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 6, Collision Chapter 6, Work, Energy and Power
Module Id	Keph_10606_eContent
Pre-requisites	Kinematics, laws of motion, basic vector algebra, work energy theorem, conservative and non-conservative forces, conservation of linear momentum
Objectives	After going through this module, the learners will be able to : • Understand Collisions • Distinguish between Elastic and inelastic collision • Follow Conservation of momentum during collision • Conceptualize Collision in one dimension • Predict velocities after collision • Solve Numerical examples
Keywords	Collision, elastic collision. collision in one dimension, inelastic collision, coefficient of restitution

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 and 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	• 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 6

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.,

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

- Conservative force: A force is said to be conservative if the work done by the force in displacing a body from one point to another is independent of the path followed by the particle and depends on the end points. Example: gravitational force.
- Non- conservative forces: If the amount of work done in moving an object against a force from one point to another depends on the path along which the body moves, then such a force is called a non-conservative force. Example: friction.

- Conservation of mechanical energy: Mechanical energy is conserved if work done is by conservative forces.
- Potential energy due to position: Work done in raising the object of mass m to a particular height (distance less than radius of the earth) = m g h.

4. INTRODUCTION

In our previous moduless on this unit of work energy and power ,we have been considering following points:

- Mechanical Work = force x displacement
- Calculation of work using equation and graph.
- Power as rate of doing work.
- Energy as ability of a body to do work.
- The two forms of mechanical energy.
- Kinetic energy- which the body possesses due to motion.
- Potential Energy- which a body possesses due to position of a body placed at a height with respect to another, or change in configuration as in the case of a spring.
- Work-Energy Theorem., a relation between work and change in mechanical energy
- Problems using work-energy relation.
- A special study of springs highlighting their importance in our daily lives.

In this module we will study collision and apply ideas of conservation of momentum and energy to understand collisions in one dimension.

5. COLLISIONS

A number of examples can be quoted for 'collisions' taking place from our day to day experiences. We relate an accident on the road as collision, a train accident and many such incidents. But collision has a larger scope.

A number of games, such as billiards, marbles games, tennis, cricket, carom etc., involve collisions. A hammer hitting a nail, a box falling off a truck, a boy jumping from a desk on a classroom floor, a mango falling from a tree and striking the ground below are some other examples of collisions from our daily life.


https://www.google.com/search?site=imghp&tbm=isch&q=collision&tbs=sur:fmc#imgrc=8zVDk_NEOYp7aM

https://www.google.com/search?site=imghp&tbm=isch&q=hammer%20nail%20in%20wood&tbs=sur:fmc#imgrc=Ggl_sP_AKsqxsM

All of these involve physical contact of one body with the other.

In physics, however, even one body affects the motion of the other without being in physical contact with it, the two bodies can still be regarded as having 'collided' with each other.

In physics we study motion, change of motion, and change in configuration of a body. At the same time we try to discover physical quantities, which do not change in a physical process. The laws of momentum and energy conservation are good examples .we are going to use these to understand collision.

How do we define collision in physics?

We can say: **A collision is a short time event in which two or more bodies interact with each other and thereby affect each other's subsequent motion.**

We shall study the collision of two masses in an idealized condition.

So, for simplicity, we take two spherical rigid balls as two interacting bodies, we take them as smooth and polished.

(**Spherical bodies are selected to help imagine interaction between objects to be at a point)**

6. ELASTIC AND INELASTIC COLLISIONS

In an isolated system whenever bodies interact the linear momentum of bodies is conserved, which means that the sum total of linear momentum before interaction is equal to total momentum after interaction.

Imagine a ball is dropped from a certain height and it rebounds to the same height, this would mean, there is no loss of kinetic energy of the ball in the form of heat, or sound, on striking the ground. Such interactions or collisions, in which the kinetic energy is also conserved, along with linear momentum, and total energy, are called **perfectly elastic collisions**. No large scale impacts are perfectly elastic.

When some part of the (initial) kinetic energy is lost in the form of heat, or sound or some other form of energy, momentum and total energy are conserved but kinetic energy is not conserved. Such collisions are called **inelastic collisions**.

