Cambridge

IGCSE

Physics

CODE: (9702)

Chapter 05

Work, energy and power

Doing work, transferring energy

In physics, we often use an everyday word but with a special meaning. **Work** is an example of this. Table 5.1 describes some situations which illustrate the meaning of **doing work** in physics.

you are not doing any work **on the weights**, because you are not transferring energy to the weights once they are above your head.

Doing work	Not doing work
Pushing a car to start it moving: your force transfers energy to the car. The car's kinetic energy (i.e. 'movement energy') increases.	Pushing a car but it does not budge: no energy is transferred, because your force does not move it. The car's kinetic energy does not change.
Lifting weights: you are doing work as the weights move upwards. The gravitational potential energy of the weights increases.	Holding weights above your head: you are not doing work on the weights (even though you may find it tiring) because the force you apply is not moving them. The gravitational potential energy of the weights is not changing.
A falling stone: the force of gravity is doing work. The stone's kinetic energy is increasing.	The Moon orbiting the Earth: the force of gravity is not doing work. The Moon's kinetic energy is not changing.
Writing an essay: you are doing work because you need a force to move your pen across the page, or to press the keys on the keyboard.	Reading an essay: this may seem like 'hard work', but no force is involved, so you are not doing any work.

Table 5.1 The meaning of 'doing work' in physics.

Calculating work done

Because **doing work** defines what we mean by **energy**, we start this chapter by considering how to calculate **work done.**

Figure 5.4 shows the two factors involved:

■ The size of the force F – the bigger the force, the greater the amount of work you do

■The distance s you push the car – the further you push it, the greater the amount of work done.

In the example shown in Figure 5.4, $F = 300\,\text{N}$ and $s = 5.0\,\text{m}$, so:

work done $W = F \times s = 300 \times 5.0 = 1500\,\text{J}$

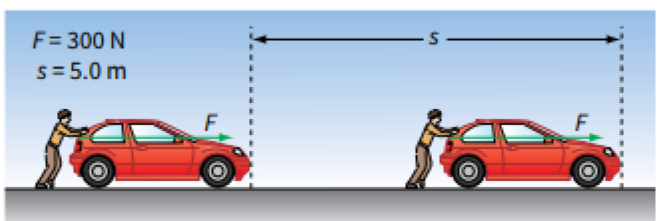


Figure 5.4 You have to do work to start the car moving.

The **work done** by a force is defined as the product of the force and the distance moved in the direction of the force:

$W = F \times s$

where s is the distance moved in the direction of the force.

Energy transferred

Doing work is a way of transferring energy. For both energy and work the correct SI unit is the joule (J). The amount of work done, calculated using W = F x *S* shows the amount of energy transferred:

work done = energy transferred

Newtons, metres and joules

From the equation W = F x S we can see how the unit of force (the newton), the unit of distance (the metre) and the unit of work or energy (the joule) are related.

1 joule = 1 newton × 1 metre

1 J = 1 N m

Since work done = energy transferred, it follows that a joule is also the amount of energy transferred when a force of 1 newton moves a distance of 1 metre in the direction of the force.

Force, distance and direction

Both the force F and the distance *s* moved **in the direction of the force** are vector quantities, so you should know that their directions are likely to be important.

Suppose that the force F moves through a distance s which is at an angle θ to F, as shown in Figure 5.6. To determine the work done by the force, it is simplest to determine the component of F in the direction of s. This component is F cos θ, and so we have:

$$\text{work done} = (F\cos\theta) \times s$$

or simply:

$$\text{work done} = Fs\cos\theta$$

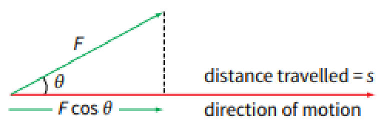


Figure 5.6 The work done by a force depends on the angle between the force and the distance it moves.

A gas doing work

Figure 5.8 shows a gas at pressure p inside a cylinder of cross-sectional area A. The cylinder is closed by a moveable piston. The gas pushes the piston a distance s. If we know the force F exerted by the gas on the piston, we can deduce an expression for the amount of work done by the gas.

From the definition of pressure (pressure = $\frac{\text{force}}{\text{area}}$), the force exerted by the gas on the piston is given by:

$$\text{force} = \text{pressure} \times \text{area}$$

$$F = p \times A$$

and the work done is force × displacement:

$$W = p \times A \times s$$

But the quantity $A \times s$ is the **increase** in volume of the gas; that is, the shaded volume in Figure 5.8. We call this ΔV, where the Δ indicates that it is a **change** in V. Hence the work done by the gas in expanding is:

$$W = p\Delta V$$

Gravitational potential energy

You lose energy, and the object gains energy. We say that the **gravitational potential energy** E_p of the object has increased.

