CHAPTER

4

Energy

Learning Objectives

- Concept of work
- Unit of work (Joule)
- Calculation of work done in simple cases
- Kinetic energy (basic concept)
- Potential energy (basic concept; gravitational potential energy)
- Calculation of kinetic and potential energies from a set of given data (Simple problems and assuming $g = 10\ m/s^2$)
- Energy transformation in common daily life situations
- Difference between energy and power

In our day-today life, we do so many and different types of work. For example, getting ready and coming to school, doing homework, running, playing, etc. Some of these activities are physical while others involve the mind. But interestingly, from physics point of view, most of the examples mentioned here are not considered as work.

Fig. 4.1 No work being done

WORK

Work is said to be done when a force produces motion or in other words a body undergoes some displacement. For example, when an engine moves a train along a railway line, it is said to be doing work; a horse pulling the cart is also doing work; and a man climbing the stairs of a house is also doing work in moving himself against the force of gravity.

Fig. 4.2 Work being done

$$\text{Work} = \text{Force} \times \text{Distance moved in the direction of force}$$

But usually we write:

$$\text{Work} = \text{Force} \times \text{Distance}$$

If a force F acts on a body and moves it a distance s in its own direction, then:

$$\text{Work done} = \text{Force} \times \text{Distance}$$

or

$$W = F \times s$$

Work Done Against Gravity

The force of gravity of the earth pulls everything towards the surface of earth. So, if we lift a book from a table, we do work against the force of gravity. Please note that when a body is lifted vertically upwards, then the force required to lift the body is equal to its weight. So, whenever work is done against gravity, the amount of work done is equal to the product of weight of the body and the vertical distance through which the body is lifted.

Suppose a body of mass m is lifted vertically upwards through a distance h. In this case, the force required to lift the body will be equal to weight of the body, $m \times g$ (where m is mass and g is acceleration due to gravity). Now,

Work done in lifting a body = Weight of body × Vertical distance

or $W = m \times g \times h$

where W = work done

m = mass of the body

g = acceleration due to gravity

and h = height through which the body is lifted

We will use this formula to calculate the work done in all those cases where the object is being lifted upwards, against the force of gravity.

Unit of Work

Work is also considered to be done when an applied force changes the speed, shape or direction of motion of an object. The unit of force is newton (N) and that of distance is metre (m), so the unit of work is newton metre which is written as Nm.

The standard unit of work is Joule. It is abbreviated as J and can be defined as follows:

When a force of 1 newton moves a body through a distance of 1 metre in its own direction, then the work done is known as 1 joule. That is,

1 joule = 1 newton × 1 metre

Or 1 J = 1 Nm

Larger unit of work is kilojoule (kJ). 1 kJ = 1000 J

Conditions for work to be done

There are three conditions that need to be fulfilled for work to be done.

- A force must be applied on the object.
- The object should move from its position of rest. In other words, there should be a displacement, or, there should be a change in the shape or size of the object.
- The displacement must be because of the force applied and should be in the direction of the force applied.

Situations of no work done

If any of the above-mentioned conditions is not satisfied, there is no work done. Thus, there can be no work done in the following situations.

When there is no force applied in situations such as reading a book, or an object resting on a surface, no force is applied. So, no work is done in these cases.

When a force is applied but there is no displacement If a person is pushing a locked door hard, he is applying force, but the door does not open. Here, even though a force is applied, there is no displacement. So, no work is done. Similarly, when a person is standing at railway station with a heavy load on his head, the force of gravity is acting on the load. But the load remains on his head without any displacement. So, no work is done.

When a force is applied, the object moves, but comes back to the starting point for example, The satellites (like the moon) move around the Earth in a circular path. In this case the gravitational force of earth acts on the satellite at right angles to the direction of motion of satellite (see figure 16). So, the work done by the earth on the satellite moving around it in circular path is zero. Similarly, the work done by the sun on planets (like the Earth) moving around it in circular orbits is zero.

When a force is acting on the object, the object moves, but not because of the applied force (when force and displacement are at right angles to each other)For example, if a man carries a suitcase strictly horizontally, he does no work with respect to gravity because the force of gravity acts vertically downwards and the angle between the displacement of the suitcase and the direction of force becomes 90°, and cos 90° becomes zero (Though the man carrying the suitcase horizontally may be doing work against the forces like friction and air resistance). There can be no work done if the directions of the applied force and the displacement are at right angles (90°) to each other.