Consider now the case of a bullet moving with a certain velocity. It hits a wooden block lying on a table and gets embedded in it. The block, with the embedded bullet, moves ahead with a certain velocity. This is an example of a **perfectly inelastic collision** in which the two colliding objects stick together after collision.

So , we have three situations

- **perfectly elastic collisions**
- **inelastic collisions**
- **perfectly inelastic collision**

7. CONSERVATION OF LINEAR MOMENTUM

In all collisions, the total linear momentum is conserved.

The initial momentum of the system is equal to the final momentum of the system.

We can argue this as follows.

When two objects collide, the mutual impulsive forces acting during the collision time Δt cause a change in their respective linear momenta

$\Delta p_1 = F_{12}\,\Delta t$

$\Delta p_2 = F_{21}\,\Delta t$

Where F_{12} is the force exerted on the first object by the second and F_{21} is the force on the second object by the first

From **Newton's third law:**

$F_{12} = -F_{21}$

This means $\Delta p_1 = -\Delta p_2$

Or $\Delta p_1 + \Delta p_2 = 0$

The above conclusion is true even though the forces vary in complex ways during the short collision time Δt .also because the third law is true at every instant, the total impulse on the first object is equal and opposite to that on the second.

On the other hand, the total kinetic energy of the system is not necessarily conserved.

The impact and deformation during collision may generate heat and sound, thus part of the initial kinetic energy is transformed into other forms of energy.

A useful way to visualise the deformation during collision is in terms of a 'compressed spring'. If the 'spring' connecting the two masses regains its original shape without loss in energy, then the initial kinetic energy is equal to the final kinetic energy but the kinetic energy during the collision time Δt is not constant.

The total linear momentum of the two objects is constant although a collision had occurred.

$$\textbf{linear momentum before collision } (\mathbf{m_1u_1 + m_2u_2})$$

$$= \boldsymbol{linear\ momentum\ after\ collision}\ (\boldsymbol{m_1v_1 + m_2v_2})$$

In collisions we are saying, the total linear momentum is always conserved. But why can we not say the same about energy? What happens to the energy?

Sometimes we hear a sound, or may see light as in the case of a match stick on striking the match box.

https://pxhere.com/id/photo/676372

So the energy can get transformed into any other forms and hence need not be conserved.

In a collision the total kinetic energy may or may not be conserved.

So now, we will distinguish between elastic and inelastic collisions.

IN AN ELASTIC COLLISION:

1. **Linear momentum of bodies before collision is equal to linear momentum of bodies after collision or linear momentum is conserved**

2. Kinetic energy of the bodies before collision is equal to kinetic energies of the interacting bodies after collision or **kinetic energy is also conserved**

So, if on the other hand the deformation may not be relieved and the two bodies could move together after the collision. A collision in which the two particles move together after the collision is called a completely inelastic collision.

The intermediate case where the deformation is partly relieved and some of the initial kinetic energy is lost is more common and is appropriately called an inelastic collision.

So, **IN AN INELASTIC COLLISION:**

1. **Linear momentum of bodies before collision is equal to momentum of bodies after collision or linear momentum is conserved**

2. Kinetic energy of the bodies before collision is not equal to kinetic energies of the interacting bodies after collision or kinetic energy is not conserved

EXAMPLE

Let us consider a person of mass 50 kg who is jumping from a height of 5 m , he will land on the ground with a velocity of $\sqrt{2gh} = \sqrt{2 \times 10 \times 5} = 10 \ ms^{-1}$ (assuming g =10m/s^2)

Now if he does not bend his knees he will come to rest very quickly say in 1/10 s.

The force can be determined from Newton's second law which states that the rate of change of momentum is proportional to the force applied

$$F = \frac{momentum\ change}{time} = \frac{50 \times 10}{1/10} = 5000N \sim 500kgf$$

This force is about 10 times the body weight of the person so he will get badly hurt.

But, if he bends his knees and increases the time of landing to say 1 s, then the force will be 10 times less than before.

What does this example tell us?

The impulse given to a body equals to change in its linear momentum.

For simplicity, we will limit our study only to elastic collision.