An equation for gravitational potential energy

The change in the gravitational potential energy (g.p.e.) of an object, E_p, depends on the change in its height, h. We can calculate E_p using this equation:

$$\text{change in g.p.e.} = \text{weight} \times \text{change in height}$$

$$E_p = (mg) \times h$$

or simply

$$E_p = mgh$$

The equation Ep = mgh represents the force needed to lift an object, where m is the object's mass and g is the acceleration of free fall. This force is determined by force multiplied by distance moved or weight multiplied by height change. However, this equation only applies to small changes in height, such as for satellites orbiting Earth.

Other forms of potential energy

Potential energy refers to the energy an object has due to its position or shape, such as gravitational potential energy. Other forms include electric potential energy when placed in an electric field and elastic potential energy when stretched, squashed, or twisted.

Kinetic energy

As well as lifting an object, a force can make it accelerate. Again, work is done by the force and energy is transferred to the object. In this case, we say that it has gained kinetic energy, E_k. The faster an object is moving, the greater its kinetic energy (k.e.)

For an object of mass m travelling at a speed v, we have:

kinetic energy = $\frac{1}{2}$ × mass × speed^2

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

Deriving the formula for kinetic energy

We imagine a car being accelerated from rest (u = 0) to velocity v. To give it acceleration a, it is pushed by a force F for a distance s. Since u = 0, we can write the equation $v^2 = u^2+2as$ as:

$$v^2 = 2as$$

Multiplying both sides by $\frac{1}{2}m$ gives:

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

Now, ma is the force F accelerating the car, and mas is the force × the distance it moves, that is, the work done by the force. So we have:

$$\frac{1}{2}mv^2 = \text{work done by force } F$$

This is the energy transferred to the car, and hence its kinetic energy.

g.p.e.–k.e. transformations

A roller-coaster car is pulled by a motor to the top of a hill, transferring energy to the car. The car gains gravitational potential energy and accelerates with a small push, gaining kinetic energy but losing g.p.e., causing a loud scream.

As the car runs along the roller-coaster track (Figure 5.13), its energy changes.

1. At the top of the first hill, it has the most g.p.e.
2. As it runs downhill, its g.p.e. decreases and its k.e. increases.
3. At the bottom of the hill, all of its g.p.e. has been changed to k.e. and heat and sound energy.
4. As it runs back uphill, the force of gravity slows it down. k.e. is being changed to g.p.e.

Down, up, down – energy changes

When an object falls, it speeds up. Its g.p.e. decreases and its k.e. increases.. Some energy is likely to be lost, usually as heat because of air resistance. However, if no energy is lost in the process, we have:

decrease in g.p.e. = gain in k.e.

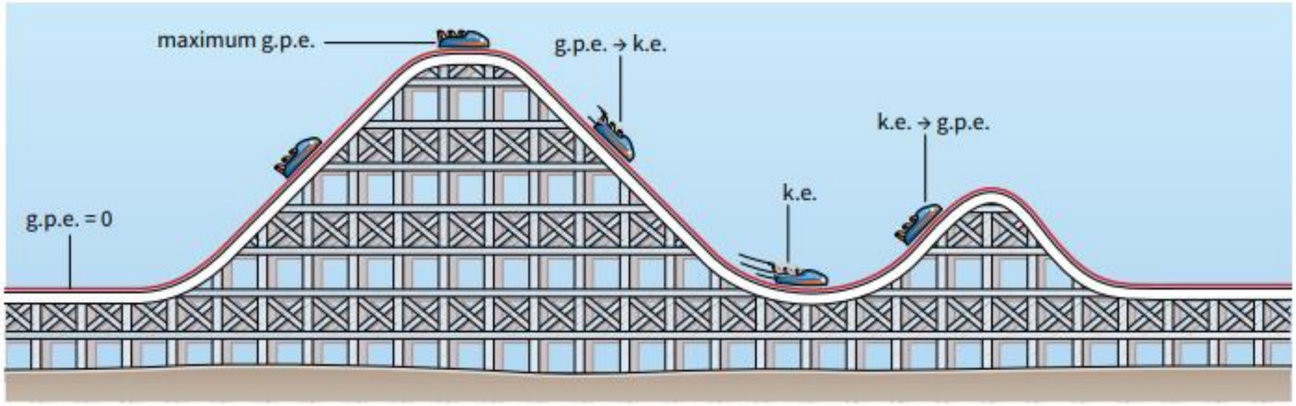


Figure 5.13 Energy changes along a roller-coaster.

