are defined as rates of other quantities. Can you think of a quantity defined this way, other than power?

Table 1. Equation for power using work done and time.

Equation	Symbols	Units
$P = \frac{\Delta W}{\Delta t}$	P = power	watts (W)
	ΔW = work done	joules (J)
	Δt = time	seconds (s)

Power is measured in watts (W). From the equation for power, you can see that:

$$1W = 1\ \text{J s}^{-1}$$

Nature of Science

Aspect: Measurement

As you have seen, power is measured in watts (W). However, we often use the term *horsepower* (hp) when we refer to the power of an engine. A 1000-horsepower racing sports car (like a Formula 1 car) is much faster than a 200-horsepower car. But where does this word come from? And why do we use the power developed by a horse as a reference?

In everyday life, we often use old units of measure that were originally developed because they were convenient at the time and easier for people to understand. This video tells you who came up with the concept of horsepower and why it was useful at the time.

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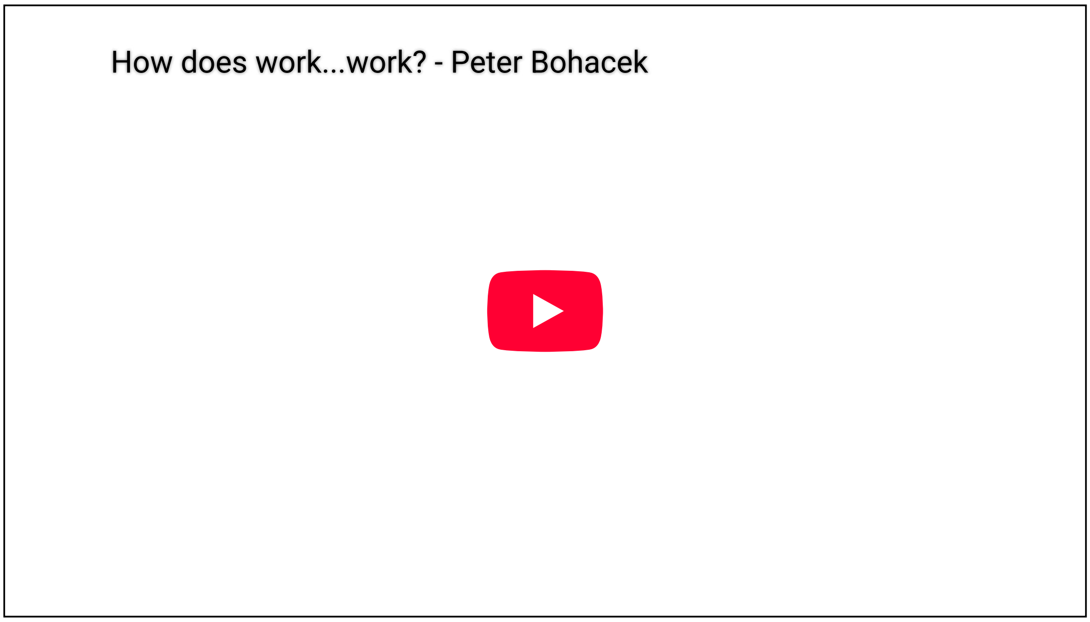

Video 2. Concepts of work and power.

Worked example 1

A winch motor is used to lift a heavy 210 kg load from the ground to a height of 6.0 m. The load rises in half a minute. Calculate the power of the motor.

Solution steps	Calculations
Step 1: recall the qualitative understanding of the physics	Power is the rate of work done. First you need to calculate the work done.
Step 2: write out the values given in the question making sure to convert to SI units The value for *g* is in [section 1.6.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/fundamental-constants-id-45155/)](/study/app/math-aa-hl/sid-423-cid-762593/book/fundamental-constants-id-45155/) of the DP physics data booklet	$m = 210\text{ kg}$ $\Delta h = 6.0\text{ m}$ $g = 9.8\text{ m s}^{-2}$ $\Delta t = 30\text{ s}$
Step 3: calculate the work done	The work done by the motor is equivalen to the change in gravitational potential energy of the load: $\begin{aligned}\Delta W &= mg\Delta h \\ &= 210 \times 9.8 \times 6.0 \\ &= 12\,400\text{ J}\end{aligned}$

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Solution steps	Calculations
Step 4: write out the equation	$P = \dfrac{\Delta W}{\Delta t}$
Step 5: substitute the values given	$= \dfrac{12\,400}{30}$
Step 6: state the answer with appropriate units and the number of significant figures used in rounding	$= 410 \text{ W } (2 \text{ s.f.})$
Step 7: does your answer make sense?	✓ Yes. The number of significant figures the same as the smallest number of significant figures in the question data.

