Module Detail	
Subject Name	Physics
Course Name	Physics 01 (Physics Part-1, Class XI)
Module Name/Title	Unit 4, Module 1, Work Chapter 6, Work, Energy and Power
Module Id	Keph_10601_eContent
Pre-requisites	Kinematics, laws of motion, basic vector algebra
Objectives	After going through this module, the learners will be able to : • Understand the meaning of work in terms of physics • Calculate work done by a constant force • Derive the unit of work • Visualize work done by variable force • Use Dot product of vectors for calculation of work • Use graphs to calculate work • Apply knowledge of calculation of work done to simple problems
Keywords	Work done by constant force ,work done by variable force, dot product ,unit of work, work, displacement

1. Details of Module and its structure

2. Development Team

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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	• Kinetic energy • Work energy theorem • Power • Numerical
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
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MODULE 1

3. WORDS YOU MUST KNOW

Let us remember the following words we will be using in our study of this physics course.

- 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

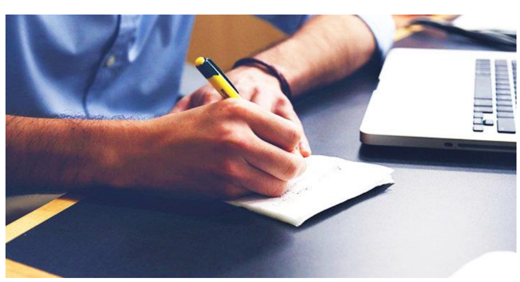
- Variable force: A force for which either magnitude or direction or both change with passage of time

- 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.

4. INTRODUCTION

The terms ‘work’, ‘energy’ and ‘power’ are frequently used in everyday language. A farmer ploughing the field, a construction worker carrying bricks, a student studying, an artist painting a landscape, all are said to be working.

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However in physics, the word 'Work' covers a definite and precise meaning. We admire a long distance runner for her stamina or energy. Energy is thus our capacity to do work. In Physics too, the term 'energy' is related to work in this sense, but as said above the term 'work' itself is defined in a different way. The word 'power' is used in everyday life with different shades of meaning. In karate or boxing we talk of 'powerful' punches. These are delivered at a great speed. This shade of meaning is close to the meaning of the word 'power' used in physics. We shall find that there is at best a loose correlation between the physical definitions and the physiological pictures these terms generate in our minds.

The aim of this module is to develop an understanding of these three physical quantities ,work , energy and power . We will also learn how we can quantify these physical quantities

Observe the use of 'work' in the following statements:

1. Mr. Sahai is *working* in an IT company.
2. Do you still *work* out in a gym during the summer months?
3. The machine is back in *working* order.
4. Let us *work* out a plan for the next year.
5. Students *work* very hard during examination time.
6. The guard *works* for eight hours sitting outside the complex.
7. the teacher is making the students *work* very hard in class.

They are all talking about *work being done*.

5. MEANING OF WORK IN PHYSICS

The term work, however, has a different meaning in Physics.

It may sound a bit surprising but in situations like: A guard doing his duty while standing at the gate of the school, a boy holding a heavy book in his hands, or a man pushing against a wall, none of them would be regarded as having done any work , in Physics.

Work is said to be done only when an unbalanced physical force, applied to an object, results in a displacement of the object.

This definition helps us to understand why we say that **no work has been done in the above cases. Because there is no displacement of the relevant 'object' in all these cases**. However, when an engine pulls a train, a crane lifts up an object, a horse pulls a cart, a workman carries a load of bricks up a ladder, a weight lifter lifts a bar bell above his head, a batsman hits a ball with his bat- and so on –

A force applied (on an object) and results in a displacement (of the object) in the direction of this force. We say that work is done.

Some questions that may come to your mind

- Is the work done by force, measurable in physics?
- Why do we need to calculate it?
- On what factors does the work done by a force depend upon?

Consider the following two situations:

1. Hira's tempo came to a halt in the middle of the road for want of petrol. The petrol pump is just 500 m away from that location. In which of the following cases, more work would be done on the tempo?
    - He himself tries to push the tempo to the petrol pump.
    - He takes help of a few people in doing so.

Assume that the maximum force applied by Hira is same in both the situations and the other people apply almost same force as Hira.