Energy transfers

Climbing bars

Suppose your weight is 600N and you climb a 2000m high mountain. The work done by your muscles is:

$$\text{work done} = Fs = 600 \times 2000 = 1200\,\text{kJ}$$

The body's inefficiency means it cannot convert 100% of food energy into gravitational potential energy. Energy is wasted during exercise, such as walking, and only 5% efficient in climbing. Many energy transfers are inefficient, with only part being transferred to desired locations and the rest wasted. Therefore, one bar of chocolate is not enough.

You can determine the efficiency of any device or system using the following equation:

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

Figure 5.16 We want a car engine to supply kinetic energy. This Sankey diagram shows that only 20% of the energy supplied to the engine ends up as kinetic energy – it is 20% efficient.

Conservation of energy

We are assuming that energy is conserved. This is a principle, known as the **principle of conservation** of energy, which we expect to apply in all situations.

> Energy cannot be created or destroyed. It can only be converted from one form to another.

Energy should be added at the beginning and accounted for at the end. To understand energy changes within a closed system, we must draw an imaginary boundary around interacting objects involved in energy transfer.

Power

The word power has several different meanings – political power, powers of ten, electrical power from power stations.

The power P of the motor is the rate at which it does work. Power is defined as the rate of work done. As a word equation, power is given by:

$$\text{power} = \frac{\text{work done}}{\text{time taken}}$$

or

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

Units of power: the watt

Power is measured in watts, named after James Watt, the Scottish engineer famous for his development of the steam engine in the second half of the 18th century. The watt is defined as a rate of working of 1 joule per second. Hence:

1 watt = 1 joule per second

or

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

In practice we also use kilowatts (kW) and megawatts (MW).

1000 watts = 1 kilowatt (1 kW)

1 000 000 watts = 1 megawatt (1 MW)

Moving power

Suppose that an aircraft is moving with velocity v. Its engines provide the force F needed to overcome the drag of the air. In time t, the aircraft moves a distance s equal to v x t . So the work done by the engines is:

work done = force x distance

$$W = F \times v \times t$$

and the power P $(= \frac{\text{work done}}{\text{time taken}})$ is given by:

$$P = \frac{W}{t} = \frac{F \times v \times t}{t}$$

and we have:

$$P = F \times v$$

power = force × velocity

Human power

We can determine the average power of all the activities of our body:

$$\text{average power} = 10\,\text{MJ per day}$$
$$= 10 \times \frac{10^6}{86\,400} = 116\,\text{W}$$

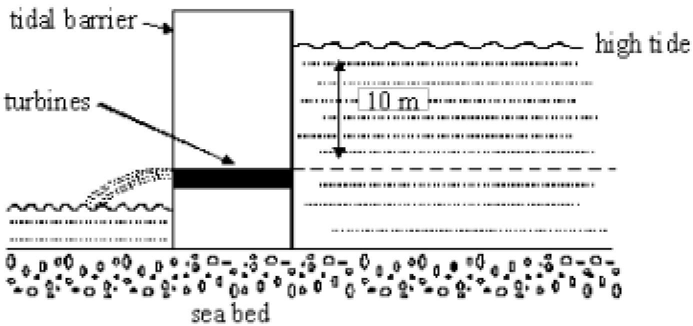
Energy dissipation is about 100W, providing as much energy to our surroundings as a 100W light bulb. However, demanding physical tasks require greater power. The human body is not perfectly efficient, as lifting heavy loads can waste energy, requiring five or ten times the energy expended by our bodies.

Revision questions

1)In an experiment to measure the power output of a motor, the motor is used to lift a metal block vertically at constant speed. You may be awarded marks for the quality of written communication in your answers.

(a) Describe an experiment to check whether the speed of the rising mass is constant.
(b) Explain how the output power of the motor is calculated, stating what measurements need to be made.

2) . Tidal power could make a significant contribution to UK energy requirements. This question is about a tidal power station which traps sea water behind a tidal barrier at high tide and then releases the water through turbines 10.0 m below the high tide mark.