Example 1: A man pushes a heavy box with a force of 450 N through a distance of 30 m in its direction. What is the work done by him?

Solution: Given: Force (F) = 450 N

Displacement (s) = 30 m

We know, $W = F \times s$

Therefore, work done on the box,

$W = 450 \times 30 = 13500$ Nm or 13500 J

So, the work done by the man is 135000 J.

Example 2: An engine does 82500 J of work by exerting a force of 1500 N. What is the displacement of the force?

Solution: We know,

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

$$= \frac{82,500}{1,500} = 55 \text{ m}$$

So, the displacement of the force is 55 m.

Example 3: Calculate the work done in lifting 200 kg of water through a vertical height of 6 metres (Assume $g = 10$ m/s²).

Solution: In this case work is being done against gravity in lifting water. Now, the formula for calculating the work done against gravity is:

$$W = m \times g \times h$$

Here, Mass of water, $m = 200$ kg

Acceleration due to gravity, $g = 10$ m/s²

And, Height, $h = 6$ m

Now, putting these values in the above formula, we get:

$$W = 200 \times 10 \times 6$$

$$W = 12000 \text{ J}$$

Thus, the work done is 12000 joules.

Think & Answer

How are work and energy useful in our day-to-day life?

ENERGY

'Work' and 'energy' are two very commonly used terms which are very closely related. The ability to do work is known as energy. We require energy to cook food, to go to school, do homework and various other activities. An object can do work equivalent to the energy it possesses. So energy and work are analogous, hence their units are the same.

Units of Energy

The standard unit of energy is joule, the same as that of work.

Energy is all around us and exists in different forms in nature. Let us study them in detail.

Mechanical Energy

Energy possessed by a body due to its position or state of motion is called mechanical energy.

When we hammer a nail into wood, the moving hammer has mechanical energy. This energy is capable of driving the nail into wood. In other words, the hammer can do work. Mechanical energy is found in two forms, kinetic energy and potential energy.

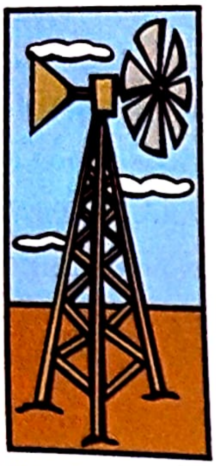

Fig. 4.3 Moving wind possesses kinetic energy

Kinetic energy

A moving cricket ball can do work in pushing back the stumps moving water can do work in turning a turbine for generating electricity; and moving wind can do work in turning the blades of windmill.

Thus, a moving body is capable of doing work and hence possesses energy. The energy of a body due to its motion is called kinetic energy.

Fig. 4.4 A body in motion has kinetic energy

Factors Determining Kinetic Energy

The kinetic energy of a body depends on its mass and the speed with which it is moving. The relation for kinetic energy is given as:

$$\text{K.E.} = \frac{1}{2} \times m \times v^2$$

Where K.E. = kinetic energy of the body

m = mass of the body

v = speed or velocity of the body

Kinetic energy is directly proportional to the square of velocity of that object and is also directly proportional to its mass. Kinetic energy has only magnitude and no direction so it is a scalar quantity. The standard unit of kinetic energy is joule. When a force of one newton causes a displacement of one metre, the work done is said to be one Joule. All moving bodies have kinetic energy, e.g. running athlete, moving car, flowing water, flying kite, a bullet fired from a gun etc. As a moving body possesses energy, it is capable of doing work.

Example 4: Calculate the kinetic energy of a body of mass 2 kg moving with a velocity of 0.1 metre per second.

Solution: The formula for calculating kinetic energy is:

$$\text{Kinetic energy} = \frac{1}{2}mv^2$$

Here, Mass, $m = 2$ kg

And, Velocity, $v = 0.1$ m/s

So, putting these values in the above formula, we get:

$$\text{Kinetic energy} = \frac{1}{2} \times 2 \times (0.1)^2$$

$$= \frac{1}{2} \times 2 \times 0.1 \times 0.1$$

$$= 0.01 \text{ J}$$

Thus, the kinetic energy of the body is 0.01 joule.