2. Priya lifts her school bag, of mass 2 kg to a height of 1m trying to place it on a desk. The same bag is lifted by Sakshi to a height of 2 m.

    Who does more work on the bag? Priya or Sakshi?

We would intuitively say that:

More work is done on the tempo when there are a number of people pushing it. This is because, the force applied on the tempo is more, as more people are applying the force, even though the distance moved (= 500 m) is the same in both the cases.

In the second situation, we would say that the work done by Sakshi is more because even though she applied the same force as Priya (-weight of the bag = 2 kg × 9.8 m/s² = 19.6 N). But she has moved the bag over a larger distance (=2m) as compared to than Priya (who lifted it by only1 m).

Our 'intuitive feeling', therefore, tells us that we should regard the work done by a force, as being determined by two factors:

(*i*) How hard we push or how much is the **magnitude of the force applied**

(*ii*) How far we push or how much is the **displacement of the object in the direction of the applied force.**

We can easily say the following:

- **In order for work to be done just exerting force on an object is not enough, the object should actually move from its position or get displaced.**
- **A man pushing against the wall or road will get tired but the mechanical work done by him is zero as neither the wall nor the road move.**
- **Work done depends upon magnitude of applied force**
- **Work done depends upon the magnitude of displacement**
- **Work should also depend upon the direction of applied force and the displacement**

6. CALCULATION OF WORK, ITS UNIT AND DIMENSIONS

Force can be constant in which case its magnitude and direction do not change with time, or it could be variable which means either its magnitude changes with time that is to say it becomes more or less, or its direction may change or both magnitude and direction may change. It may increase or decrease in a patterned way or do so randomly.

Calculation of work done a constant force:

Let us take an example of a man pulling a box by applying a force F and thus causing a displacement S of the box.

Work done by the force = force × displacement

Mathematically, work can be expressed by the following equation.

$$\mathbf{W} = \vec{\mathbf{F}}.\vec{\mathbf{S}}$$

Where, **F is the force** and **S is the displacement**. Remember both are vectors

This is a product of two vectors and work has no direction, it is a scalar. The product F .S is a scalar or dot product which means $W = \vec{F}.\vec{S}$

Or $W = |F||S|cos\theta$

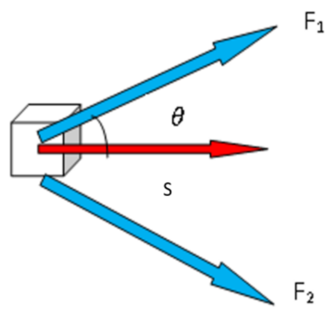
The angle (θ - theta) is defined as the angle between the force and the displacement vector.

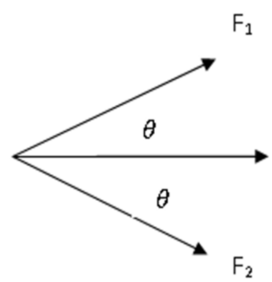
We can also understand this as follows

Since the force causes a displacement in a direction other than the force, we can consider the component of force F along the direction of displacement. This will be F cosθ . you may imagine this as the effective portion of the force in the direction of displacement . to make our point in case the direction of force and displacement were same the angle θ would be 0 or cosθ = cos 0 =1

Simple way to show that work is a scalar

Consider a box and two forces F_1 and F_2 can act on the box to cause a displacement of S





So, mathematically work is the same in the two cases, this would not be possible if work had directional properties. Hence we see that **work is a scalar quantity**.

Unit of Work:

Let us consider the unit of work

W=F (N) S (m) cos θ

Unit of work is **Newton- metre N m**, also called **joule** and represented by J in honour of the famous British Physicist James Prescott Joule.

One joule equals the work done by a force of one Newton when the point of application of this force moves through a distance of one metre in the direction of this force.

Dimensional formula for work:

Let us find out its dimensions

Dimensions of force ($F = ma$) is M LT^{-2} and that of displacement is M^0LT^0

Hence that for work will be $MLT^{-2}M^0LT^0$

= $\mathbf{ML^2T^{-2}}$

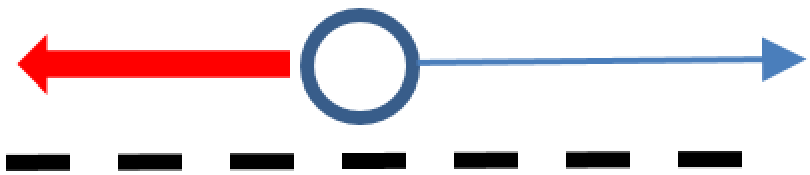
7. WORK CAN BE POSITIVE, NEGATIVE OR ZERO

Perhaps the most difficult aspect of the above equation is the angle θ "theta." Which we have defined as the measure is defined as the angle between the force and the displacement.

