1. Details of module and its Structure

Module Detail	
Subject Name	Physics
Course Name	Physics 01 (Physics Part-1, Class XI)
Module Name/Title	Unit 4, Module 3, Conservative and Non-Conservative forces and Potential Energy Chapter 6,Work, Energy and Power
Module Id	Keph_10603_eContent
Pre-requisites	Kinematics, laws of motion, basic vector algebra , work , energy theorem, mechanical energy ,law of conservation of energy
Objectives	After going through this module, the learners will be able to • Classify conservative and non-conservative forces • Understand term potential energy • Describe potential energy due to position of a body • Apply conservation of mechanical energy principle to a falling body • Relate potential energy concepts to problems in real life
Keywords	Conservative force, non-conservative force, potential energy, conservation of mechanical energy

2. Development Team

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Programme Coordinator	Dr. Mohd. Mamur Ali	Central Institute of Educational Technology, NCERT, New Delhi
Course Coordinator / PI	Anuradha Mathur	Central Institute of Educational Technology, NCERT, New Delhi
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1. UNIT SYLLABUS

UNIT IV: CHAPTER 6: WORK ENERGY AND POWER

Work done by a constant force and a variable force; kinetic energy; work energy theorem; power; Notion of potential energy; potential energy of a spring conservative and non-conservative forces; conservation of mechanical energy (kinetic and potential energies) non-conservative forces; motion in a vertical circle; Elastic and inelastic collisions in one and two dimensions.

2. MODULE-WISE DISTRIBUTION OF UNIT SYLLABUS 7 Modules

The above unit is divided into 7 modules for better understanding.

Module 1	• Meaning of work in the physical sense • Constant force over variable displacement • variable force for constant displacement • Calculating work • Unit of work • Dot product • Numerical

Module 2	• Different forms of energy • Kinetic energy • Work energy theorem • Power
Module 3	• Potential energy • Potential energy due to position • Conservative and non-conservative forces • Calculation of potential energy
Module 4	• Potential energy • Elastic Potential energy • Springs • Spring constant • problems
Module 5	• Motion in a vertical circle • Applications of work energy theorem • Solving problems using work power energy
Module 6	• Collisions • Idealism in Collision in one dimension • Elastic and inelastic collision • Derivation
Module 7	• Collision in two dimension • Problems

MODULE 3

3. WORDS YOU MUST KNOW

Let us keep the following concepts in mind

- Rigid body: An object for which individual particles continue to be at the same separation over a period of time.
- Point object: **Point object** is an expression used in kinematics: it is an **object** whose dimensions are ignored or neglected while considering its motion.

- Distance travelled: change in position of an object is measured as the distance the object moves from its starting position to its final position. Its SI unit is m and it can be zero or positive.
- Displacement: a **displacement** is a vector whose length is the shortest distance from the initial to the final position of an object undergoing motion. . Its SI unit is m and it can be zero, positive or negative.
- Speed: Rate of change of position .Its SI unit is ms^{-1}.
- Average speed: $\frac{\text{total path length travelled by the object}}{\text{total time interval for the motion}}$

  Its SI unit is ms^{-1}.
- Velocity (v): Rate of change of position in a particular direction.
  Its SI unit is ms^{-1}.
- Instantaneous velocity: velocity at any instant of time.

$$v_{instaneous} = \lim_{\Delta t \to 0} \frac{\Delta x}{\Delta t}$$

Instantaneous velocity is the **velocity** of an object in motion at a specific time. This is determined by considering the time interval for displacement as small as possible .the instantaneous velocity itself may be any value .If an object has a constant **velocity** over a period of time, its average and **instantaneous velocities** will be the same.

- Uniform motion: a body is said to be in uniform motion if it covers equal distance in equal intervals of time

- Non uniform motion: a body is said to be in non- uniform motion if it covers unequal distance in equal intervals of time or if it covers equal distances in unequal intervals of time
- Acceleration (a): time rate of change of velocity and its SI unit is ms^{-2}. Velocity may change due to change in its magnitude or change in its direction or change in both magnitude and direction.
- Constant acceleration: Acceleration which remains constant throughout a considered motion of an object