8. ELASTIC COLLISION IN ONE DIMENSION

Meaning considering collision between objects moving along a straight path so the path is along a straight line before and after collision

Do you think collision of carom coins will be collision in one dimension, also can we consider the carom coin collision in one dimension under any restricted condition?

Consider two bodies of masses m_1 and m_2 moving along a straight line path in the same direction with velocities u_1 and u_2 respectively.

The bodies collide elastically, and after collision let them start moving with velocities v_1 and v_2 along the same straight line.

REMEMBER

- **We are considering two body collision**
- **The two bodies move along a straight line path so it is called 'collision in one dimension'.**
- **Collision is elastic collision**
- **We refer 'before collision' and 'after collision' to state the condition of velocities, momentum, kinetic energies before and after collision.**

- **Linear momentum is conserved**
- **Kinetic energy is conserved**

Let us consider the total momentum of the colliding bodies before and after the collision. Since the collision is elastic the two should be equal so we can write

$$\boldsymbol{m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2} \quad ..... \quad (1)$$

Because the collision is elastic the kinetic energy will also be conserved so

$$\boldsymbol{\frac{1}{2}m_1u_1^2 + \frac{1}{2}m_2u_2^2 = \frac{1}{2}m_1v_1^2 + \frac{1}{2}m_2v_2^2} \dots \dots (2)$$

From equation (1) we get

$$m_1(u_1 - v_1) = m_2(v_2 - u_2) \quad \dots \dots \dots \dots .... \; (3)$$

And from equation (2) we get

$$m_1(u_1^2 - v_1^2) = m_2(v_2^2 - u_2^2) \; .... \; (4)$$

Dividing equation (4) by (3) we get

$$\boldsymbol{u_1 + v_1 = v_2 + u_2}$$

Or

$$\boldsymbol{u_1 - u_2 = v_2 - v_1 \dots} .... \; (5)$$

or

$$\boldsymbol{u_1 - u_2 = -(v_1 - v_2)} \quad .... \; (6)$$

Equation (6) means:

Relative Velocity before collision is equal and opposite to the relative velocity of colliding particles/bodies after collision.

9. PREDICTING VELOCITIES AFTER COLLISION

It is interesting, to work out mathematically, from the above equations velocity of objects after collision

Using equation (6) and substituting the value of v_2 in equation (3)

We get

$$v_1(m_1 + m_2) = u_1(m_1 - m_2) + 2m_1m_2$$

Which in turn gives the value of

$$v_1 = u_1\frac{(m_1-m_2)}{(m_1+m_2)} + 2\frac{m_2}{(m_1+m_2)}u_2 \quad \text{.............. (7)}$$

So we have the value of v_1 in terms of u_1, u_2 m_1 and m_2

In the same way using equation (6) we get

$$v_2 = 2\frac{m_1}{(m_1+m_2)}u_1 - u_2\frac{(m_1-m_2)}{(m_1+m_2)} \quad \text{.................. (8)}$$

Thus knowing the initial velocities of the colliding bodies we can find out the final velocities after collision.

Interesting!

Special cases:

We will consider some examples of elastic collisions under restricted conditions

Case 1:

The two colliding spherical objects are of the same mass and are same in diameter

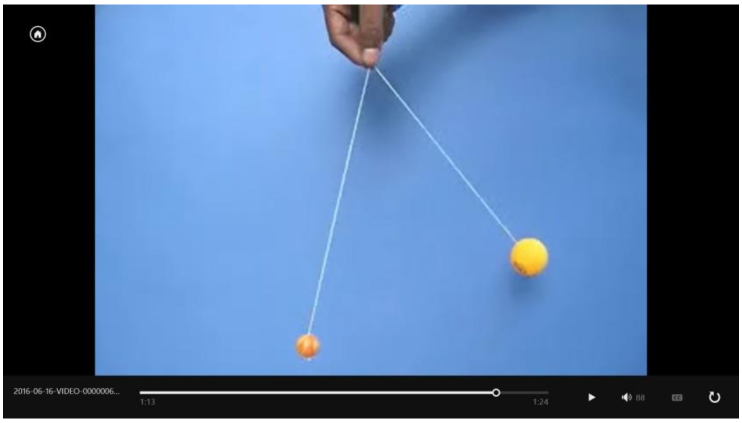
$$m_1 = m_2 = m$$

$$v_1 = u_2 \text{ and } v_2 = u_1$$

Thus in head-on collision between two spherical identical balls, the two balls exchange their velocities after collision

