WORK & ENERGY

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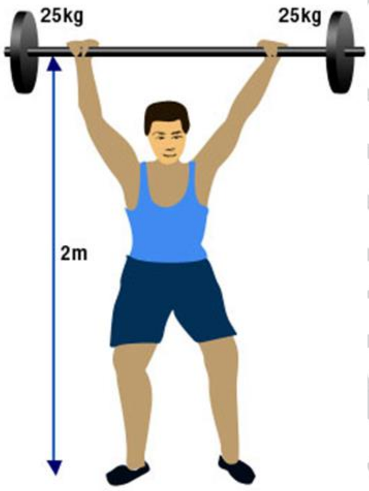
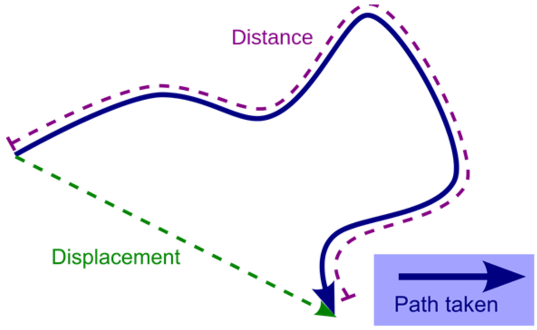
Defining Work
The scientific definition of work is different in many ways from its everyday meaning. The definition of work in physics reveals its relationship to energy – whenever work is done, energy is transferred.
For a work to be done, in a scientific sense, a force must be exerted and there must be displacement in the direction of the force. With this said, we can say that
Work is the product of the component of the force in the direction of the displacement and the magnitude of this displacement.
Mathematically, the above statement is expressed as follows:
$W = (F \cos \theta)\, d = F.\, d$
Where,

- W is the work done by the force.
- F is the force, d is the displacement caused by the force
- θ is the angle between the force vector and the displacement vector

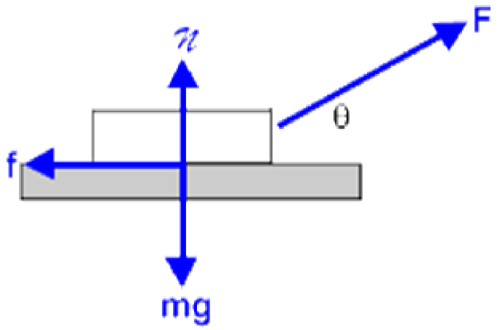
Unit of Work
The SI unit of work is the **joule (J)**, which is defined as the work done by a force of 1 Newton in moving an object through a distance of 1 meter in the direction of the force.



A weightlifter lifts a barbell weighing 25 kg and displaces it from the ground by 2 m. Here, the work done upon the barbell is against gravity.
The work done upon the weight against gravity can be calculated as follows:
Work Done = (Mass × acceleration due to gravity) × Displacement
= (25 × 9.8) × 2 J
What is 1 Joule Work?
A situation where 1 Newton force is applied on an object that can move the object by a distance of 1m in the direction of the applied force, then 1 joule of work is said to be done.
Factors Affecting Work
Let us now consider the factors on which work done on an object by a force depends.
Force:
Force is defined as a push or a pull that can cause any object with a mass to change its velocity and acceleration. Force is a vector quantity and has both a magnitude and a direction. If the force acting on an object is zero irrespective of the state of the object (dynamic or static) that work done by the force is zero.
Displacement:
Displacement is a vector quantity that gives the shortest distance between the initial position and the final position of any object. If the resulting displacement in the direction of force, due to force acting on any object is zero, the net work done by that force on that object is zero. For e.g., if we push a rigid wall with all our might and still fail to displace it, then we can say no work has been performed by us on the wall.
The Angle between the Force Vector and the Displacement Vector



The work done by a force on an object can be positive, negative, or zero, depending upon the direction of displacement of the object with respect to the force. For an object moving in the opposite direction to the direction of force, such as friction acting on an object moving in the forward direction, the work is done due to the force of friction is negative.



Similarly, an object experiences a zero force when the angle of displacement is perpendicular to the direction of the force. Consider an example of a coolie lifting a mass on his head moving at an angle of 90˚ with respect to the force of gravity. Here, the work done by gravity on the object is zero.