Power and moving vehicles

Imagine a car moving at a constant velocity on a straight flat road. Since the car's velocity does not change, the resultant force on the car must be zero (according to Newton's first law of motion) (**Figure 2**).

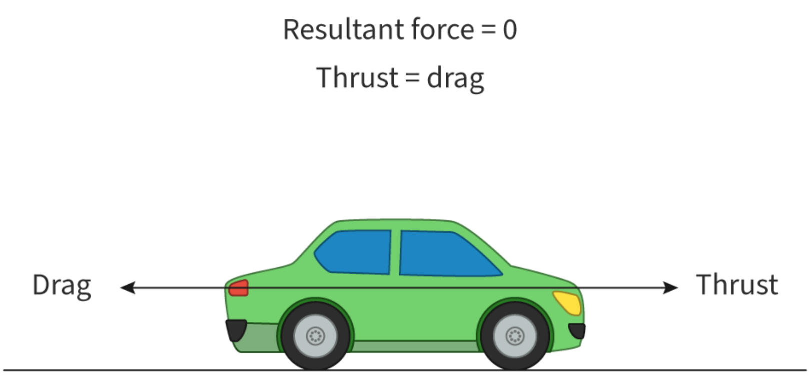

Figure 2: Horizontal forces on a car travelling at a constant velocity along a straight flat road.

More information for figure 2

The image illustrates a simple diagram of a car on a flat road, showing the horizontal forces acting upon it. The front of the car is labeled "thrust," with an arrow pointed forward, indicating the force propelling the car. The back of the car is labeled "drag," with an arrow pointing backward, indicating the opposing force. Above the car is a note that

Student view

states "Resultant force = 0" and "Thrust = drag," suggesting that these forces are equal and opposite, resulting in a net force of zero, allowing the car to move at a constant velocity.

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How much power does the engine need to develop in order to maintain the car's constant velocity over a total displacement s?

The work done by the thrust F of the engine is:

$$W = Fs$$

To calculate the power developed by the engine, divide the above equation by time:

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

When the velocity is constant (as in this case), displacement over time is equal to velocity:

$$\frac{s}{t} = v$$

Substituting the velocity, you can write the power developed by the car's engine as:

Table 2. Equation for power using force and velocity.

Equation	Symbols	Units
$P = Fv$	P = power	watts (W)
	F = force	newtons (N)
	v = velocity	metres per second (m s^{-1})

You have derived another equation for power that is often used to solve problems involving moving vehicles.

What do you think ultimately happens to the power developed by the car's engine?

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Making connections

Different equations to the ones derived above are used to calculate electrical power. This will be discussed in subtopic B.5 (:sectionlink:123822).

Efficiency

In many real-life processes, some of the energy input into a system is dissipated (or wasted) instead of being usefully transferred.

The efficiency η of an energy transfer is defined as the ratio of useful energy output to total energy input. Efficiency can also be defined in terms of power, as the ratio of useful power output to total power input. The equation for efficiency is:

Table 3. Equation for efficiency.

Equation	Symbols	Units
$\eta = \frac{E_{\text{output}}}{E_{\text{input}}} = \frac{P_{\text{output}}}{P_{\text{input}}}$	η = efficiency	unitless
	E_{output} = useful energy output	joules (J)
	E_{input} = total energy input	joules (J)
	P_{output} = useful power output	watts (W)
	P_{input} = total power input	watts (W)

Recall that:

$$E_{\text{input}} = E_{\text{useful}} + E_{\text{wasted}}$$

where E_{useful} is the useful energy output and E_{wasted} is the wasted energy output.

You should notice that efficiency is a unitless quantity, since it is a ratio.

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Making connections

The refractive index of a substance is also a unitless quantity, since it is defined as the ratio between the speed of light in a vacuum and the speed of light in the substance. Can you think of any other physical (or mathematical) quantities that are defined as ratios and hence have no units of measure?

Efficiency can be expressed as a fraction or as a percentage. This is the equation to calculate efficiency as a percentage:

$$\eta\% = \frac{E_{\text{output}}}{E_{\text{input}}} \times 100\% = \frac{P_{\text{output}}}{P_{\text{input}}} \times 100\%$$

Study skills

When you substitute numbers into the equations for efficiency, you should always make sure that the numerator is smaller than the denominator. The upper limit to the efficiency of any machine is 1 (or 100%), corresponding to a perfect process in which all the total input energy is transferred to useful output energy and no energy is wasted. An efficiency higher than 1 does not make sense, since in no physical process can the output energy be greater than the input energy.