Example 5: Two bodies of equal masses move with uniform velocities v and $3v$ respectively. Find the ratio of their kinetic energies.

Solution: In this problem, the masses of the two bodies are equal, so let the mass of each body be m. We will now write down the expressions for the kinetic energies of both the bodies separately.

i. Mass of first body = m

Velocity of first body = v

So, K.E. of first body = $\frac{1}{2}mv^2$ (1)

ii. Mass of second body = m

Velocity of second body = $3v$

So, K.E. of second body $= \frac{1}{2}m(3v)^2$

$= \frac{1}{2}m \times 9v^2$

$= \frac{9}{2}mv^2$ (2)

Now, to find out the ratio of kinetic energies of the two bodies, we should divide equation (1) by equation (2), so that:

$$\frac{\text{K.E. of first body}}{\text{K.E. of second body}} = \frac{\frac{1}{2}mv^2}{\frac{9}{2}mv^2}$$

$$\frac{\text{K.E. of first body}}{\text{K.E. of second body}} = \frac{1}{9}$$

Thus, the ratio of the kinetic energies is 1 : 9.

We can also write down the equation (3) as follows:

K.E. of second body = 9 × K.E. of first body

That is, the kinetic energy of second body is 9 times the kinetic energy of the first body. It is clear from this example that when the velocity (or speed) of a body is "tripled" (from v to $3v$), then its kinetic energy becomes "nine times".

Potential energy

The energy possessed by an object due to its position is called potential energy. There are different types of potential energies, we will discuss about gravitational potential energy here.

Gravitational potential energy

The energy acquired by a body when it is raised at some height from the ground level is known as gravitational potential energy. This energy is stored in the body due to the work done on it, when it is raised against the gravitational force.

The gravitational potential energy depends on the mass of the body and the height to which it has been lifted. Greater the mass or height of an object, more the potential energy it will have. Gravitational potential energy of a body

$$\text{GPE} = m \times g \times h$$

where m = mass of the body

g = acceleration due to gravity

and h = height of the body

above a reference point, say the surface of earth

Fig. 4.5 Water in overhead tank has gravitational potential energy

The ground is considered to be a position of zero height. The gravitational potential energy of an object is directly proportional to the height above the ground i.e., above the zero height. If the height is doubled then the gravitational potential energy is also doubled. A rock situated on a hill, a ball kept on the roof top, stored water in an overhead tank, etc., are some of the examples.

Example 6: What is the energy stored in a stone of mass 450 g, which is kept at the top of a building of height 30 m? (Take $g = 10\ \text{ms}^{-2}$)

Solution: Given, $m = 450$, $g = 0.45$ kg

Acceleration due to gravity, $g = 10\ \text{ms}^{-2}$

height, $h = 30$ m

As P.E. $= mgh = 0.45 \times 10 \times 30 = 135$ J

So, the energy stored in the stone is 135 J. This energy stored is gravitational potential energy.

Example 7: What is the weight of the object that has gravitational potential energy of 4800 J if it is dropped from the height of 6 m?

Solution: Given P.E. = 4800 J, Height = 6 m

We know, P.E. = weight × height

$$\text{Weight} = \frac{\text{P.E}}{\text{Height}}$$

$$= \frac{4,800}{6} = 800 \text{ N}$$

So, the weight of the object is 800 N.

Example 8: A 34 N object is lifted to a height of 12 metres. What is the gravitational potential energy of this object?

Solution: Given, Weight = 34 N, Height = 12 meters

We know, Gravitational potential energy

$$\text{P.E} = \text{weight} \times \text{height}$$

$$= 34 \times 12$$

$$= 408 \text{ J}$$

So, the gravitational potential energy of the object is 408 J.

Elastic potential energy

The energy of a body due to a change in its shape and size is called elastic potential energy. Elastic potential energy is associated with the state of 'compression' or 'extension' of an object. For example, the energy possessed by a 'compressed spring' or an 'extended spring' (stretched spring) is the elastic potential energy.