That is, if one of them was stationary before collision, then the first becomes stationary after collision and the second moves with the velocity of the first

You might have seen an interesting toy

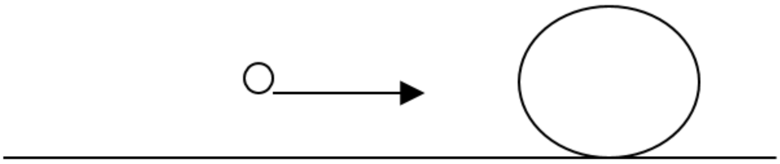


Arvind Gupta bouncy balls NROER

https://www.youtube.com/watch?v=BEJNe6a7IqY

Case 2:

If the mass of the second is larger than the first, and the second is stationary before collision



The diagram appears in correct, because if you imagine it in a vertical plane the small ball cannot hold itself in mid-air, but in a horizontal plane say on a polished floor, or smooth table top it will be able to show the condition of mass difference between two interacting balls

$$m_2 > m_1 \ \ and \ \ u_2 = 0$$

$$v_1 = -u_1 \ \ and \ v_2 = 0$$

When a light particle with a very massive particle at rest, the velocity of the light particle is reversed.

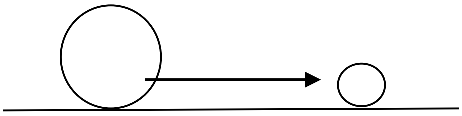
This is like a ball collides with a smooth floor, it will rebound with a reversed velocity to almost the same height through which it fell, while the floor remains at rest.

The picture here is only to assist us to imagine the height to which a bounced ball rises up to, because in one dimension the ball should retrace its path

Case 3:

If the mass of the colliding particle is very large compared to a stationary particle