- Momentum (p): The impact capacity of a moving body. It depends on both mass of the body and its velocity. Given as p = mv and its unit is kg ms^{-1}.
- Force (F): Something that changes the state of rest or uniform motion of a body. SI Unit of force is Newton (N). It is a vector, because it has both magnitude, which tells us the strength or magnitude of the force and direction. Force can change the shape of the body.
- Constant force: A force for which both magnitude and direction remain the same with passage of time
- Variable force: A force for which either magnitude or direction or both change with passage of time
- External unbalanced force: A single force or a resultant of many forces that act externally on an object.
- Dimensional formula: An expression which shows how and in which way the fundamental quantities like, mass (M), length (L) and time (T) are connected
- Kinematics: Study of motion of objects without involving the cause of motion.
- Dynamics: Study of motion of objects along with the cause of motion.
- Vector: A physical quantity that has both magnitude and direction .displacement, force, acceleration are examples of vectors.
- Vector algebra: Mathematical rules of adding, subtracting and multiplying vectors.
- Resolution of vectors: The process of splitting a vector into various parts or components. These parts of a vector may act in different directions. A vector can be resolved in three mutually perpendicular directions. Together they produce the same effect as the original vector.
- Dot product: If the product of two vectors (A and B) is a scalar quantity. Dot product of vector A and B: A.B= $|A||B|cos\theta$ where θ is the angle between the two vectors

  Since Dot product is a scalar quantity it has no direction. It can also be taken as the product of magnitude of A and the component of B along A or product of B and component of A along B.

- Work: Work is said to be done by an external force acting on a body if it produces displacement W= F.S cosθ, where work is the dot product of vector

F(force) and Vector S (displacement) and θ is the angle between them . Its unit is joule and dimensional formula is ML^2T^{-2}. It can also be stated as the product of component of the force in the direction of displacement and the magnitude of displacement. Work can be done by constant or variable force and work can be zero, positive or negative.

- Energy: The ability of a body to do work

- Kinetic Energy: The energy possessed by a body due to its motion = ½ mv^2, where 'm' is the mass of the body and 'v' is the velocity of the body at the instant its kinetic energy is being calculated.

- Work Energy theorem: Relates work done on a body to the change in mechanical energy of a body i.e.,

  $W = F.S = \frac{1}{2} mV_f^2 - \frac{1}{2} mV_i^2$

4. INTRODUCTION

We have considered kinetic energy in module 2, which is the energy of moving objects due to their motion. Another form of **mechanical energy possessed by objects is due to their position and configuration.** This is called **potential energy.**

The word potential suggests 'capacity' for action. The term 'potential energy' brings to one's mind the idea of 'stored energy'. A rubber band can be stretched holding a small paper pellet. The pellet shoots in the opposite direction, the moment rubber band is released .A slingshot gullel'' can be an example of potential energy as the work done in stretching the rubber band is stored in it (as its potential energy) which can be converted into the kinetic energy of a pebble as missile.

Note, for the rubber band or the slingshot to do work on the pellet it must be stretched but ,it is essential that the rubber band is not stretched to a point that it does not come back to its original shape.

A mountain climber does work in taking himself against gravity to the summit and this work can be said to increase the potential energy of the climber.

What would happen to a bag that he was carrying while climbing and he decides to release the bag? What causes the bag to fall?

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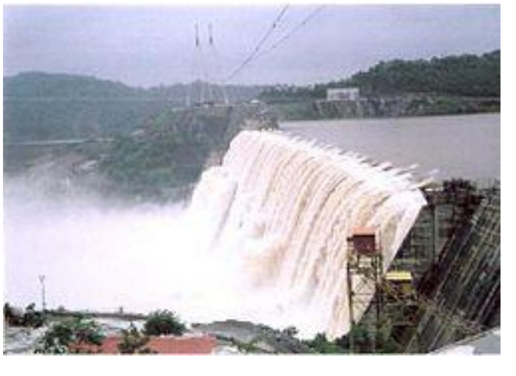
Energy: The ability of a body to do work.
The bag stored the potential energy as the climber moved higher, also understand that it is not just the weight of the bag or gravitational pull that is making the bag to fall with more energy as the height of release increases, because the weight remains the same at all heights (if g is constant).



Water, at the top of a water fall, and the coiled spring of a toy car, or clock with a winding knob are some other examples of 'potential energy'.

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No wonder hydroelectric power plants have dams on rivers at a height above the turbines.

The waterfall has potential energy which gets converted into kinetic energy as the water falls. This energy is used to rotate the blades of turbines at hydro power generation.