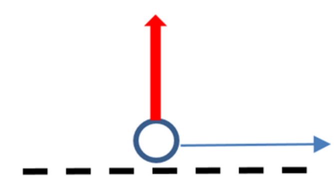
Consider the following four cases:

- **Case 1:** A force acts rightward upon and an object is displaced rightward. In such an instance, the force vector F and the displacement vector S are in the same direction. Thus, the angle between F and S is 0 degrees.

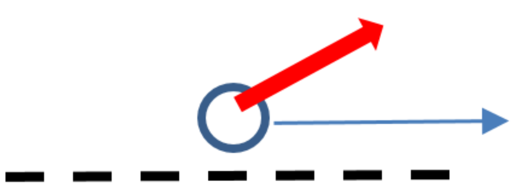
- **Case 2:** A force F acts leftward upon an object that is displaced rightward S. In such an instance, the force vector and the displacement vector are in the opposite direction. Thus, the angle between F and S is 180 degrees.

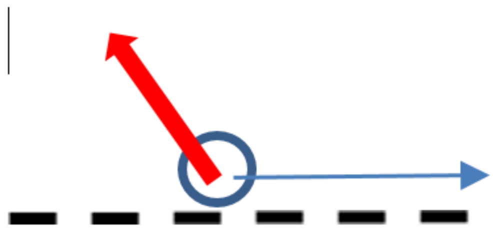


- **Case 3:** A force Fa cts upward on an object as it is displaced rightward by a displacement S. In such an instance, the force vector and the displacement vector are at right angles to each other. Thus, the angle between F and S is 90 degrees.



- **Case 4:** the angle between force and displacement is an acute angle or an obtuse angle





The red arrow is for force and the blue represents displacement

EXAMPLE:

A man pulls the box by applying a force of 20 N and displaces it by 2 m in the direction of the force. Calculate the work done by the man.

SOLUTION

The work done by the man on the box = 20 N × 2 m = 40 N-m. Since both force and displacement are in the same direction the angle θ = 0 and cos θ = 1.

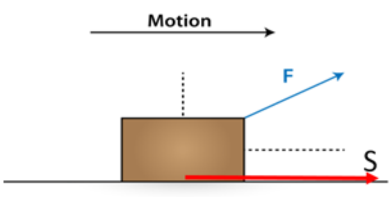
So, W = F S

Work done is positive

EXAMPLE:

A man pulling a cart by applying a constant force 200 N inclined at an angle 60^0 (say) with the ground causing a displacement 10 m (say) of the point of application of force as shown in the diagram. Calculate the work done.

SOLUTION



W = $10m \times 200N cos 60^0$

$= 2000 \ \frac{1}{2}$ Nm

=1000 Nm

= 1000 J

Fcos 60^0 is the component of the force along the positive x direction, the displacement is also in the same direction, so the work done is **positive**

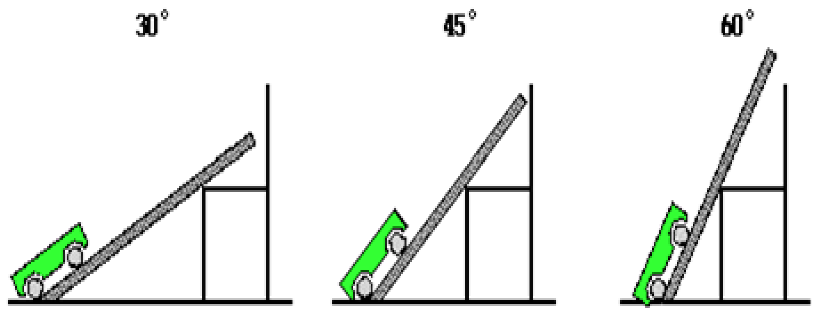
EXAMPLE:

A box sliding down due to its weight along an incline .The force along the incline is mg sin θ and the displacement is the length of the slide S if it slides down from the top. Identify the force that is sliding the box.