- Depending upon the direction of displacement and force applied the nature of work done may vary. Consider the table given below:

The direction of Displacement	**Work Done**	**Nature of Work Done**	**Angle between Force applied and Displacement occurred**
Same as the direction of Force	W = F * d	Positive	0^{o} (Force and Displacement are Parallel to each other)
Opposite as direction of Force	W = -F * d	Negative	180^{o}
No change in position	W = F * 0 = 0	Zero	90^{o}

Frequently Asked Questions – FAQs

1. **What is the standard unit of measurement for work?**
   The standard unit of measurement for work is Joule.
2. **When a body falls freely under gravity, the work done by gravity is positive or negative?**
   If a force acting on a body has a component in the direction of displacement, then the work done by the force is positive. Hence, when a body falls freely under the influence of gravity the work done by the gravity is positive.
3. **When a body slides against a rough surface, the work done by friction is positive or negative?**
   If a force acting on a body has a component in the direction opposite to displacement, then the work done by the force is negative. Hence, the work done by the frictional force on the body is negative.

4. **Superman stops a truck from moving downhill by applying force in it. Is this an example of work being done?**
   No. As there is no displacement no work is done. He is merely holding the car to prevent its descent down the hill.
5. **A string is tied to an eraser, a person holds the string and applies a tension force to the string as it made to move in a circle at a constant speed. Is this scenario an example of work being done?**
   For uniform circular motion, the force acts perpendicular to the direction of the motion and so the force never does any work upon the object.

What is Energy?

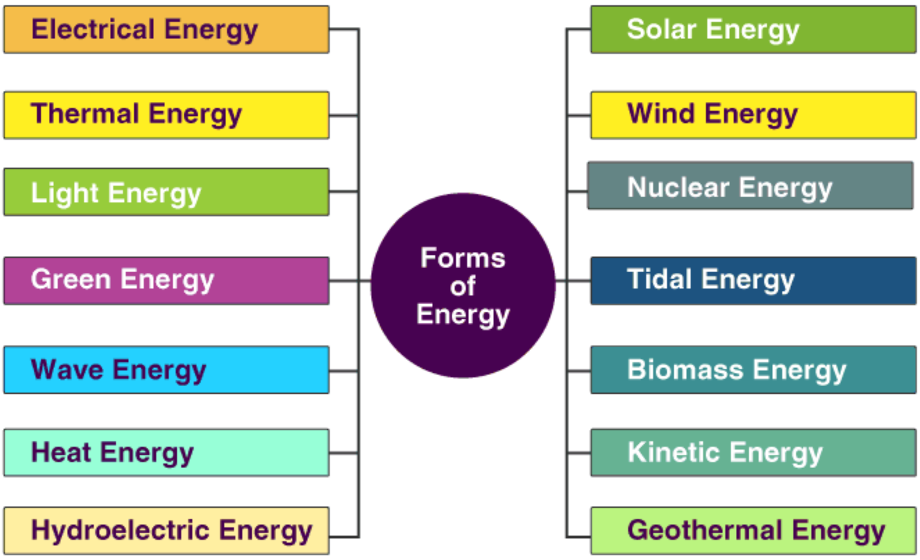
Energy is essential to life and all living organisms. The sun, directly or indirectly, is the source of all the energy available on Earth. In Physics, energy is a quantitative property that must be transferred to an object in order for it to perform work. Hence, we can define energy as the strength to do any kind of physical activity. Thus, they say,

Energy is the ability to do work

Energy is a conserved quantity and the law of conservation of energy states that energy can neither be created nor destroyed but can only be converted from one form to another. The SI unit of energy is Joule.

Units of Energy

The International System of Units of measurement of energy is **Joule**. The unit of energy is named after James Prescott Joule. Joule is a derived unit and it is equal to the energy expended in applying a force of **one newton through a distance of one meter**. However, energy is also expressed in many other units not part of the SI, such as ergs, calories, British Thermal Units, kilowatt-hours, and kilocalories, which require a conversion factor when expressed in SI units.



Energy Conversion: Transfer and Transform

The movement of energy from one location to another is known as energy transfer. There are energy transfers going on all the time – whenever a system changes there is a change in the way some or all of the energy is stored.