SI Unit of potential energy is joule denoted by symbol J and its dimensions are: ML^2T^{-2}

This might interest you

The earth's crust is not uniform, but has discontinuities and dislocations that are called fault lines. These fault lines in the earth's crust are like 'compressed springs'. They possess a large amount of potential energy. An earthquake results when these fault lines readjust. **Thus, potential energy is the 'stored energy' by virtue of the position or configuration of a body. The body left to it releases this stored energy in the form of kinetic energy or other forms of energy.**

Potential energy is, therefore the energy possessed by an object by virtue of its

- **Position with respect to a reference level**
- **Temporary change in configuration**.

Physically, the notion of potential energy is applicable only to the class of forces where work done against the force gets 'stored up' as energy. When external constraints are removed, it manifests itself as kinetic energy.

We can, however, associate a 'well defined' potential energy, with an object, only when the force is conservative.

It is easy to realize that we can associate a definite, or unique value, of 'potential energy', with a definite position or configuration of an object, only if the work done, in bringing the object to that position (or configuration) depends only on that position (or configuration) and not on the way, or path, through which that position (or configuration) has been attained.

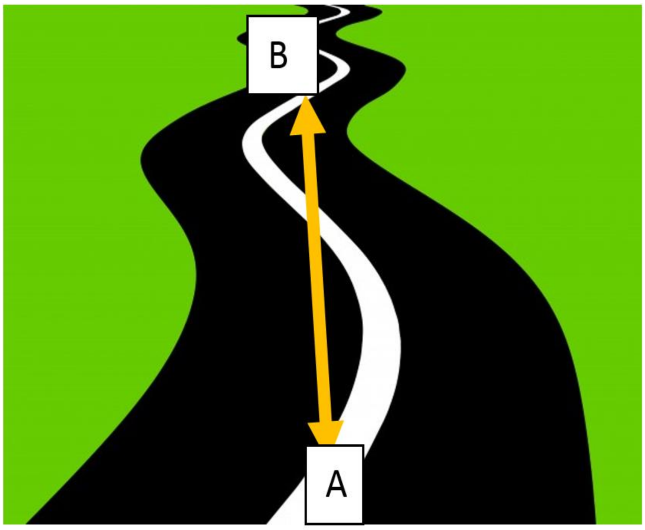
In other words, **the forces, involved must be such that the work done by, or against, them, is path independent**

5. CONSERVATIVE AND NON-CONSERVATIVE FORCES

In order to understand conservative and non-conservative forces, consider the following.

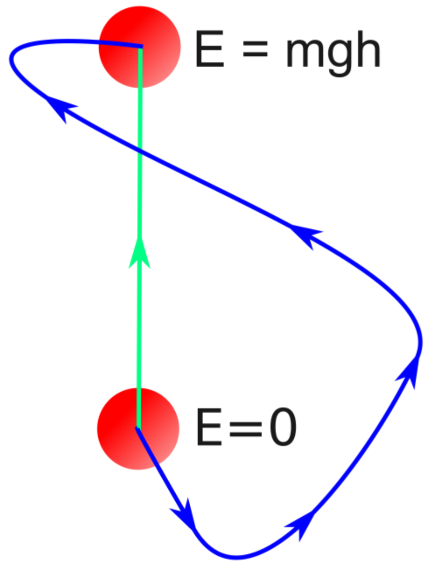
Let us say a force F is applied on a body, and some work is done by the applied force. This work as we know is given by F.S, where S is the displacement in the direction of the force..

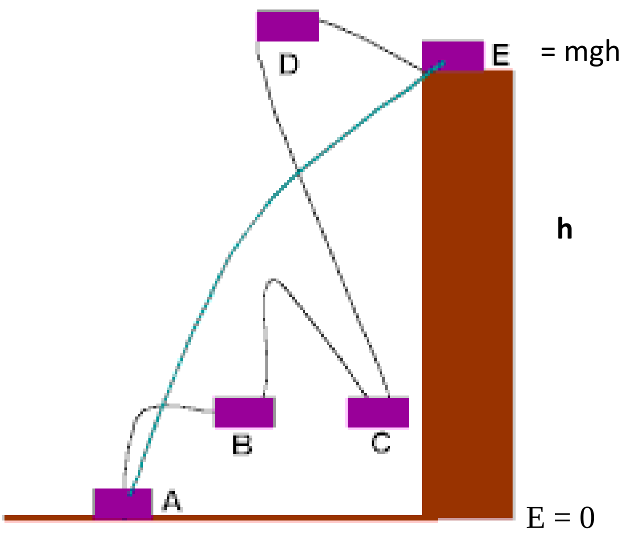
In the diagram, A is the initial position and B is the final position so displacement is AB, the object can cover AB along the road in two ways along the yellow line or along the white line. The path length in the two cases is different. The force of friction will be more along the longer path; hence work done in the two cases will be different. The force is said to be non-conservative.