$m_1 \gg m_2$ and $u_2 = 0$

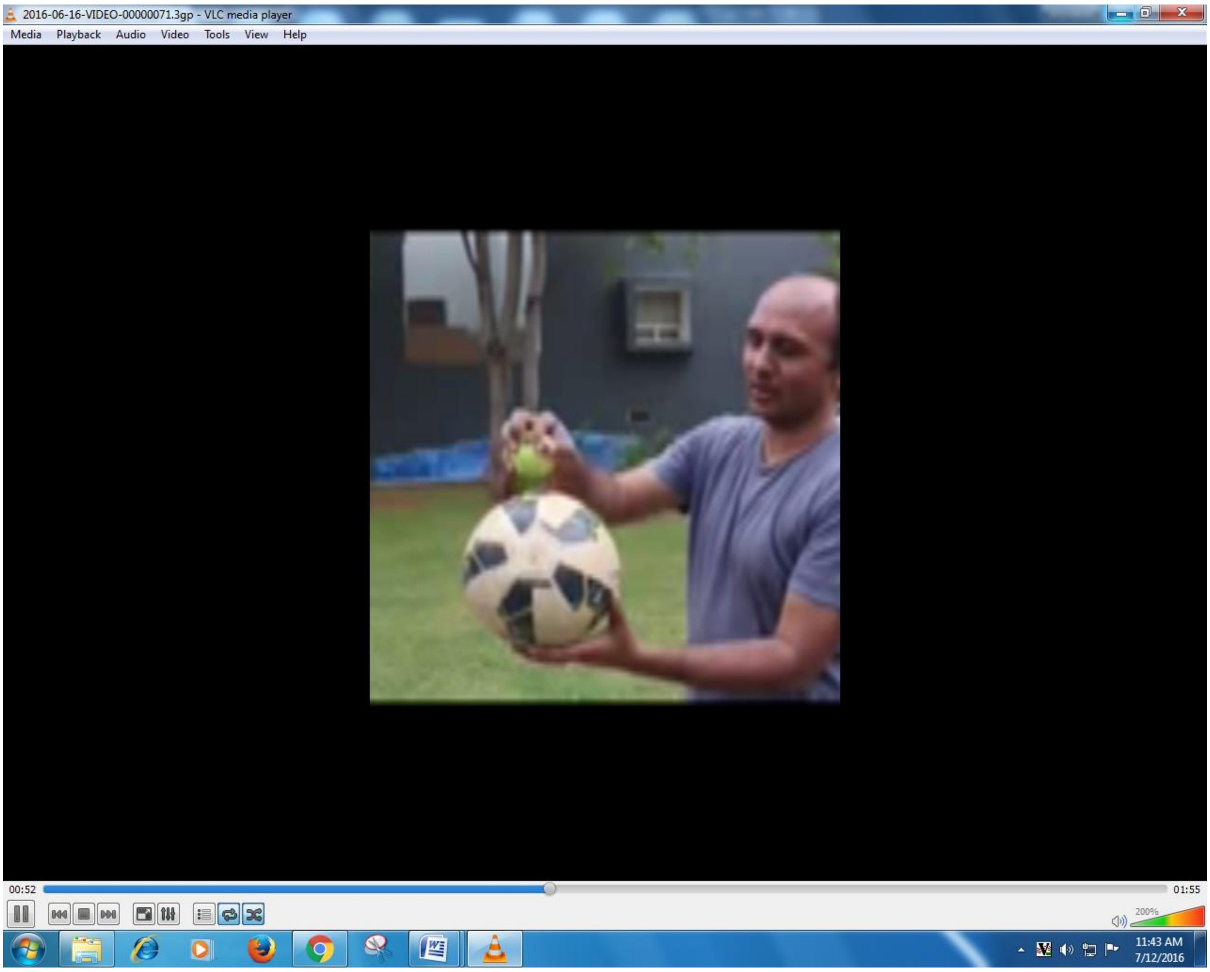


$$v_2 = 2u_1 \text{ and } v_1 = u_1$$

This means that the velocity of the heavier colliding particle is virtually unchanged, while that for the lighter stationary one rebounds with velocity twice as much as the incident particle velocity.

- **We have seen how the effects of collision depend on the relative masses of the colliding particles**
- **Also the energy transfer is maximum if the particles have same masses.**

An interesting activity, as in NCERT book



Super Bouncy Ball | English | Conservation of Momentum

Watch Video by Arvind Gupta

An experiment on head-on collision.

In performing an experiment on head collision on a horizontal surface, we face three difficulties.

1. **There will be friction and bodies will not travel with uniform velocities.**

2. If two bodies of different sizes collide on a table, it would be difficult to arrange them for a head-on collision unless their centres of mass are at the same height above the surface.

3. It will be fairly difficult to measure velocities of the two bodies just before and just after collision.

By performing this experiment in a vertical direction, all the three difficulties vanish.

Take two balls, one of which is heavier (basketball/football/volleyball) and the other lighter (tennis ball/rubber ball/table tennis ball).

First take only the heavier ball and drop it vertically from some height, say 1 m.

Note the height to which it rises.

This gives the velocities near the floor or ground, just before and just after the bounce

(by using $v^2 = 2gh$).

Hence you will get the coefficient of restitution.

Now take the big ball and a small ball and hold them in your hands one over the other, with the heavier ball below the lighter one, as shown here. Drop them together, taking care that they remain together while falling, and see what happens.

You will find that the heavier ball rises less than when it was dropped alone, while the lighter one shoots up to about 3 m. With practice, you will be able to hold the ball properly so that the lighter ball rises vertically up and does not fly sideways. This is head-on collision. You can try to find the best combination of balls which gives you the best effect. You can measure the masses on a standard balance. We leave it to you to think how you can determine the initial and final velocities of the balls.

Watch another interesting video

What happens when you drop a perfectly balanced stack of balls? The classic momentum transfer demonstration, taken to the next level.

https://www.youtube.com/watch?v=2UHS883_P60

EXAMPLE

A spherical body of mass 0.01kg having an initial velocity of 5 m/s suffers elastic collision with another spherical body of mass 0.03 kg moving with a velocity of 5 m/s in the opposite direction .What is the final velocity of each after collision?