Following are the four ways through which energy can be transferred:

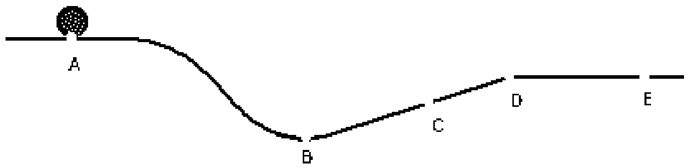
- **Mechanically – By the action of force**
- **Electrically – Electrically**
- **By Radiation – By Light waves or Sound waves**
- **By Heating – By conduction, convection, or radiation**

The process which results in the energy changing from one form to another is known as energy transformation. While energy can be transformed or transferred, the total amount of energy does not change – this is called energy conservation.

Scenario	*Energy conversions involved*
Rubbing both hands together for warmth	Kinetic Energy to Thermal Energy
A falling object speeding up	Gravitational Potential Energy to Kinetic Energy
Using battery-powered torchlight	In the battery: Chemical to Electrical Energy In the bulb: Electrical to Radiant Energy
In Geothermal Power Plant	Heat Energy to Electrical Energy
In Thermocouple	Heat Energy to Electrical Energy
In Hydroelectric Dams	Gravitational potential energy to Electric Energy
In Electric Generator	Kinetic energy / Mechanical work to Electric Energy
In Windmills	Wind Energy to Mechanical Energy or Electric Energy
In OTEC	Heat Energy to Electric Energy or Mechanical Energy
Using Microphone	Sound Energy to Electric Energy
Photosynthesis in Plants	Solar Energy to Chemical Energy
In Piezoelectrics	Strain to Electric Energy
In Electric lamp	Electric Energy to Heat and Light Energy
Burning of wood	Chemical energy to Heat and Light Energy
In Fuel cells	Chemical Energy to Electric Energy
In steam engine	The heat energy to Mechanical Energy
In Electric heater	Electric Energy to Heat

Practice Questions

Using the following diagram answer the following questions. Neglect the effect of resistance forces.



- **What happens to the sum of gravitational potential and kinetic energies when the object moves from point A to point D across the surface?**

Answer: The total mechanical energy (i.e., the sum of the kinetic and potential energies) remains the same whenever there are no external or non-conservative forces (such as friction or air resistance) doing work.

- **At what point will the object have a minimum gravitational potential energy?**

Answer: The gravitational potential energy depends on the height. The potential energy is minimum when the height is minimum. At point B, the object will have minimum gravitational potential energy.

- **At which point in the diagram is the object's kinetic energy lesser than the object's kinetic energy at C?**

Answer: Since the total mechanical energy is conserved, kinetic energy will be greatest when the potential energy is smallest. Point B is the only point that is lower than point C. The reasoning would follow that point B is the point with the smallest PE, the greatest KE, and the greatest speed. Therefore, the object will have less kinetic energy at point C than at point B (only).

Kinetic Energy

Every moving object possesses some energy called **Kinetic Energy**. As the speed of the object increases so is its kinetic energy.

Formula for Kinetic Energy

$\therefore$ Work done $\rightarrow$ $W = F \times s$ ... (i)

due to force the velocity changes to v, and the acceleration produced is a

$\therefore$ relationship between v, u, a and $s = v^2 - u^2 = 2as$

$$\therefore \quad s = \frac{v^2 - u^2}{2a} \qquad \text{... (ii)}$$

$$F = ma \qquad \text{... (iii)}$$

Substitute (ii) and (iii) in (i) we get

$$W = F \times s$$

$$= ma \times \frac{v^2 - u^2}{2a}$$

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

if $u = 0$, (object starts at rest)

