Year 11

Physics

4.1 Energy

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Subtopic 4.1: Energy

Students use mathematical relationships to determine and measure quantities based on work done, conservation of energy, and power. They investigate the efficiency of different mechanical systems and explore emerging technologies in sustainable energy generation.

Science Understanding	Possible contexts
The work done on an object is equivalent to the change in energy of that object. When a force is applied to an object causing a displacement over a distance, work is done. • Explain work in terms of an applied force. • Solve problems using $W = \Delta E$ and $W = Fs$ where the displacement is parallel to the force. Energy exists in a number of different forms. • Describe different forms of energy including kinetic, elastic, gravitational potential, rotational kinetic, heat, and electrical. Energy can be transferred from one object to another or transformed into different forms of energy. • Describe examples of energy being transferred from one object to another. • Describe examples of energy being transformed. • Explain qualitatively the meaning and some applications of various forms of energy, including kinetic energy and potential energy. • Solve problems using $E_K = \frac{1}{2}mv^2$ and $E_P = mgh$. • Describe energy transfers between objects and within different mechanical systems. Energy is conserved when transferred from one object to another in an isolated system. • Solve problems using the conservation of energy. • Describe and explain the energy losses that occur in systems involving energy transfers. Power is defined as the rate at which work is done and is equivalent to the rate at which energy is used. • Solve problems using $P = \frac{W}{t}$ and $P = Fv$. • Interpret solutions in context.	*This connects to the concept of energy used in Stage 1, Subtopic 6.4: Induced nuclear reactions and Stage 2, subtopics 2.2: Motion of charged particles in electric fields and 3.2: Wave–particle duality.* Investigate the work done on an object when the net force acting on the object is not in the direction of the displacement, using trigonometric calculations, $W = Fs\cos\theta$. Connect to work done when a projectile with air resistance moves through air. Show how the relationship $W = \Delta E$ can be derived using the definition of force and $E_K = \frac{1}{2}mv^2$. Demonstrate energy transfers using a steam engine, combustion engine, or other similar engines. Investigate the relationship between power and mechanical advantage using simple machines. *The concept of efficiency can be developed here; it is also covered in Stage 1, Subtopic 2.4: Electrical power.* Utilize computer interactive 'Energy Forms and Changes': https://phet.colorado.edu/. *The simple harmonic motion of pendulums links to Stage 1, Topic 5: Waves.*
	Design and conduct individual or group experiments to determine the efficiency of different systems involving energy transfers. Test the conservation of energy by recording and measuring objects falling from different heights and recording their speed as they hit the ground.
	Design and build a 'gravity car' — a car that uses a falling weight to transfer energy to wheel rotation. Investigate the motion of pendulums, demonstrating the law of conservation of energy.
	Explore the difficulty of developing international conventions to define concepts such as energy and work to facilitate communication and collaboration. Assess the economic advantage of efficiency in different mechanical systems and any implications for developing or emerging technology such as regenerative brakes.

1 Work

Work is said to be done by the force when the force applied on a body displaces it. To do work, energy is required. In simple words, energy is defined as the ability to do work.

Energy is the capacity to cause change.

Work causes a change in energy, i.e. $W = \Delta E$.

More specifically, work is defined as the product of the force causing the energy change and the displacement of the object in the direction of the force during the energy change:

The rate of work done is called power.

Mathematically, the work done 'W' when a force, 'F', causes a displacement of magnitude 's', in the direction of the force, is defined as:

work = magnitude of the force × displacement in the direction of the force

$$\boxed{W = Fs.}$$

In fact, the amount of work depends directly on the magnitude of the force and the displacement of the object along the line of the force.

Although both force and displacement are vectors, work is a scalar unit. (Multiplication of two vectors is a scalar).

The SI unit of work is the Joule 'J'. One joule of work is done when a force with a magnitude of one newton causes a displacement of one metre in the same direction as the force. That is

$$\boxed{1J = 1N \times 1m = 1Nm}$$

Because energy is a measure of the capacity to do work, the SI unit of energy is also the joule. So both energy and work have no direction.

2 A Force with NO Work

Work done is zero in the following cases.

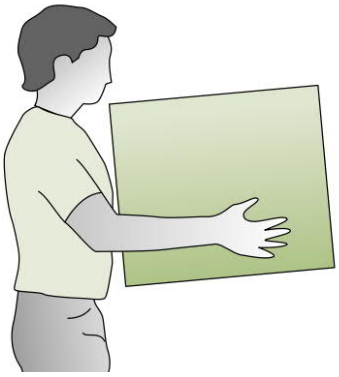
2.1 When the force is zero (F = 0)

When a body is moving on a horizontal smooth frictionless surface will continue to do so as no force (not even friction) is acting along the plane. (This is an ideal situation.)

2.2 When the displacement is zero (s = 0)

When force is applied on a rigid wall it does not produce any displacement. Hence, the work done is zero

While picking up a heavy box requires work, holding the box at a constant height does no work on the box.