Angle, ϴ between force and displacement is zero

But can you explain why we have taken sin θ

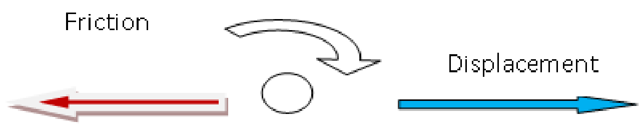
So $W = mg \sin\theta . S$



In the three cases, if the car has to climb the incline, work would be different because the angle of incline with the horizontal is different. **In all the above cases, work done is positive.**

EXAMPLE:

Show that work done by friction force on the ball is negative.



SOLUTION

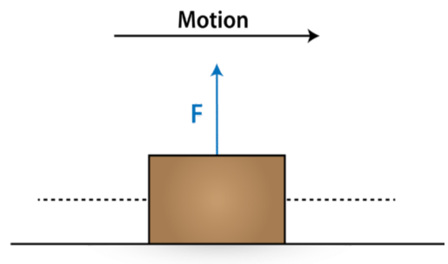
When a block is moved up by a person against the force of gravity, work done by the applied force is negative work.
When an object is moved over a rough surface, the force of friction acts along the direction opposite to its direction of motion. Hence work done by the force of friction is negative.

EXAMPLE:

No work is done if Force causes no displacement.

Or

Force and displacement are perpendicular to each other.



Let us calculate the amount of work done in carrying a briefcase on a straight office corridor

$W = F\,S\cos 90^0$

W = 0

Why is work equal to zero?

Consider work done by man against gravity to lift his bag

But when the office-goer starts to climb stairs the work is being done because the man now is raising the (displacing the bag) against gravity.

EXAMPLE:

When a stone, tied to one end of a string, is whirled in a horizontal circle, the centripetal force acts towards the centre along the radius and the displacement is along the tangent. Hence, θ = 90° and work done is zero.

COMMON MISCONCEPTION:

‘Work done by the force of friction is always negative’.

The work done by the force of friction can however be zero, positive or negative depending on the situation.

Case 1: If a force, F = 10 N, is applied to move a block of 20 kg on a horizontal surface with coefficient of friction = 0.2, the force of friction f = 0.2 x 200 = 40 N.
Hence, in this case, there would be no displacement of the object and thus work done by the force of friction is zero.

Case 2: If the applied force is large enough (say 50 N) to overcome the frictional force, the object will move but the work done by the force of friction would be negative.

Case 3: If a block A is placed on a block B, and block A is pulled with a force F, the frictional force does a negative work on block A but a positive work on block B.

CHECK YOUR UNDERSTANDING:

1. **A coolie carries a bag on his head and moves 2 km. He then puts the bag on the ground and drags it through 0.5 km. In which case does he do more work and why?**

2. **Does the work done, by a given force, depend on its velocity or on its acceleration?**

3. **A block is first pulled and then pushed down on an inclined plane through the same distance. How do the work done, by the force of friction in the two cases, compare?**

4. **Two persons are travelling in two separate lifts. One of the lifts is going up while the other is coming down with the same acceleration. Both persons lift a mass of m kg from the surface of lift to a height h. Which person does more work?**

5. **A ball is tied to a string and whirled in a horizontal circle. Find the work done by the tension in the string on the rotating ball.**

6. **The electrons in an atom orbit around its nucleus, in a way somewhat similar to the way the planets orbit around the Sun. What can we say about the work done by the force due to the:**
   - ***(i)*** **Nucleus on the electrons?**
   - ***(ii)*** **Sun on the planets?**

7. **For each situation given below:**

- **Is some work getting done in this situation?**
- **If no, why?**
- **If yes, what is the nature and magnitude of this work?**

(*i*) A boy holding a bundle of books.
(*ii*) A person, with a briefcase, moving up a staircase.
(*iii*) A wooden block dragged up an inclined plane
(*iv*) A child running while holding a bag in his hands.
(*v*) A man whirling a stone tied to a string in a circle.
(*vi*) A juggler playing with balls

you can think of more examples.

SOMETHING TO THINK ABOUT:

We are calculating work done by a constant force.