Exercise 1

Click a question to answer

Making connections

The efficiency of heat engines will be discussed in subtopic B.4 (:sectionlink:123824).

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Activity

- **Learner profile attribute:** Thinker
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time to complete activity:** 20 minutes
- **Activity type:** Individual activity

Instructions

Complete the following tasks on your own during class or at home. The tasks make sure that you can work with the new learning in this section.

1. A person with a mass of 72 kg runs up a set of stairs in 15 s. The change in the vertical position of the person is 3.0 m. Determine the power developed by the person.

   The work done by the person is equal to the change in their gravitational potential energy:

   $$W = mg\Delta h$$

   Hence, the power developed by the person is:

   $$\begin{aligned} P &= \frac{W}{\Delta t} \\ &= \frac{mg\Delta h}{\Delta t} \\ &= \frac{72\times 9.8\times 3.0}{15} \\ &= 140\ \mathrm{W}\ (2\ \mathrm{s.f.}) \end{aligned}$$

2. A car travels on a straight flat road at a constant velocity. The thrust from the car's engine is 2000 N. The car takes 5 minutes to move 1.2 km. Calculate the power developed by the car's engine.

   The power developed by the car's engine is:

   $$P = Fv$$

   Since the car's velocity is constant, use the equation:

   $$v = \frac{s}{t}$$

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Substituting the expression for the velocity into the equation for power:

$$\begin{aligned} P &= \frac{Fs}{t} \\ &= \frac{2000 \times 1200}{5 \times 60} \\ &= 8000 \text{ W (1 s.f.)} \end{aligned}$$

3. Verify that the units in the equation $P = Fv$ are consistent (the units on the left-hand side of the equation are equal to the units on the right-hand side of the equation).

Power is measured in watts (W), force is measured in newtons (N), and velocity is measured in metres per second (m s^{-1}). Therefore the units in the equation are:

$$\text{W} = \text{N m s}^{-1}$$

Using the idea of power as rate of work done:

$$1 \text{ W} = 1 \text{ J s}^{-1}$$

Using Newton's second law of motion $(F = ma)$:

$$1 \text{ N} = 1 \text{ kg m s}^{-2}$$

Substituting into the previous equation:

$$\text{J s}^{-1} = \text{kg m s}^{-2} \text{ m s}^{-1}$$

Using the equation for work $(W = Fs)$ and Newton's second law $(F = ma)$:

$$\begin{aligned} 1 \text{ J} &= 1 \text{ N m} \\ &= 1 \text{ kg m s}^{-2} \text{ m} \\ &= 1 \text{ kg m}^2 \text{ s}^{-2} \end{aligned}$$

Substituting into the previous equation:

$$\text{kg m}^2 \text{ s}^{-3} = \text{kg m}^2 \text{ s}^{-3}$$

So the units of the equation are consistent.

4. A vehicle moves along a straight flat road at a constant velocity. The thrust of the vehicle's engine does work and develops power. Sketch two graphs to show how the work done and the power developed vary with time.

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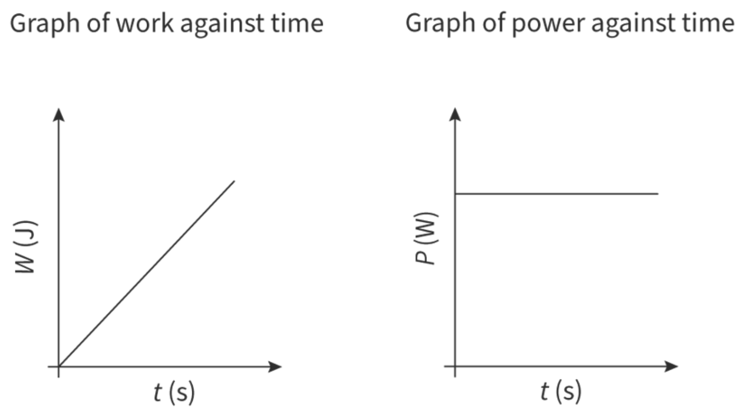
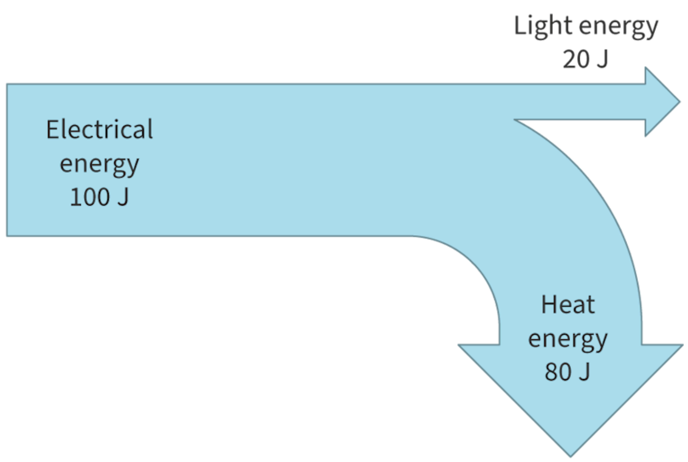


Work done and power for a vehicle at constant velocity.