SOLUTION

In case of elastic collision

Momentum before = 0.01 x 5 - 0.03 x 5

And

Momentum after collision = 0.01 x v_1 + 0.03 x v_2

We now equate momentum before collision to momentum after collision and solve for v_1 and v_2

v_1 = - 10 m/s

v_2 = 0 or the second comes to rest

What if the collision is not elastic?

If the collision is not perfectly elastic, the relative velocity after collision will be reduced by a fraction as compared to relative velocity of approach. This we describe in terms of coefficient of restitution which is denoted by ‘e’.

10. COEFFICIENT OF RESTITUTION

$$\textbf{Coefficient of restitution} = e = \frac{\text{relative velocity of separation after collision}}{\text{relative velocity of appraoch before collision}}$$

$$e = \frac{v_2 - v_1}{u_1 - u_2}$$

- **For perfectly elastic collision, e = 1.**
- **For perfectly inelastic collision, its value is 0.**
- **But for all other collisions e lies between 0 and 1.**

EXAMPLE

When a ball is dropped on a horizontal surface from a height h, the height of rebound is $h' = e^2 h$, verify.

SOLUTION

You can easily verify this $u_2 = v_2 = 0$,

$u_1 = -\sqrt{2gh}$

and

$v_1 = \sqrt{2gh'}$

We have considered upward direction as positive

$$e = \frac{v_2 - v_1}{u_1 - u_2}$$

$$e = \sqrt{\frac{h'}{h}}$$

Thus,

If the ball is dropped from a height of 100 cm to the floor it rebounds to a height of 60 cm

The coefficient of restitution must be $\sqrt{\frac{h'}{h}} = \sqrt{0.6} = 0.77$

We have seen how the effects of collision depend upon the relative masses of the colliding objects

EXAMPLE

A raw mango and a ripe one fall from a tree. Think what would be the difference between the collisions when they strike the ground?

SOLUTION

The raw mango will split as the impulse would be high while the ripe mango will get a depression only as the impulse will not be high

What about other fruits say jamun, coconut etc?

EXAMPLE

Is there a relation between transfer of kinetic energy when the colliding objects are of the same mass?

SOLUTION

Let us consider a stationary object struck by a steadily moving one

So we find the ratio between KE of second object after collision and KE of first object before collision

$$\frac{\text{KE of second object after collision}}{\text{KE of first object before collision}} = \frac{\frac{1}{2}m_2v_2^2}{\frac{1}{2}m_1u_1^2}$$

$$= \frac{4m_1m_2}{(m_1+m_2)2} = \frac{4\left(\frac{m_1}{m_2}\right)}{\left(1+\frac{m_1}{m_2}\right)^2}$$

This will be maximum only if the two masses are equal

11. INELASTIC COLLISIONS IN ONE DIMENSION

Consider two bodies of masses m_1 and m_2, moving along a straight line path in the same direction, with velocities u_1 and u_2 respectively.

The two bodies undergo a head–on inelastic collision.

In such a case,

1. Linear momentum will remain conserved.

2. Some part of the initial kinetic energy will be lost.

EXAMPLE

A wooden block, of mass M, freely suspended from a string, is initially at rest. It gets stuck by a dart of mass m, moving horizontally with a speed v. The dart gets stuck into the block and the combination moves with a speed V after this 'collision'. Calculate the fractional loss in K.E. in this 'collision'.

SOLUTION

Initial momentum = mv

Final momentum = (M + m) V

Initial KE $=\frac{1}{2}mv^2$

Final KE $=\frac{1}{2}(m+M)V^2$

Fractional loss $=\frac{\text{loss in KE}}{\text{initial KE}}$

https://www.youtube.com/watch?v=QJtyCp7dbdo

The video suggests simple methods of problem solving in case of in elastic collision.

12. SUMMARY

In this module we have:

- Understood the meaning of collision.
- Understood that momentum and impulse are vectors.
- Understood the reason for linear momentum conservation in collisions
- Understood the meaning of elastic and inelastic collisions.
- Considered a limiting case of perfectly elastic collision for simplicity of understanding.
- Worked out mathematically the velocities of colliding objects after collision in terms of the velocities before collision.
- Learnt to apply the equations to simple numerical problems.
- Understood that kinetic energy is not conserved in inelastic collision.