The gravitational potential energy as well as elastic potential energy are commonly known as just potential energy.

Fig. 4.6 A stretched spring possesses elastic potential energy

Test Your Understanding

1. Write T for true and F for false statements.

a. Work is said to be done if a person pushes a wall.

b. 1 joule = 25 N m

c. Is any work said to be done when you complete your homework sitting at one place.

d. Kilojoule is the smaller unit of work.

e. Someone pushing a cart is doing no work.

f. The equation to show work done is $W = F \times s$.

g. The unit of force is metre (m).

h. Water stored in a dam will have kinetic energy.

i. Energy is defined as capacity to do work.

j. Kinetic energy of an object depends on its height.

2. What kind of energy is possessed by the following?

a. A stone kept on roof-top.

b. A running car.

c. Water stored in the reservoir of a dam.

d. A compressed spring.

e. A stretched rubber band.

TRANSFORMATION OF ENERGY

All forms of energy follow a universal law known as 'Law of Conservation of Energy' which states that 'energy can neither be created nor be destroyed, but transforms from one from to another'. This implies that all forms of energy are inter-convertible. The process of change of one form of energy into another is called as energy transformation. Some examples of these inter-conversions are given below:

1. Consider a ball falling from the top floor of a building. Initially, it has potential energy due to

its height. As the ball falls, the potential energy changes to kinetic energy due to its motion and when it strikes the ground, the kinetic energy changes to sound and heat energy.

2. In the process of photosynthesis, plants convert the light energy of the Sun into chemical energy in the form of food.
3. Bulbs, tubelights etc. convert electrical energy into light energy.
4. Automobile engine, fans, electric motors etc. convert electrical energy to mechanical energy.
5. Microphones convert sound energy to electrical energy.
6. Loud speakers convert electrical energy to sound energy.
7. In solar cells, the light energy gets converted to electrical energy.
8. In electromagnets, the electrical energy is converted to magnetic energy.
9. Charging of battery converts electrical energy to chemical energy.
10. Batteries and cells convert chemical energy to electrical energy.

All these forms of energy can be converted from one form to another, but, energy cannot be created or destroyed. This is the law of conservation of energy. According to this law, the sum total of energies of all kinds in an isolated system always remains constant. Let us understand this with the help of some examples.

Conservation of Energy in a Simple Pendulum

A simple pendulum consists of a small metal ball (called bob) suspended by a long thread from a rigid support, such that the bob is free to swing back and forth when displaced (see figure 4.7). Initially, the simple pendulum is at rest with its bob in the centre position (or mean position) A.

When the pendulum bob is pulled to one side to position B (to give it potential energy because of higher position of B with respect to position A), and then released, the bob starts swinging (moving back and forth) between positions B and C (see figure 4.7).

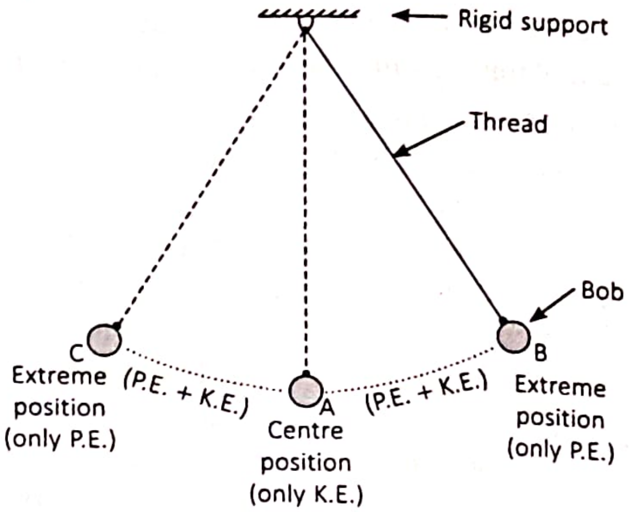

Fig. 4.7 A swinging (or oscillating) simple pendulum. Its energy is continuously transformed (or converted) from potential energy to kinetic energy and vice-versa.

i. When the pendulum bob is at position B (see figure 4.7), it has only potential energy (but no kinetic energy).
ii. As the bob starts moving down from position B to position A, its potential energy goes on decreasing but its kinetic energy goes on increasing.
iii. When the bob reaches the centre position A, it has only kinetic energy (but no potential energy).
iv. As the bob goes from position A towards position C, its kinetic energy goes on decreasing but its potential energy goes on increasing.
v. On reaching the extreme position C, the bob stops for a very small instant of time. So at position C, the bob has only potential energy (but no kinetic energy).