5. A light bulb has an efficiency of 20%. Sketch a Sankey diagram for the bulb. Give possible values of the total input energy, useful output energy and wasted output energy. Then name the input and output energy stores.



Sankey diagram for a light bulb.

6. A wind turbine uses 200 kW of wind power to generate 50 kW of electrical power. Calculate the efficiency of the wind turbine and determine what percentage of the input power is dissipated.

Student view

Efficiency is calculated as the ratio of useful power output to total power input. Therefore, the efficiency of the wind turbine is:

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$$\begin{aligned}\eta &= \frac{E_{\text{output}}}{E_{\text{input}}} \\ &= \frac{50}{200} \\ &= 0.25 \\ &= 25\%\end{aligned}$$

The wind turbine dissipates 75% of the input power (150 kW).

5 section questions

Question 1

SL HL Difficulty:

Two people are stacking boxes onto a shelf. Person X lifts the boxes in 2.0 minutes, while person Y takes 4.0 minutes to lift the same number of identical boxes onto the same shelf. Which statement is correct?

1 Person X develops more useful power than person Y. ✓

2 Person X develops less useful power than person Y.

3 Person X does more useful work than person Y.

4 Person X does less useful work than person Y.

Explanation

Since the two people are lifting the same number of identical boxes onto the same shelf, the work they do is identical. The difference is that person X performs this task in less time. Hence, the power developed by person X is more than the power developed by person Y.

Question 2

SL HL Difficulty:

A truck moves along a straight flat road. One of the physical quantities needed to calculate the power developed by the truck's engine is the magnitude of the thrust force. What else must be known?

1 Both the distance moved by the truck and the time for which the thrust force acts. ✓

2 Only the distance moved by the truck.

Student
view

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3 Only the time for which the thrust force acts.

4 Neither the distance moved by the truck nor the time for which the thrust force acts.

Explanation

The power developed by the truck's engine is calculated as the product of force and velocity. The distance moved by the truck and the time for which the thrust force acts are both needed in order to determine the velocity of the truck: velocity = distance/time.

Question 3

SL HL Difficulty:

A machine is used to raise a 300 N load through a vertical height of 5.0 m. The machine's power input is 180 W. The machine dissipates 80 W of energy as heat and sound each second. How long does it take to lift the load?

1 15 s ✓

2 1500 s

3 150 s

4 1.5 s

Explanation

The useful work done by the machine is equal to the change in gravitational potential energy of the load:

$$W = mg\Delta h$$

Dividing this equation by time gives an expression for the useful power developed by the machine:

$$P = \frac{mg\Delta h}{\Delta t}$$

The useful power developed by the machine is:

$$\begin{aligned} P &= 180 \text{ W} - 80 \text{ W} \\ &= 100 \text{ W} \end{aligned}$$

Rearranging the equation for the time Δt and substituting the numbers in:

Student view

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$$\begin{aligned}\Delta t &= \frac{mg\Delta h}{P}\\ &= \frac{300\times5.0}{100}\\ &= 15\ \text{s (2 s.f.)}\end{aligned}$$

Question 4

SL HL Difficulty:

A lift with a mass of 250 kg is powered by a motor with an efficiency of 55%. Three people enter the lift at ground level and use it to move to a floor 16 m above. The average mass of each person entering the lift is 75 kg. Calculate the total input electrical energy used by the motor. Give your answer to two significant figures.