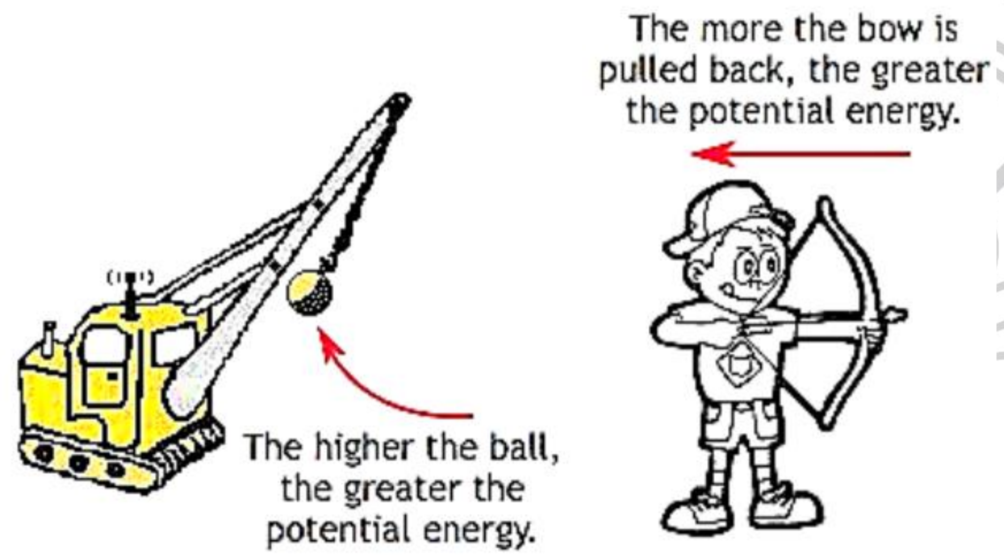
$$\therefore \quad W = \frac{1}{2} mv^2$$

Work done = Change in kinetic energy

$$\therefore \quad \boxed{E_k = \frac{1}{2} mv^2}$$

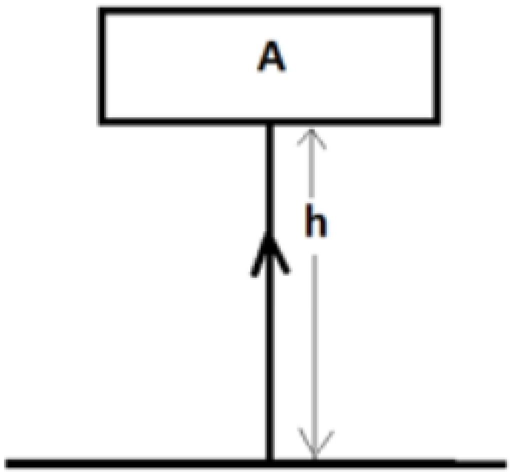
Potential Energy

Every object possesses some energy called **Potential Energy**. An object when gains energy may store it in itself as potential energy.



We know that when an object rises above the ground some work is done against gravity. Since work is done on the object, the object would gain some energy. The energy that the object gains at a height is called **Gravitational Potential Energy**. It is defined as the amount of work done required in raising an object above the ground up to a certain point against the gravity

Consider the example given below,



An object ‘A’ having mass ‘m’ is raised by height ‘h’ above the ground. Let us calculate the potential energy of object A at height ‘h’:
We know that,

W = F * d = F * h (height)
And F = m * g (because the force is applied against gravity)
So, W = m * g * h
Hence potential energy of object A, **PE = m * g * h**

- Gravitational potential energy does not get affected due to the path taken by the object to reach a certain height.

Other forms of Energies:

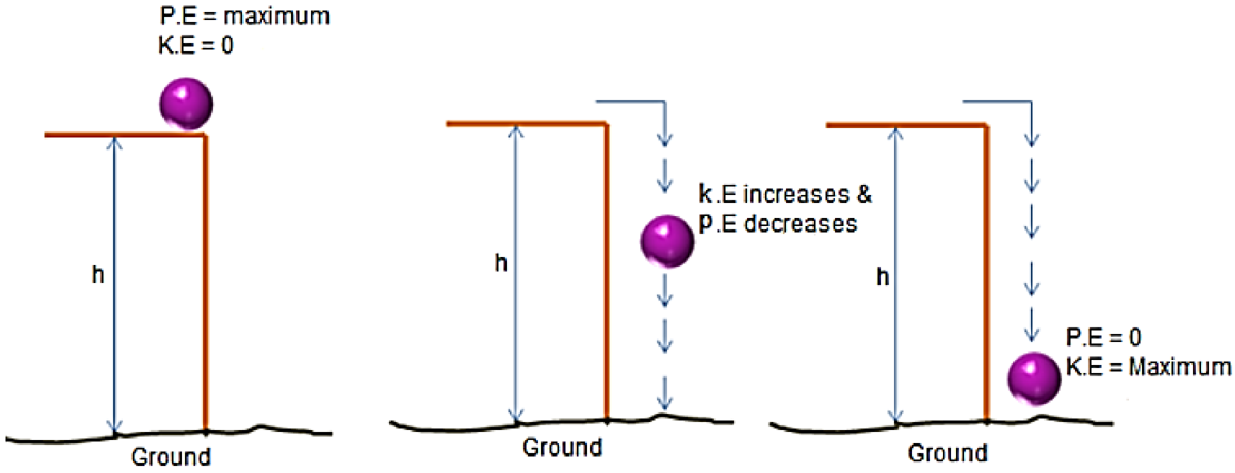
- **Mechanical Energy** – It is the sum of kinetic and potential energy of an object. Therefore, it is the energy obtained by an object due to motion or by the virtue of its location. **Example**, a bicycle climbing a hill possesses kinetic energy as well as potential energy.
- **Heat Energy** – It is the energy obtained by an object due to its temperature. It is also called **Thermal Energy**. **Example**, energy possessed by a hot cup.
- **Chemical Energy** – It is the energy accumulated in the bonds of chemical compounds. Chemical energy is released at the time of chemical reactions. **Example**, energy possessed by natural gas and biomass.
- **Electrical Energy** – It is kind of kinetic energy caused due to the motion of electrons. It depends upon the speed of electrons. As the speed increases so does the electrical energy. **Example**, electricity produced by a battery, lightning at thunderstorms
- **Light Energy** – It is the energy due to light or electromagnetic waves. It is also called as **Radiant Energy** or **Electromagnetic Energy**. **Example**, energy from the sun
- **Nuclear Energy** – It is the energy present in the nucleus of an atom. Nuclear energy releases when the nucleus combines or separate. Therefore, we can say that every atom in this universe comprises of nucleus energy. **Example**, uranium is a radioactive metal capable of producing nuclear energy in nuclear power plants
- **Sonic Energy** – It is the energy produced by a substance as it vibrates. This energy flows through the substance in the form of sound waves. **Example**, music instruments produce sound energy
- **Ionization Energy** – It is the energy that binds electrons with its nucleus. It is thus the amount of energy required to remove one electron completely from its atom (called **First Ionization Energy**). Subsequently, the ionization energy increases as we remove the second electron from the atom (called **Second Ionization Energy**).

- One form of energy can be transformed into other forms of energy.

Law of Conservation of Energy

According to the law of conservation of energy, the total amount of energy before and after transformation remains the same.

Consider the following example where an object of mass 'm' is made to fall freely from a height 'h'.



Instant	**Height at an instant**	**Kinetic Energy**	**Potential Energy**	**Sum of KE + PE = ME**
1	Height = h	0 (velocity is 0)	mgh	0 + mgh
2	Height = k	(1/2) $mv1^2$ (velocity = v1)	mgk	(1/2) mv_1^2 + mgk
3	Height = 0	(1/2) $mv2^2$ (velocity = v2)	0	(1/2) mv_2^2 + 0

We can see that the sum of kinetic energy and potential energy at every instant is constant. Hence, we can say the **energy is conserved during transformation**.

Power – The rate of doing work is defined as **Power**.

Power = Work Done / Time
P = W/ t
SI Unit: W (Watt) or J/s
1 kilowatt = 1000 watts
1 kW = 1000 W
1 W = 1000 J s^{-1}
Average Power = Total Energy Consumed / Total Time taken

Commercial Unit of Power

We cannot use Joule to measure power commercially. Instead, we use kilowatt-hour (kWh).
Commercial unit of energy = 1 kilowatt hour (kwh)
∴ 1 kWh = 1 kilowatt × 1 hour
= 1000 watt × 3600 seconds
= 3600000 Joule (watt × second)
1 kWh = 3.6×10^6 J.
∴ 1 kWh = 1 unit
The energy used in one hour at the rate of 1 kW is called 1 kWh.