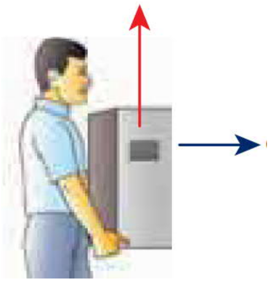


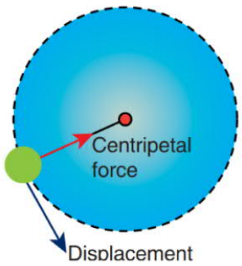
Assuming the box has a weight of 100 N and that it is lifted from the ground to a height of 1.2 m, the work done lifting it would be: $W = Fs = 100 \times 1.2 = 120$ J. In this case, energy is being transformed from chemical energy inside the person's body into the gravitational potential energy of the box.

However, when the box is held at a constant height, the definition of work gives: $W = Fs = 100 \times 0 = 0$ J. So, no work is being done on the box. Although there would be energy transformations going on inside the person's body to keep their muscles working, but the energy of the box does not change, therefore no work has been done on the box.

2.3 When the force and displacement are perpendicular to each other

When a body moves on a horizontal direction, the gravitational force (mg) does no work on the body, since it acts at right angles to the displacement



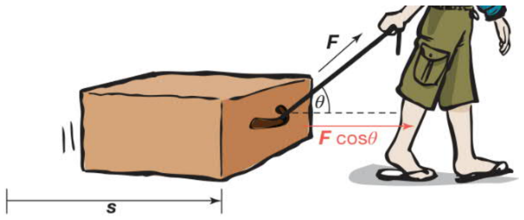


In circular motion the centripetal force does not do work on the object moving on a circle as it is always perpendicular to the displacement

3 Work at an angle

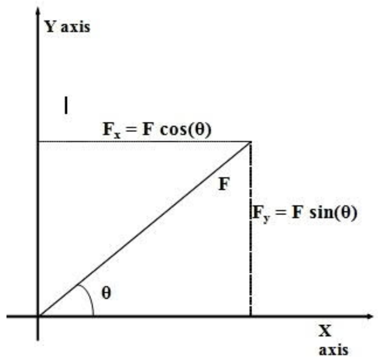
Sometimes, when a force is applied, the object does not move in the same direction as the force.

Now consider a box being dragged across a smooth floor by means of a rope that makes an angle θ with the floor



In this case, only the component of the force that is acting in the same direction as the box's displacement, F cos θ, will contribute to the work being done.

The vertical component of this force F sin θ is percendicular to the displacement, so will not contribute to the work being done.



In situations like this, work can be calculated using the general equation:

$$\boxed{W = Fs \cos\theta}$$

Example

A box is pulled with a force of 25 N to produce a displacement of 15 m. If the angle between the force and displacement is 30°, find the work done by the force.

$W = Fs \cos\theta$

$W = 25 \times 15 \times \cos 30$

$W = 324.76\ J$

Example

If an object of mass 2 kg is thrown up from the ground reaches a height of 5 m and falls back to the Earth (neglect the air resistance). Calculate

(a) The work done by gravity when the object reaches 5 m height

(b) The work done by gravity when the object comes back to Earth

(c) Total work done by gravity both in upward and downward motion and mention the physical significance of the result.

When the object goes up, the displacement points in the upward direction whereas the gravitational force acting on the object points in downward direction. Therefore, the angle between gravitational force and displacement of the object is 180°.

(a) The work done by gravitational force in the upward motion.

$F = mg = 2 \times 10 = 20\,N$ [kg x ms^{-2} = N]

$W = Fs \cos \theta$

$W = 20 \times 5 \times \cos 180$ [cos 180 = -1]

$W_{up} = -100\,J$

(b) When the object falls back, both the gravitational force and displacement of the object are in the same direction. This implies that the angle between gravitational force and displacement of the object is 0°.

$W = 20 \times 5 \times \cos 0$ [cos 0 = 1]

$W_{down} = 100\,J$

c) The total work done by gravity in the entire trip (upward and downward motion)

$W_{total} = W_{up} + W_{down} = 0\,J$

It implies that the gravity does not transfer any energy to the object. When the object is thrown upwards, the energy is transferred to the object by the external agency, which means that the object gains some energy. As soon as it comes back and hits the Earth, the energy gained by the object is transferred to the surface of the Earth (i.e., dissipated to the Earth).

Example

A weight lifter lifts a mass of 250 kg with a force 5000 N to the height of 5 m.

(a) What is the workdone by the weight lifter?

(b) What is the workdone by the gravity?

(c) What is the net workdone on the object?

(a) When the weight lifter lifts the mass, force and displacement are in the same direction, which means that the angle between them θ = 0^0.

$W_{w\,l} = 5000 \times 5 \times \cos 0 = 25000\,J = 25\,kJ$

(b) When the weight lifter lifts the mass, the gravity acts downwards which means that the force and displacement are in opposite direction. Therefore, the angle between them θ = 180^0

$W_g = Fs\cos\theta = mg \times s \times \cos\theta = 250 \times 10 \times 5 \times \cos 180 = -12500\,J = -12.5\,kJ$

(c) The net workdone (or total work done) on the object $W_{net} = 25 - 12.5 = 12.5\,kJ$