140 000 J ✓

Accepted answers

140 000 J, 140000 J, 140 kJ , 1.4 × 10^5 J, 1.4 × 10^2 kJ , 1.4×10^5 J, 1.4×10^2 kJ, 1.4 x 10^5 J, 1.4 x 10^2 kJ , 1.4x10^5 J, 1.4x10^2 kJ, 1.4 * 10^5 J, 1.4 * 10^2 kJ , 1.4*10^5 J, 1.4*10^2 kJ

Also accepted

140000 joules

Explanation

The useful output energy transferred by the lift's motor is equal to the gravitational potential energy gained by the lift and the people inside it:

$$E_{\text{output}} = mg\Delta h$$

The mass *m* is the combined mass of the lift and the people:

$$\begin{aligned}m &= 250 + (3\times75)\\ &= 475\ \text{kg}\end{aligned}$$

Efficiency is the ratio of useful energy output to total energy input:

$$\eta = \frac{E_{\text{output}}}{E_{\text{input}}} = \frac{mg\Delta h}{E_{\text{input}}}$$

Rearranging for the total input electrical energy and substituting the numbers in:

$$\begin{aligned}E_{\text{input}} &= \frac{mg\Delta h}{\eta}\\ &= \frac{475\times9.8\times16}{0.55}\\ &= 140\,000\ \text{J (2 s.f.)}\end{aligned}$$

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Question 5

SL HL Difficulty:

A cyclist, initially at rest, accelerates along a straight horizontal road under the action of the constant thrust developed by the movement of the pedals. Friction and air resistance are negligible. What is the relationship between power developed by the cyclist and time?

1. Power increases linearly with time. ✓
2. Power does not change with time.
3. Power decreases linearly with time.
4. Power increases non-linearly with time.

Explanation

The equation for the power developed by the cyclist is:

$$P = Fv$$

where *F* is the thrust developed by the movement of the pedals and *v* is the velocity at which the cyclist moves.

The force *F* is constant, but the velocity *v* is not (since the cyclist accelerates from rest). The dependence of the power on the time then lies in the dependence of the velocity on the time. Since the only force *F* acting on the cyclist is constant, the cyclist accelerates with constant acceleration. This means that the velocity increases linearly with time. Therefore, power also increases linearly with time.

A. Space, time and motion / A.3 Work, energy and power

Energy density of fuels

A.3.11: Energy density of the fuel sources

Learning outcomes

By the end of this section you should be able to define the energy density of a fuel and calculate it.

Student view

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The majority of energy that is used worldwide for the production of goods or to power households and factories has been generated by harnessing the chemical potential energy stored within fossil fuels, such as coal, petroleum or natural gas. Nowadays, around 80% of the world's electrical energy is produced by the burning of fossil fuels.

Making connections

The burning of fossil fuels is a direct cause of the enhanced greenhouse effect, which will be discussed in subtopic B.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43134/).

In the 1950s, nuclear fuel started to be used as an alternative to fossil fuels. Uranium is the most widely used nuclear fuel. In 2023, 10% of the electrical energy generated worldwide comes from nuclear power plants.

Alternative fuels such as biodiesel, hydrogen, vegetable oil and biomass are also occasionally used. Wood is also considered to be a fuel.

Use **Interactive 1** to see how the electricity in your country is generated. Click on the 'Edit countries and regions' button and select your own country from the list.

Student view

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Interactive 1. Exploring how electricity is generated.

More information for interactive 1

The "Global Electricity Production by Source" interactive from Our World in Data provides a visual representation of electricity generation trends from 1985 to 2023, measured in terawatt-hours. Using a stacked area chart, it illustrates how different energy sources—including coal, gas, oil, nuclear, hydropower, wind, solar, bioenergy, and other renewables—have contributed to global electricity production over time.

Users can explore historical trends by observing how fossil fuels dominated electricity generation for decades and how renewables like wind and solar have grown in recent years. The color-coded chart allows for an easy comparison of the relative share of each energy source, highlighting shifts in global energy dependence. Additionally, the country and region filter enables users to analyze regional differences, revealing how different areas have adopted various energy sources at different rates.

By adjusting the timeline slider, users can examine how technological advancements, policy changes, and economic factors have influenced electricity production over time. The interactive also includes options to switch between a graphical (chart) view and a tabular data view, providing flexibility in data interpretation. Icons at the bottom allow users to download data, enlarge the chart, or customize visualization settings for deeper analysis.

Through this interactive, users gain a deeper understanding of global energy transitions, the shift from fossil fuels to renewables, and variations in electricity production across different regions.

How can we evaluate which of these energy sources is the best? What factors should we consider? How can they be measured? How does this make you feel about your own energy use?

Energy density

A fuel is a material that can be made to react with other substances in order to produce thermal energy or mechanical energy that can be used to do work.

One of the things to consider when choosing a suitable fuel is energy density, which is defined as the amount of energy in a fuel per unit volume. Energy density is measured in joules per cubic metre (J m^{-3}).

Study skills

To remember how energy density is defined and calculated, you should focus on the term *density*. The density of an object is defined as the ratio between an object's mass and its volume. Similarly, energy density is a ratio with volume as the

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denominator, but instead of having the mass as the numerator, you have energy.