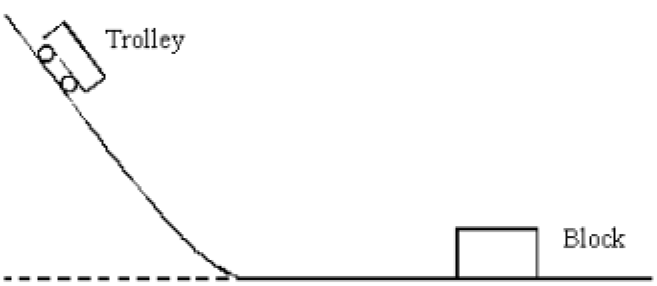


(i) Calculate the mass of sea water covering an area of 120 km^2 and depth 10.0 m.
density of sea water = 1100 kg m^{-3}

(ii) Calculate the maximum loss of potential energy of the sea water in part (i) when it is released through the turbines.

(iii) The potential energy of the sea water released through the turbines, calculated in part (ii), is lost over a period of 6.0 hours. Estimate the average power output of the power station over this time period. Assume the power station efficiency is 40%.

3) The diagram represents an experiment that can be used to investigate stopping distances for a moving trolley.



The trolley is placed on the raised section of the track. When released it moves down the track and then travels along the horizontal section before colliding with the block. The trolley and block join and move together after the collision. The distance they move is measured.

a) State the main energy changes taking place
(i) as the trolley descends,
(ii) after the collision, as the trolley and block move together.

(b) Describe how the speed of the trolley, just before it collides with the block may be measured experimentally. You may be awarded marks for the quality of written communication in your answer

(c) State and explain how the speed of the trolley, prior to impact could be varied.

4)A skydiver of mass 70 kg, jumps from a stationary balloon and reaches a speed of 45 m s–1 after falling a distance of 150 m.

(a) Calculate the skydiver's

(i) loss of gravitational potential energy,

(ii) gain in kinetic energy.

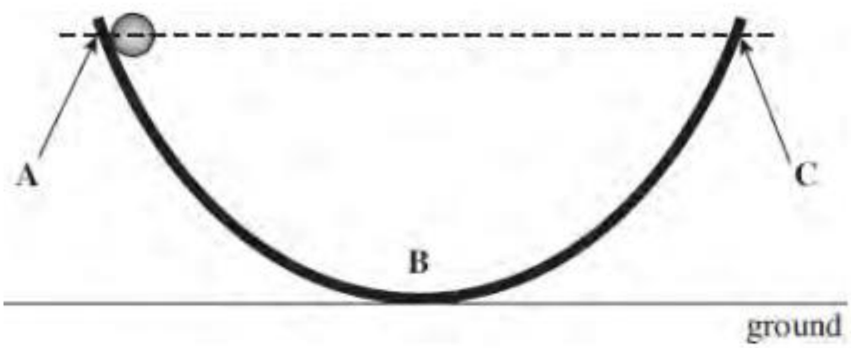
(b) The difference between the loss of gravitational potential energy and the gain in kinetic energy is equal to the work done against air resistance. Use this fact to calculate

(i) the work done against air resistance,

(ii) the average force due to air resistance acting on the skydiver.

5) In the 17th century, when thinking about forces, Galileo imagined a ball moving in the absence of air resistance on a frictionless track as shown in Figure 1.

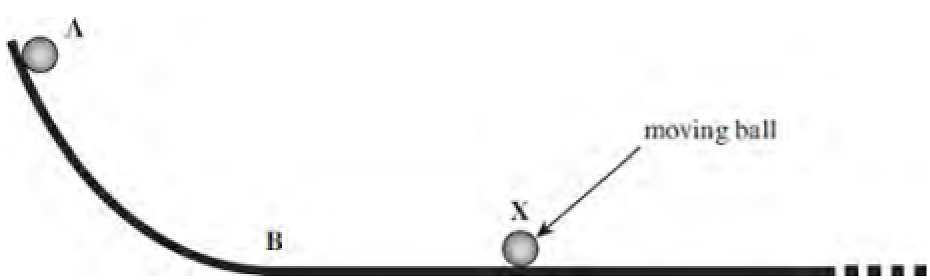
Figure 1



(a) Galileo thought that, under these circumstances, the ball would reach position C if released from rest at position A. Position C is the same height above the ground as A.
Using ideas about energy, explain why Galileo was correct.