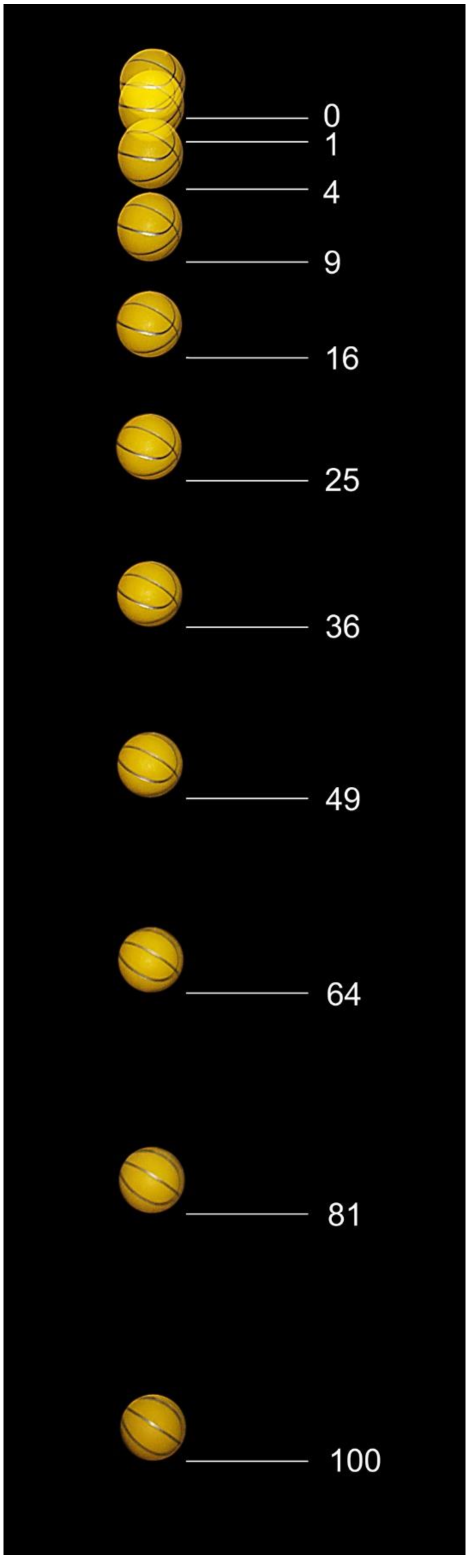
Constant force produces constant acceleration, so the displacement about every second is different given by ,$\mathbf{s = ut + \frac{1}{2}at^2}$.

So work done is calculated in all the above cases after a certain time elapsed for the net displacement, ignoring the fact that the work done per second is different.

A good example to imagine this better is to consider the work done by gravitational force on a falling body. force is constant , acceleration is constant but distance travelled per second is different.

See the picture of a ball falling under constant force, hence with constant acceleration

$$\mathbf{s \propto t^2}$$



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8. CALCULATION OF WORK DONE USING GRAPH

We can even use graphs to calculate work done by:

a) Constant force

b) Variable force: (i) constantly increasing force

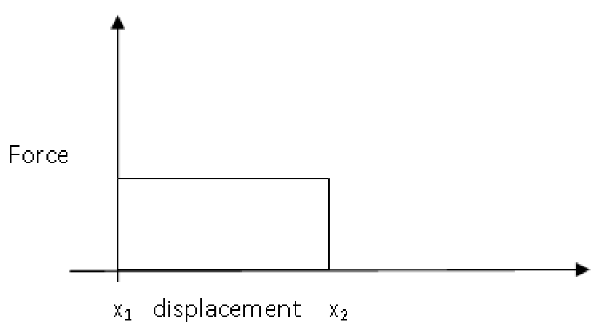
(ii) Randomly variable force

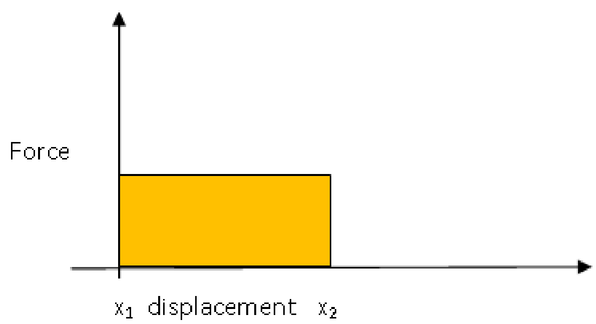
Such graphs are useful if we plot **force versus displacement.**

(a) Constant force:

The work done by a force can also be calculated by finding the area under the force – displacement graph. For a constant force, acting along the *x*-axis (say), this graph would be a straight line parallel to the *x*-axis and the area under this graph gives the work done by such a (constant) force.