Table 1 gives the approximate energy densities of some common fuels.

Table 1. Energy densities of some common fuels.

Fuel	Energy density (J m^{-3})
Uranium	10^{18}
Coal	10^{10}
Wood	10^{9}
Natural gas	10^{8}

Notice how the energy density of uranium is several orders of magnitude larger than the energy densities of the other fuels. The higher the energy density of a fuel, the smaller the volume needed in order to produce a certain amount of energy. Knowing the energy density of a fuel is crucial in order to determine the volume of fuel that needs to be transported and stored to produce the amount of energy needed.

Activity

- **IB learner profile attribute:**
  - Inquirer
  - Knowledgeable
  - Thinker
  - Communicator
- **Approaches to learning:**
  - Thinking skills — Combining different ideas in order to create new understandings
  - Social skills — Working collaboratively to achieve a common goal
- **Time to complete activity:** 10 minutes
- **Activity type:** Pair activity

Student view

Instructions

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Energy density has the same unit as another physical quantity you should know from previous studies. When two physical quantities have the same units, they are equivalent (for example, work and energy).

1. Discuss this with your partner, then use dimensional analysis (use known physical equations to work out the fundamental units of physical quantities) to find out which other physical quantity from the list has the same unit of measure as energy density.

   A. Power

   B. Pressure

   C. Force

   D. Density

   An example of dimensional analysis is given below for work/energy.

   The equation for work is:

   $$W = Fd$$

   So the unit for work (the joule, J) is equivalent to 1 N m.

   To find out what 1 N (the newton) is equivalent to, use Newton's second law:

   $$F = ma$$

   Therefore, 1 N is equivalent to 1 kg m s^{-2}.

   Multiplying this by 1 m, you get the expression for 1 J in SI base units:

   1 J = 1 kg m^2 s^{-2}

B. Pressure

Unit of energy density = J m^{-3} = N m^{-2}

Unit of pressure = Pa = N m^{-2}

2. Explain mathematically the equivalence between energy density and the unknown physical quantity from question 1.

Pressure may be considered to be a measure of energy density (energy per unit volume). Pressure is defined as force per unit area:

$$P = \frac{F}{A}$$

Using the equation for work, the force F can be written as:

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$$F = \frac{W}{s}$$

where s is displacement.

Substituting into the equation for pressure:

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

The product of displacement and area is dimensionally a volume, hence:

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

This links pressure to work (or energy) per unit volume, and hence to energy density.

5 section questions

Question 1

SL HL Difficulty:

Which of the substances is **not** considered to be a fuel?

1 Carbon dioxide ✓

2 Coal

3 Hydrogen

4 Wood

Explanation

Carbon dioxide is not a fuel as it cannot be used currently to generate electricity. Scientists are trying to convert carbon dioxide back into useful fuel, although, so far, all their attempts have been unsuccessful.

Coal, hydrogen and wood are all examples of fuels.

Question 2

SL HL Difficulty:

What is the definition of the energy density of a fuel?

Student
view

1 The amount of energy in a fuel per unit volume. ✓

2 The amount of energy in a fuel per unit mass.

3 The amount of energy in a fuel per unit time.

4 The amount of energy in a fuel per unit mole.

Explanation

The energy density of a fuel is defined as the amount of energy in a fuel per unit volume. In general, a density of a quantity is always the ratio of that quantity to volume.

Question 3

SL HL Difficulty:

What are the fundamental SI units of measure of energy density?

1 kg m^{-1} s^{-2} ✓

2 kg m s^{-2}

3 kg m^{2} s^{-2}

4 kg m^{-1} s^{-1}

Explanation

Energy density is defined as the ratio of energy to volume.

Hence, it has units:

J m^{-3} = N m^{-2} = kg m^{-1} s^{-2}

Question 4

SL HL Difficulty:

Consider a fuel with mass density ρ and energy density ε. What mass of fuel is needed in order to produce an amount of thermal energy E?

1 $\frac{\rho E}{\varepsilon}$ ✓

2 $\frac{\rho \varepsilon}{E}$

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3 $\frac{\varepsilon E}{\rho}$

4 $\rho\varepsilon E$

Explanation

The mass density of the fuel is the ratio of mass to volume of the fuel:

$$\rho = \frac{m}{V}$$

The energy density of the fuel is the ratio of energy to volume of the fuel:

$$\varepsilon = \frac{E}{V}$$

Therefore, the mass of energy needed in order to produce an amount of energy *E* is:

$$m = \frac{\rho E}{\varepsilon}$$

This has the dimensions of a mass (kg).