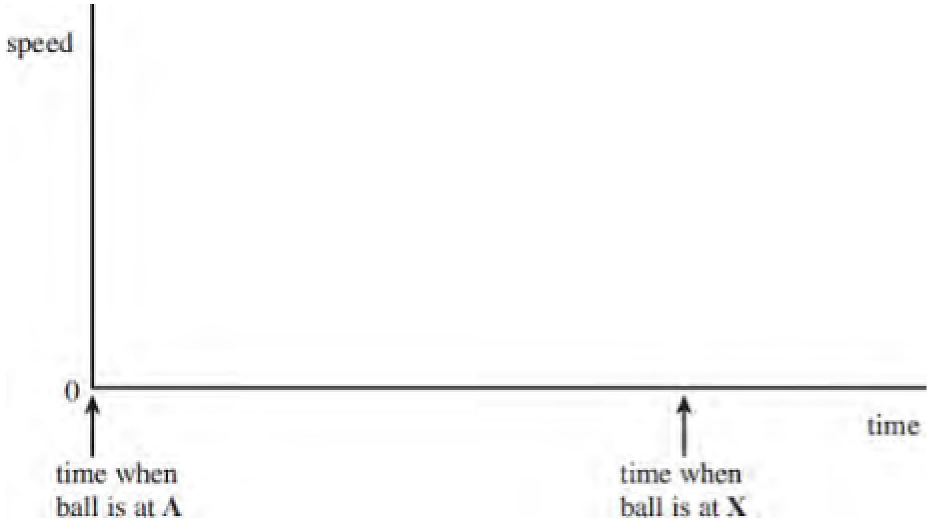
(b) Galileo then imagined that the track was changed, as shown in Figure 2.

Figure 2



The slope beyond **B** was now horizontal.

On the axes below, sketch a speed – time graph for the ball from its release at A until it reaches the position X shown in Figure 2. Indicate on your graph the time when the ball is at B.



(c) Newton later published his three laws of motion. Explain how Newton's first law of motion is illustrated by the motion of the ball between B and X.

6) . It has been predicted that in the future large offshore wind turbines may have a power output ten times that of the largest ones currently in use. These turbines could have a blade length of 100 m or more. A turbine such as this is shown in the diagram below.

At a wind speed of 11 m s–1 the volume of air passing through the blades each second is 3.5 × 105 m^3

(i) Show that the mass of air that would pass through the blades each second is about 4 × 105 kg. The density of air is 1.2 kg m–3

(ii) Calculate the kinetic energy of the air that would enter the turbine each second.

(iii) It has been predicted that the turbine would produce an electrical power output of 10 MW in these wind conditions. Calculate the percentage efficiency of the turbine in converting this kinetic energy into electrical energy.

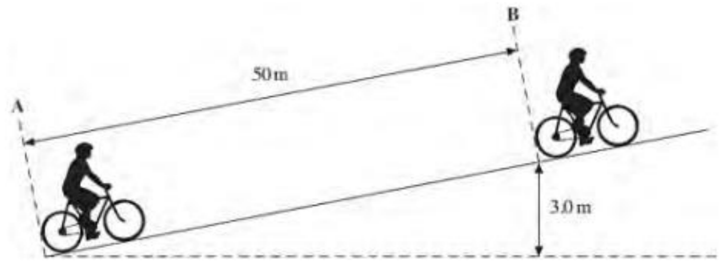
(b) State one advantage and one disadvantage of wind power in comparison to fossil fuel.

7) An 'E-bike' is a bicycle that is assisted by an electric motor. The figure below shows an E⍰bike and rider with a total mass of 83 kg moving up an incline.

(a) (i) The cyclist begins at rest at A and accelerates uniformly to a speed of 6.7 ms^{-1} at B. The distance between A and B is 50 m. Calculate the time taken for the cyclist to travel this distance.

(ii) Calculate the kinetic energy of the E-bike and rider when at B. Give your answer to an appropriate number of significant figures.

(iii) Calculate the gravitational potential energy gained by the E-bike and rider between A and B.



(b) Between A and B, the work done by the electric motor is 3700 J, and the work done by the cyclist pedalling is 5300 J.
(i) Calculate the wasted energy as the cyclist travels from A to B.
(ii) State two causes of this wasted energy.

8) (a) Explain why a raindrop falling vertically through still air reaches a constant velocity. You may be awarded marks for the quality of written communication in your answer.

b) The figure below shows apparatus that can be used to investigate energy changes.

The trolley and the mass are joined by an inextensible string. In an experiment to investigate energy changes, the trolley is initially held at rest, and is then released so that the mass falls vertically to the ground. You may be awarded marks for the quality of written communication in your answer.
(a) (i) State the energy changes of the falling mass.
(ii) Describe the energy changes that take place in this system
(b) State what measurements would need to be made to investigate the conservation of energy
(c) Describe how the measurements in part (b) would be used to investigate the conservation of energy.