Only if motion is on a completely friction less surface, the value of work will be the same . But in real life this is not possible.

So can we have a force that can do work and is path independent?

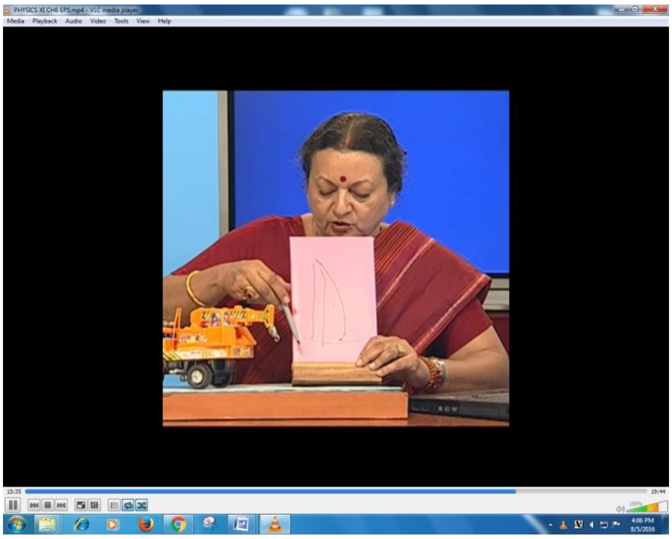




In the above two cases the displacement h from E = 0 to E = m g h is the same.

We can see different paths and imagine many more, but as displacement 'h' remains the same the work done is the same or work is path independent.

Force F is said to be conservative if work done by it remains the same no matter how you get the same displacement 'h'.



We therefore, can realize why we can associate the concept of a unique potential energy only for the position of a body when it is ‘acted upon’ by conservative forces.

There are three conservative forces which we come across

a) **Gravitational force.**
b) **Elastic forces**
c) **Electrostatic forces**

6. POTENTIAL ENERGY

We will only consider gravitational forces and elastic forces.

Key features about potential energy and conservative forces:

- **Potential energy is a result of the force (s) that act on an object because forces do work only on interaction with objects.**
- **Potential energy is the stored energy due to change in position or change in shape**
- **It is a scalar quantity**
- **The value can be positive, negative or zero depending upon whether the work is done by the force or against the force, or no work is done**
- **Forces like friction or air resistance, viscous drag etc are non-conservative forces, they cannot be used to store energy.**

- **The work done by the conservative force depends only on the end points. This can be seen from the relation,**

  $W = K_f - K_i = V(x_i) - V(x_f)$ which depends on the end points only

  The work done by this force in a closed path is zero.

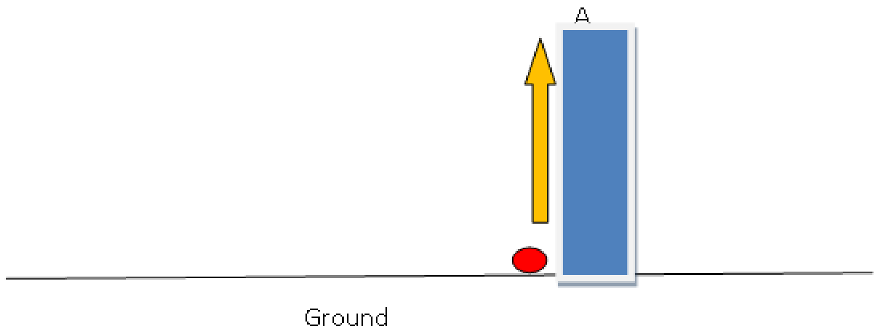
Thus,

The principle of conservation of total mechanical energy can be stated as:

The total mechanical energy (kinetic as well as potential) of a system is conserved if the forces, doing work on it, are conservative.