Question 5

SL HL Difficulty:

A fossil fuel power station has an efficiency of 30% and is powered by coal with an energy density of 1 × 10^{10} J m^{-3}. The power station generates 2000 MW of electrical power.

The volume of fuel consumed each second is 1 0.7 ✓ m^3 s^{-1}. Give your answer to an appropriate number of significant figures.

Accepted answers and explanation

#1 0.7

General explanation

Rearranging the equation for efficiency, you can calculate the total input power:

$$\begin{aligned} P_{\text{input}} &= \frac{P_{\text{output}}}{\eta} \\ &= \frac{2\times10^9}{0.30} \\ &= 6.667\times10^9 \text{ W} \end{aligned}$$

Power is energy over time.

Student view

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Since energy density is energy over volume, the volume of fuel consumed each second is given by:

$$\begin{aligned}\frac{V}{t} &= \frac{P_{\text{input}}}{\text{energy density}}\\ &= \frac{6.667\times10^{9}}{1\times10^{10}}\\ &= 0.6667\\ &= 0.7\ \text{m}^3\ \text{s}^{-1}\ (1\ \text{s.f.})\end{aligned}$$

A. Space, time and motion / A.3 Work, energy and power

Summary and key terms

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/summary-and-key-terms-id-43088/print/) Assign

- Energy is stored in a variety of forms and can be transferred from one store to another. The work done is equivalent to a transfer of energy. Energy and work are measured in joules (J).
- Mechanical energy is the sum of kinetic energy, gravitational potential energy and elastic potential energy within a system. In the absence of resistive forces, mechanical energy is always conserved.
- When resistive forces (such as friction and drag) are present, mechanical energy is not conserved, and some of it is transferred to the surroundings as thermal energy. The ‘missing’ mechanical energy is equal to the work done by the resistive forces.
- Power is defined as the rate of work done or the rate of energy transfer. It is measured in watts (W).
- Efficiency is defined as the ratio of useful energy output to total energy input, or as the ratio of useful power output to total power input. Efficiency is always a number between 0 and 1 (or a percentage between 0% and 100%).
- Most electrical and mechanical energy is generated by harnessing the energy stored within fuels. When choosing a fuel, it is useful to consider its energy density amongst other factors. The energy density of a fuel is defined as the energy to volume ratio for that fuel.

Student view

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/power-and-efficiency-id-43086/print/) Assign

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Key terms

Review these key terms. Do you know them all? Fill in as many gaps as you can using the terms in this list.

1. is the product of displacement and component of the force parallel to the displacement.
2. is the active energy of a moving mass.
3. is the energy stored in a mass due to its position within a gravitational field.
4. is the rate of energy transferred.
5. is the ratio of useful energy output to total energy input.
6. Energy transferred and work done are both measured in .
7. Power is measured in .
8. is the ratio of energy to volume for a fuel source.

joules | Gravitational potential energy | Kinetic energy | Efficiency | Power | Energy density | Work done | watts

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/energy-density-of-fuels-id-43087/print/) Assign

Check

Interactive 1. Energy Transfers Between Stores.

A. Space, time and motion / A.3 Work, energy and power

Checklist

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/checklist-id-43089/print/) Assign

What you should know

After studying this subtopic, you should be able to:

- Identify key energy stores and describe energy transfers.

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- Define work and use the equation for work to solve problems.
- Calculate the work done by a force as the area under a force—displacement curve.
- Describe that the work done by the resultant force on an object is equivalent to the change in energy of the object.
- Define kinetic energy, gravitational potential energy and elastic potential energy, and use the respective equations to solve problems.
- State the principle of conservation of energy and apply it to solve problems.
- Draw and interpret Sankey diagrams.
- Define power and use the equation for power to solve problems.
- Define efficiency in terms of energy and power.
- Define the energy density of a fuel and calculate it.

A. Space, time and motion / A.3 Work, energy and power

Investigation

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/investigation-id-43090/print/) Assign

- **IB learner profile attribute:**
  - Thinkers
  - Inquirers
- **Approaches to learning:**
  - Thinking skills – Providing a reasoned argument to support conclusions
  - Communication skills – Using digital media for communicating information
- **Time to complete activity**: 60–75 minutes
- **Activity type:** Individual activity

Your task

A roller coaster ride consists of a thrilling launch, a steep hill, tight corners, and a vertical loop. What is the effect of a fully loaded train compared to an empty one?

Student view

Assume that the roller coaster uses a mechanism that gives the train a large acceleration so that it can rapidly climb the initial hill, as seen in **Video 1**. You do not have to consider the details of that mechanism (although if you are interested, you could research roller coaster launch mechanisms and choose one).