From the above discussion we conclude that at the extreme positions B and C of a swinging pendulum, all the energy of pendulum bob is potential, and at the centre position A, all the energy of the pendulum bob is kinetic. At all other intermediate positions, the energy of pendulum bob is partly potential and partly kinetic. But the total energy of the swinging pendulum at any instant of time remains the same (or conserved).

It should be noted that the body which does work loses energy and the body on which work is done, gains energy. For example, when we lift a stone from the ground and raise it to a height, we have to do some work on the stone. As a result of doing this work, we lose some energy from our body. On the other hand, the stone which we raised, gains an equal amount of potential energy. Thus, the total energy remains the same. Now, when we kick a ball, we do some work. In doing this work we lose some energy from our body. On the other hand, the ball gains an equal amount of kinetic energy and starts moving. Here also, the total energy of the system is conserved. And when we rub our hands vigorously against each other, we do work. The energy lost by our body in doing this work is transformed into heat energy. We are now in a position to answer the following questions:

Test Your Understanding

Very Short Answer Type Questions

Name the devices or machines which convert:

1. Mechanical energy into electrical energy.
2. Chemical energy into electrical energy.
3. Electrical energy into heat energy.
4. Light energy into electrical energy.
5. Electrical energy into light energy.

Work-Energy Relationship

You know that energy is the ability of a body to do work. So, there is a direct relationship between energy and work. For example, when an object is at a height from the ground, it has a certain amount of potential energy. When you drop the object, it falls down because of the force of gravity. So, work is being done on the object. While falling down, its potential energy is gradually used up until it becomes zero (just when the object touches the ground). At any point during its fall, the amount of potential energy which is used up by the object is equal to the distance the object has travelled (work done). So,

Work done by a body = Energy change in the body

POWER

Power is the rate of doing work or of transferring energy. Therefore, power is the rate of doing work per unit time. Power is related to rate at which work is done.

$$\text{Power} = \frac{\text{Work done by a body}}{\text{Time taken}}$$

$$\text{Power} = \frac{\text{work}}{\text{time}}$$

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

The SI unit of power is joule per second (J/s). also known as watt (W).

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

$$\text{KW} = 1000\text{ W}$$

Kilowatt is the bigger unit of power.

Nowadays, machines are having power ratings. This power rating indicates the rate at which a machine can do work.

Difference between Energy and Power

Energy	Power
Energy is defined as the capacity to do work.	Power is defined as the rate at which work is done or energy is transmitted.
Energy can transform from one form to another.	Power doesn't transform forms.
We can store energy that is generated.	Power cannot be stored.
SI unit of energy is joule (J).	SI unit of power is watt (W) or joules per second (J/s).

Know Your Scientist

James Prescott Joule (1818–1889) was an English physicist and mathematician who discovered the relationship between heat and mechanical energy. He was instrumental in the formulation of the Law of Conservation of Energy and the development of the First Law of Thermodynamics.
The unit of work 'Joule' was named in his honour.

Keywords

Energy: The ability of a body to do work

Potential energy: It is the energy possessed by a body by virtue of its position

Kinetic energy: The energy possessed by a body by virtue of its motion

Gravitational potential: The energy stored in an object on the earth because of its vertical position or energy height is called gravitational potential energy

Joule: When a force of one Newton causes a displacement of one meter, the work done is said to be one Joule. Joule is the unit of work

Power: It is the rate of work done with respect to time or the rate of consumption of energy with respect to time

Summary

- Work is said to be done when a force produces motion or in other words a body undergoes some displacement.
- The standard unit of work is Joule (J). Larger unit of work is kilojoule (kJ).
- The ability to do work is known as energy.
- An object can do work which is equivalent to the energy it possesses. This way energy and work are analogous. The units of energy and work are also the same i.e., joule.
- Kinetic energy is the energy possessed by an object due to its state of motion.