7. CALCULATION OF GRAVITATIONAL POTENTIAL ENERGY DUE TO POSITION OF A BODY

EXAMPLE:



Let us take an example of a ball which is to be raised through a height h, to a point, say A, above the surface of the earth. Some work has to be done by an external agent against gravity by applying a force equal to the weight of the ball.

Assume that *h* is very small as compared to the radius of the earth so that we can assume *g* to be a constant.

As the ball moves up, the work done, by the external agent, say a person against the force of gravity, will be $(mg)(h)(\cos\theta) = m\,g\,h$.

Here, $\theta = 0°$

$\cos\theta = 1$

This work done on the ball does not change its kinetic energy as we are not imparting any velocity to the ball. However, **this work changes its position with respect to the**

ground itself and hence gets stored in the ball-earth system in the form of its gravitational potential energy.

In this case, the zero of the potential energy is taken on the earth's surface which is the ground.

Hence, 'm g h' is actually the difference in the potential energy between point A and a point on the ground.

It then follows that **an increase in the height to which the ball is raised above the surface of earth, increases the potential energy stored in it.**

The relative position where we are considering the zero potential energy is completely our choice, and we must express it as potential energy of a body with respect to a point.

EXAMPLE:

Take a look at the slide in a playground. A child must climb stairs and go to the top by using his energy.

The child gains potential energy = m g h

Where mg is the weight of the child (mg) which is the force he needs to apply on himself to raise to the height of the seat above the ground.

Then the child sits on the top and may slide down with thrilling speed enjoying the slide.

Some other examples of gravitational potential energy are given below.

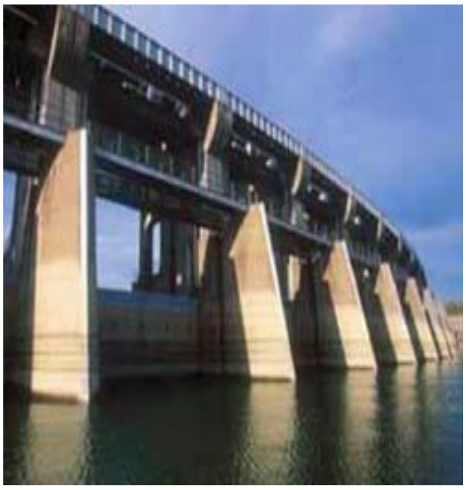
a) **A roller coaster has the maximum gravitational potential energy when it stops momentarily at the top of a big 'drop'**.

b) **The massive wrecking ball of a demolition truck when taken backwards to a higher position possesses huge amount of gravitational potential energy.**

This manifests itself in the form of its kinetic energy when it is swinging forward to demolish a structure or a building.

d)A barbell, lifted to a particular height above the head of a weightlifter, also has gravitational potential energy stored in it.

d) **A large amount of gravitational potential energy is stored in the water that is held by a dam. This water can convert its potential energy to kinetic energy when it comes down. It is this kinetic energy that is then used to produce electricity by rotating the blades of turbines in a hydroelectric power station.**



e)A book, at rest, in the top shelf of a rack in the library, has gravitational potential energy stored in it which can get converted into kinetic energy when it falls down from the rack to the ground.

In all the above cases, gravity is responsible for storing potential energy.

This potential energy can get converted into kinetic energy.

Identify in each of the above cases if friction or conversion into other forms of energy will reduce the kinetic energy.

EXAMPLE:

A helicopter is dropping an armored tank. Can you give three factors on which the potential energy of the tank will depend upon? Which of these are likely to give an error in our calculation? And why?

Hint: The value of acceleration due to gravity changes with height.

8. CONSERVATION OF MECHANICAL ENERGY FOR A FREELY FALLING BODY

Potential energy is the 'stored energy' by virtue of the position or configuration of a body. The body left to itself releases this stored energy in the form of kinetic energy.
When released, the ball comes down with an increasing speed and thus we can say that the potential energy of the ball transforms itself in the form of its kinetic energy on reaching the ground.

Since gravitational forces are conservative forces, all the gravitational potential energy converts to kinetic energy and to no other form.
We can say that the mechanical energy is conserved.

THINK THIS OUT:

- **Would all the potential energy gained by a child going up a slide convert to kinetic energy just before the child reaches the ground?**

- **Would all the potential energy of the water in the reservoir convert to kinetic energy just before it strikes the turbine blades in a hydroelectric power plant**?

Let us make our notion of potential energy more concrete.