Let us consider a force which always acts along the *x*-axis but whose magnitude keeps on varying. To find the work done by this force, in moving an object from x_1 to x_2 (say).



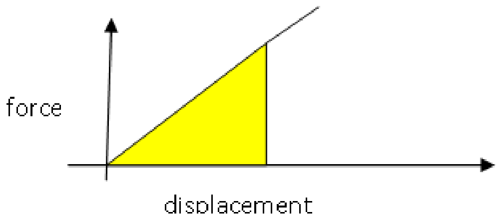


Work done = F(x_2-x_1) = which is area of the coloured rectangle or area under the curve.

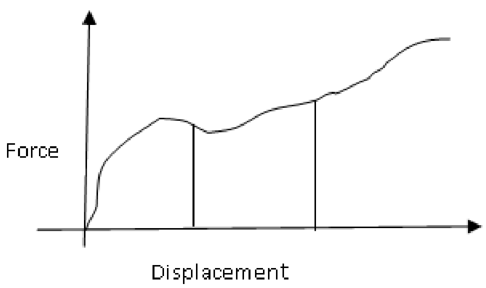
(b) Variable force

Work done by a variable force that is **constantly increasing-variable force**

Area under the graph between constant force and the displacement gives the work done by the force.

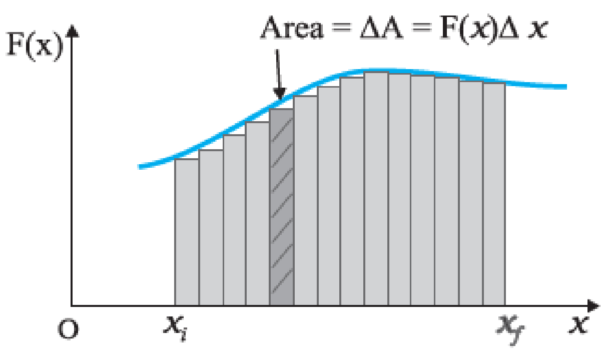


Work done by a variable force that is **constantly changing or randomly variable force.**



9. CALCULATION OF WORK DONE USING INTEGRATION

Alternately we can use integration for calculations of work done by a variable force.
A constant force is not commonly encountered in everyday life. It is the variable force, which is more commonly encountered.



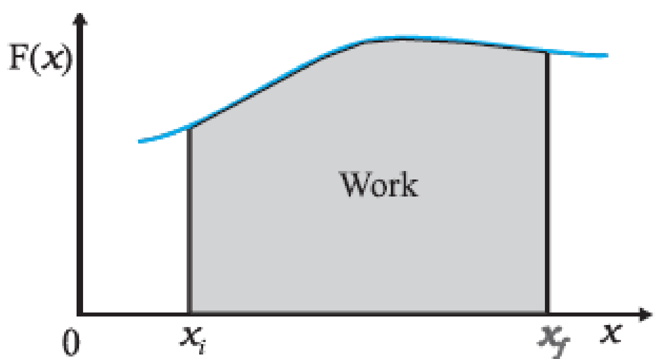
(a)

The given graph:

(a) It is a plot of a varying force F(x) versus displacement(x) in one dimension.

The shaded rectangle represents the work done by the varying force F(x), over the small displacement Δx, ΔW = F(x) Δx.

(b) Adding the areas of all the rectangles, we find that for Δx →0, the area under the curve (b) is exactly equal to the work done by F(x).



(b)

Integration helps us calculate work easily in this case.

If the displacement Δx is small, we can take the force F(x) as approximately constant and the work done is then:

ΔW =F(x) Δx

Adding successive rectangular areas, we get the total work done as:

$$\mathbf{W \cong \sum_{x_i}^{x_f} F(x)\Delta x = \int_{x_i}^{x_f} F(x)dx}$$

This integration is for function F(x) which is varying with distance (x). So, limits are from x_i to x_f ,and the displacements are allowed to approach zero, then the number of terms in the sum increases without limit, but the sum approaches a definite value equal to the area under the curve. Thus, for a varying force the work done can be expressed as a definite integral of force over displacement (x), having limits from $x = x_i$ and $x = x_f$.