Video 1. The launch of roller coaster Kingda Ka.

More information for video 1

The video provides a thrilling front-seat perspective of the Kingda Ka roller coaster, one of the fastest and tallest roller coasters in the world. It begins with the Kingda Ka logo set against a stark white background. The logo features a tiger's intense gaze, framed by three jagged claw marks that emphasize the ride's ferocity. The name "Kingda Ka" appears in a glowing yellow font, reinforcing the excitement and power associated with the ride.

As the scene transitions, the viewer is placed at the front of the roller coaster car, offering an immersive experience. The car slowly moves forward along the track. The towering main structure of the roller coaster looms ahead, its dark silhouette reaching into the bright blue sky. The roller coaster gradually approaches its launch position, and the camera captures a small white sign beside the track that reads: "ARMS DOWN HEAD BACK HOLD ON" in bold letters. This instruction serves as a crucial safety reminder, preparing riders for the intense acceleration that is about to take place. Suddenly, the train is launched forward by a high-powered mechanism, accelerating from 0 to 206 km/h in just 3.5 seconds. The video vividly captures this rapid acceleration as the track blurs past, emphasizing the immense forces at play.

As the coaster speeds toward the towering main structure, it ascends steeply, climbing 139 meters into the sky. The on-screen perspective tilts upward, revealing the vast blue sky above as the train reaches its peak. At this point, the ride momentarily slows before plunging into a near-vertical drop of 127 meters. The camera view shifts downward, displaying the dizzying descent as the ground rushes up at breathtaking speed. The surrounding amusement park, including other roller coaster tracks and a sprawling parking lot, flashes into view for a brief moment before the ride levels out.

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The momentum from the descent propels the train forward along a twisting and curving track. The perspective shifts to capture the ride's remaining sections, where the coaster continues at high speed before gradually slowing to a stop. As the ride concludes, the screen transitions to black, and the Kingda Ka logo reappears, reinforcing the sheer intensity of the experience.

This video serves as a visual representation of fundamental physics concepts related to motion, energy, and acceleration. The launch mechanism demonstrates Newton's Second Law of Motion, where the net force applied by the motors results in rapid acceleration. The transformation of energy is also a key takeaway: at the start, the roller coaster is provided with a large amount of kinetic energy, allowing it to ascend the tall structure. As it reaches the peak, much of this kinetic energy is converted into gravitational potential energy. When the train begins its descent, this stored energy transforms back into kinetic energy, enabling it to maintain momentum through the rest of the ride. By watching the video, viewers gain an understanding of how energy, velocity, acceleration, and gravitational forces interact in an amusement park ride. Observing the ride in action reinforces how controlled energy transfer and structural design enable thrilling yet safe roller coaster experiences.

Use considerations of energetics, centripetal force and resistive forces to discuss the effect of the train's mass on:

- the launch
- the journey up the steep hill
- the motion round the tight corners
- the motion on the vertical loop.

For each of the bullet points, write a detailed paragraph, explain on a video or model with diagrams. You should use what you learned in this subtopic, but you can also use knowledge from other subtopics.

Making connections

Resistive forces and centripetal force (including relevant equations) are discussed in subtopic A.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43136/).

A vertical loop is probably the most exciting feature of a roller coaster.

Student view

Write a detailed paragraph to answer the following question: Why is no work done on a body moving at a constant speed along a circular trajectory?

In your answer, specify any assumptions under which this is valid.

A. Space, time and motion / A.3 Work, energy and power

Reflection

Teacher instructions

The goal of this section is to encourage students to reflect on their learning and conceptual understanding of the subject at the end of this subtopic. It asks them to go back to the guiding questions posed at the start of the subtopic and assess how confident they now are in answering them. What have they learned, and what outstanding questions do they have? Are they able to see the bigger picture and the connections between the different topics?

Students can submit their reflections to you by clicking on 'Submit'. You will then see their answers in the 'Insights' part of the Kognity platform.

Reflection

Now that you've completed this subtopic, let's come back to the guiding questions introduced in The big picture (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43083/).

- How are concepts of work, energy and power used to predict changes within a system?
- How can a consideration of energetics be used as a method to solve problems in kinematics?
- How can transfer of energy be used to do work?

With these questions in mind, take a moment to reflect on your learning so far and type your reflections into the space provided.

You can use the following questions to guide you:

- What main points have you learned from this subtopic?
- Is anything unclear? What questions do you still have?
- How confident do you feel in answering the guiding questions?
- What connections do you see between this subtopic and other parts of the course?

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Once you submit your response, you won't be able to edit it.

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