The gravitational force on a ball of mass m is mg, where g may be treated as a constant near the earth surface. By 'near' we imply that the height 'h' of the ball above the earth's surface is very small compared to the earth's radius R, and we ignore any variation in the value of g due to any other factor.
In what follows we have taken the upward direction to be positive.
Let us raise the ball up to a height h.
The work done by the external agency against the gravitational force is 'mgh'.
We have said above that this work gets stored as potential energy.

Gravitational potential energy of an object, as a function of the height h, is denoted by V(h) and it is the negative of work done by the gravitational force in raising the object to that height.

The negative sign indicates that the gravitational force is downward. When released, the ball comes down with an increasing speed. Just before it hits the ground, its speed is given by the kinematic relation, $\mathbf{v^2 = 2gh}$. This equation can be written as

$$\frac{1}{2}\mathbf{mv^2} = \mathbf{mgh}$$

which shows that the gravitational potential energy of the object at height h, when the object is released, manifests itself as kinetic energy of the object on reaching the ground.

Physically, the notion of potential energy is applicable only to the class of forces where work done against the force gets 'stored up' as energy or are conservative in nature. When external constraints are removed, it manifests itself as kinetic energy

The total mechanical energy of a system is conserved if the forces, doing work on it, are conservative.

Mathematically for an object **Initial (KE + PE) = Final (KE + PE)**

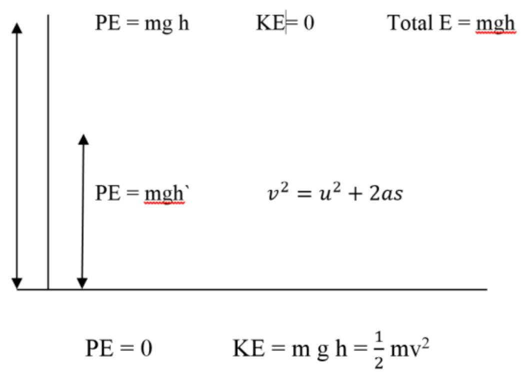
Or

Initial Mechanical energy, $(E)_{initial}$ = Final Mechanical energy $(E)_{final}$

EXAMPLE:

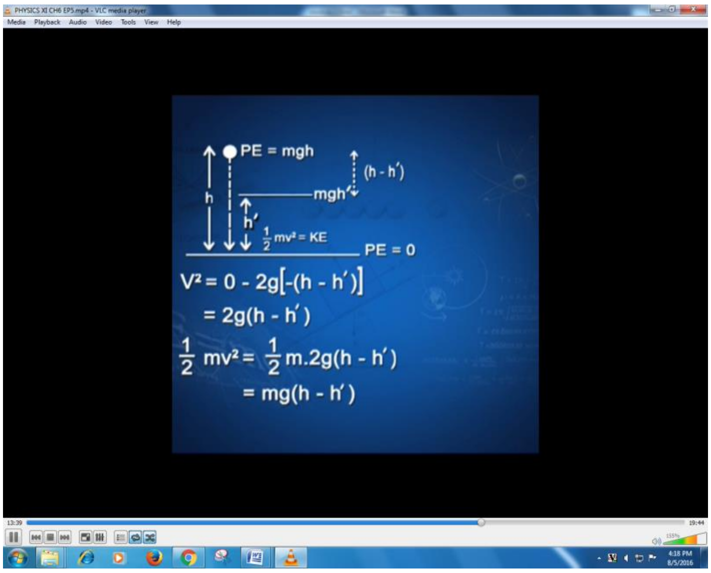
A body is located at a height of h above a horizontal level. If it is dropped what will be its kinetic and potential energy at a height h`. What will be the kinetic and potential energy at the horizontal level?

SOLUTION:



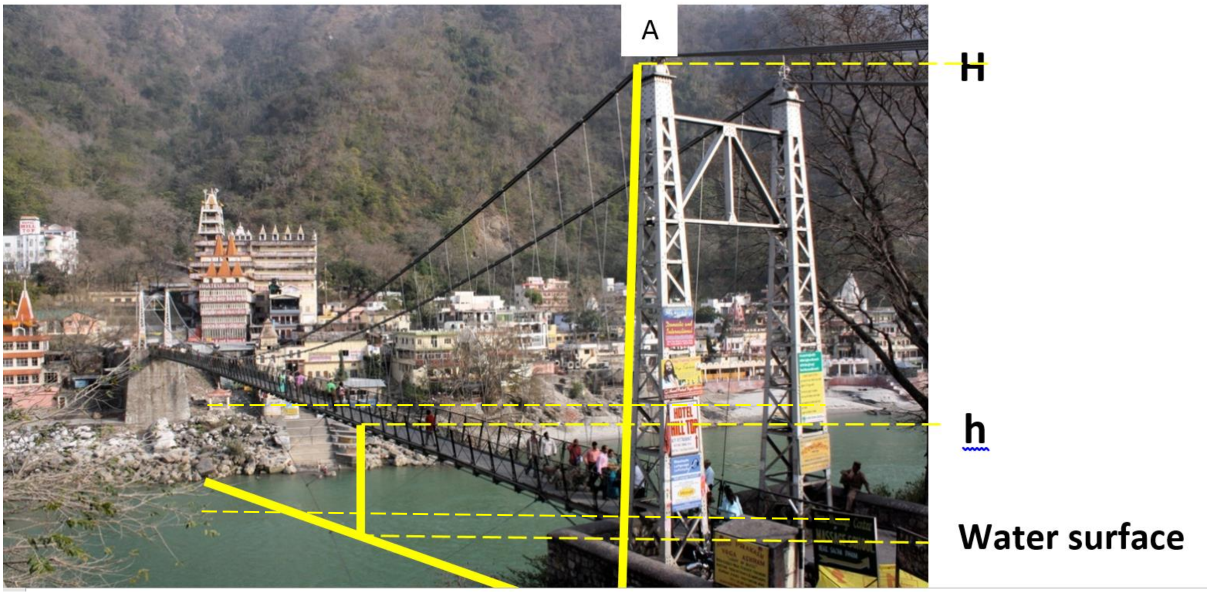
The speed with which it strikes the ground is v

$$v = \sqrt{2gh}$$



9. SOME EXAMPLES

EXAMPLE:



A crow perched on top of the point A at a height of H above the water level, on the Laxman Jhoola in Rishikesh, has a pebble in its beak,. It drops the pebble. The mass of the pebble is m.

Answer the following:

1. **Calculate the potential energy of the pebble at height H.**
2. **Is the initial potential energy of the crow and the pebble the same?**
3. **How did the pebble get the energy?**

4. **Why are we calling it potential energy?**
5. **What is the potential energy of the pebble at the instant it crosses the bridge level?**
6. **If energy was stored due to conservative forces and we ignore air resistance what is the kinetic energy of the pebble as it crosses the bridge level?**
7. **What is the speed of the pebble at the instant it crosses the bridge level?**
8. **Will the speed of the pebble increase further as it strikes the water surface? Why?**
9. **What is the kinetic energy of the pebble just before it strikes the water surface?**
10. **What is the velocity of the pebble before it strikes the water surface?**

Graphical representation of potential energy and height above a horizontal level:

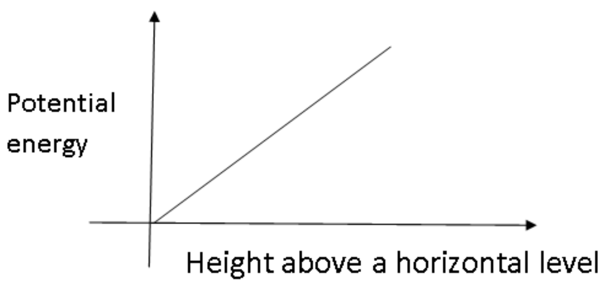
Remember **PE = m g h**

So **y = m x + c,**

the slope of the line is mg or the weight of the object.

The line must pass through (0, 0),

implying at the chosen reference horizontal level potential energy is zero.



You can try making a graph:

- **Total mechanical energy verses height above a horizontal level**
- **Kinetic energy of a falling object versus potential energy**

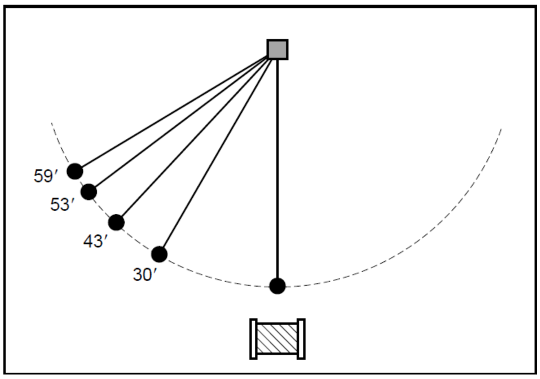
WORK ENERGY THEOREM - CHANGE IN MECHANICAL ENERGY:

"Work done by a conservative force causes a decrease in the PE of a system while work done against a conservative force, causes an increase in the PE of the system"

EXAMPLE

A pendulum as seen in the diagram, shows the bob can be raised above the mean position making angles of 30^0, 43^0, 53^0, 59^0. As you can see the height of the bob of the pendulum is maximum when it is raised by making the string by 59^0 to the vertical.

a) **At what angle does the pendulum have maximum potential energy?**
b) **Is this energy gravitational potential energy?**
c) **How did the pendulum gain energy?**
d) **What will happen when the pendulum is released from 59° positions?**
e) **Why does it swing back and forth after being released?**
f) **Why does the pendulum have a tendency to stop after some time?**
g) **Can we calculate the velocity of the pendulum when it reaches the mean position?**



SOLUTION:

a) When the string makes an angle of 59° with the vertical.

b) This is gravitational potential energy because the pendulum bob is raised above the mean position.

c) The agency that takes the bob of the pendulum to the new position, does work on it.

d) The pendulum swings back and forth.

e) It swings back and forth as the PE gets converted to KE at the mean position, the KE takes the bob up to a height where all the KE gets converted to PE and the process continues

f) The pendulum stops after some time as some energy is lost due to air resistance

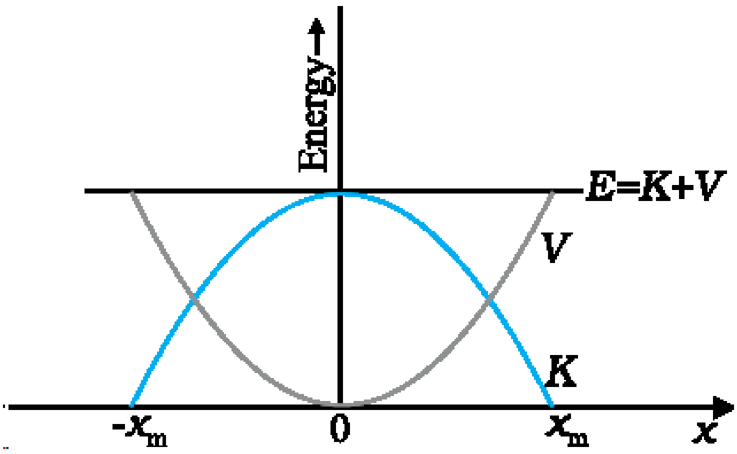
g) Yes

EXAMPLE:

For a simple pendulum, show the relation between kinetic energy and potential energy using a suitable graph.

SOLUTION:

We can graph the PE and KE of the swinging pendulum on an Energy vs displacement from the mean position graph, the parabolic plots of the PE (V) and KE (K) of a block attached to the string. The two plots are complimentary one decreasing as the other increases. The total mechanical energy remains the same E = K+V.



CHECK YOUR UNDERSTANDING

i) **A book is lifted up from the floor and is kept in an almirah. One person says that the potential energy of the book has increased by 20 J and the other says that the potential energy of the book has increased by 40 J. Is it possible that both of them are correct? If yes what is the condition?**
ii) **If you lift a 30 kg mass through 0.5 meters, how much Potential energy has it gained?**
iii) **A 12 kg box is resting on a tabletop 1.5 m off the ground. It is then lifted up to 3.2 m off the ground. What is its increase in potential energy**?

ANSWERS:

(Using g = 10 m s^{-2})

i) Yes, if the observers are at different levels

ii) 150 J

iii) 204 J

10. SUMMARY

We have learnt in this module

- A force is conservative if work done by it on an object is path independent and depends only on the end points
- The work done by the force is zero for an arbitrary closed path taken by the object such that it returns to its initial position.
- Potential energy due to position is the stored energy by doing work in raising it above a certain level ,taken as zero or initial level
- The gravitational potential energy of a particle of mass m at a height h above the earth's surface is V(h) = m g h, where the variation of g with height is ignored.
- The principle of conservation of mechanical energy states that the total mechanical energy of a body remains constant if the only forces that act on the body are conservative.
- Any falling body converts gravitational potential energy to kinetic energy.
- The total mechanical energy i.e., sum of potential energy and kinetic energy remains constant for a falling body.