10. NUMERICAL PROBLEMS

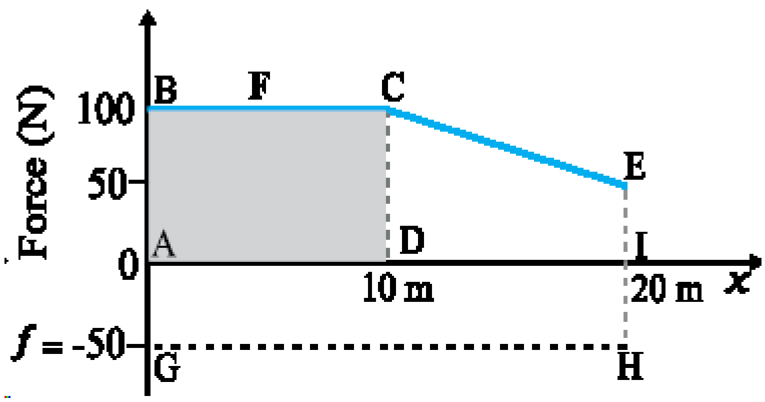
EXAMPLE:

A woman pushes a trunk on a railway platform which is a rough surface. She applies a force of 100 N over a distance of 10 m. Thereafter she gets tired and her applied force reduces linearly with distance to 50 N. The total distance by which the trunk has been moved is 20 m.

Plot a force applied by the woman and the frictional force, which is 50N.

Calculate the work done by the two forces over 20 m.

SOLUTION



The plot of the applied force versus displacement is shown in above Fig. At x = 20 m, F = 50 N (≠ 0).

We are given that the frictional force f is |f|= 50 N.

It opposes motion and acts in a direction opposite to F. It is therefore, shown on the negative side of the force axis.

The work done by the woman is:

W = Area of the rectangle ABCD + Area of the trapezium CEID

$= AB \times AD + \frac{1}{2} \times (CD + EI) \times DI$

$= 100 \times 10 + \frac{1}{2}(100 + 50) \times 10$

= (1000 + 750) J

= 1750 J

The work done by the frictional force is:

W_f = area of the rectangle AGHI

$W_f = (-50) \times 20$

= − 1000 J

The area on the negative side of the force axis has a negative sign.

EXAMPLE:

A cyclist comes to a skidding stop in 10 m. During this process the force on the cycle due to the road is 200N and is directly opposed to the motion.

a) How much work does the road do on the cycle?

b) How much work does the cycle do on the road?

SOLUTION

Work done on the cycle by the road is the work done by the stopping (frictional) force on the cycle due to the road.

(a) The stopping force and the displacement make an angle of 180° (or π rad) with each other. Thus, work done by the road,

$W_r = FS \cos\theta$

$= 200 \times 10 \times \cos \pi$

= – 2000 J

It is this negative work that brings the cycle to a halt.

(b) From Newton's Third Law an equal and opposite force acts on the road due to the cycle. Its magnitude is 200 N.

However, the road undergoes no displacement. Thus, **work done by cycle on the road is zero.**

Important to note:

Though the force on a body 'A' exerted by the body 'B' is always equal and opposite to that on 'B' by 'A' (Newton's Third Law); the work done on 'A' by 'B' is not necessarily equal and opposite to the work done on 'B' by 'A'.

11. SUMMARY

This module serves as an introduction to the concept of 'work' as we refer to in physics. We have seen that:

- The concept of work is very important in physics.
- Work is said to be done when an external force on a body causes a displacement.
- It is calculated by taking the product of component of the force in the direction of the displacement and the magnitude of the displacement.

  W= F.S or FS cosθ, Where F is the force that causes a displacement S, θ is the angle between F and S and F and S are vectors but W is a scalar.
- Work is a scalar quantity and its unit is Joule.
- W can be positive, negative or zero.
- Force can be constant or variable.
- We can use graphs to calculate work done which is the area under the F-S graph.
- Integration helps us when the force is variable over the displacement.