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 3, Module 3, Third law of Motion Chapter 5, Laws of motion
Module Id	Keph_10503_eContent
Pre-requisites	Kinematics vector algebra, first and second law of motion, impulse, momentum
Objectives	After going through this lesson, the learners will be able to • Understand Third law of motion and its applications • Relate to misconceptions in use of third law • Apply conservation of momentum to real life problems
Keywords	Momentum, conservation of momentum, Third law of motion, action reaction pair.

2. Development Team

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1. UNIT SYLLABUS

Chapter 5: Laws of Motion

Intuitive concept of force; Inertia; Newton's first law of motion; momentum and Newton's second law of motion; Impulse; Newton's third law of motion.

Law of conservation of linear momentum and its applications.

Equilibrium of concurrent forces, Static and kinetic friction, laws of friction, rolling friction, lubrication.

Dynamics of uniform circular motion: Centripetal force, examples of circular motion (vehicle on a level circular road, vehicle on banked road).

2. MODULE-WISE DISTRIBUTION OF UNIT SYLLABUS 7 Modules

The above unit is divided into seven modules as follows:

Module 1	• Force • inertia • First law of motion
Module 2	• Momentum • Second law • Impulse • F=ma • Constant and variable force
Module 3	• Third law • Conservation of linear momentum and its applications
Module 4	• Types of forces (tension, normal, weight, …) • Equilibrium of concurrent forces • FBD
Module 5	• Friction • Coefficient of friction • Static friction • Kinetic friction • Rolling friction • Role of friction in daily life
Module 6	• Dynamics of circular motion • Centripetal force • Banking of roads
Module 7	• Using laws of motion to solve problems in daily life

MODULE 3

3. WORDS YOU MUST KNOW

- Rest: A body is said to be at rest if it does not change its position with time with respect to its surroundings.

- Motion: A body is said to be in motion if it changes its position with time with respect to its surroundings.

- Velocity: The time rate of change of displacement is called velocity.

- Acceleration: Time rate of change of velocity of a particle, equals its acceleration.

- Force: A body will continue in its state of rest, or uniform motion until and unless it is acted upon by an external unbalanced force.
- Inertia: An inherent property of all objects; an object continues in its state of rest or uniform motion unless and until a non-zero external force acts on it.

- Vector: A physical quantity that needs both a magnitude and a direction for its specification.

- Vector Algebra: The branch of mathematics that deals with computations involving addition, subtraction, and multiplication of vectors.

- Uniform motion: When a particle has equal displacements, in equal intervals of time, (howsoever small this time interval may be) it is said to have a uniform motion. The acceleration for a particle in uniform motion would be zero.

- Non-uniform motion: When a particle has unequal displacements, in equal intervals of time, (howsoever small this time interval may be) it is said to have a non-uniform motion. The acceleration for a particle in such motion may be constant or variable. Acceleration. In uniform motion is zero

- Momentum (**p**): An indicator of the impact capacity of a moving body. Given by product of mass and velocity. p= mv

  It is a vector. Its unit is kg ms^{-1}. Dimensional formula is MLT^{-1}

- Impulse: Rate of change of momentum. Impulse is the product of force and time which equals change in momentum. The notion of impulse is useful when a large force acts for a short time to produce measurable change in momentum. Since the time of action of the force is very short, one can assume that there is no appreciable change in the position of the body during the action of the impulsive force.

- Newton's first law of motion: Everybody continues to be in its state of rest or of uniform motion in a straight line, unless compelled by some external force to act otherwise". In simple terms, the First Law is "If external force on a body is zero, its acceleration is zero".

- Newton's second law of motion: The rate of change of momentum of a body is proportional to the applied force and takes place in the direction in which the force acts. Thus

$$F = k\frac{dp}{dt} = kma$$

Where F is the net external force on the body and 'a' its acceleration. We set the constant of proportionality k=1 in SI units. Then

$$F = \frac{dp}{dt} = ma$$

The SI unit of force is Newton: 1 N = 1 kg m s^{-2}.

(a) The second law is consistent with the First Law (F = 0 implies a = 0)
(b) It is a vector equation
(c) It is applicable to a particle, and also to a body or a system of particles, provided F is the total external force on the system and 'a' is the acceleration of the system as a whole.
(d) F at a point at a certain instant determines 'a' at the same point at that instant. That is the Second Law is a local law; a at an instant does not depend on the history of motion

4. INTRODUCTION

The second law relates the external force on a body to its acceleration. What is the origin of the external force on the body? What agency provides the external force? The simple answer in Newtonian mechanics is that the external force on a body always arises due to some other body.

Consider a pair of bodies A and B. Body B gives rise to an external force on body A. A natural question is: Does body A in turn give rise to an external force on body B? In some examples, the answer seems clear.

If you press a coiled spring, the spring is compressed by the force (push or pull) by your hand. The compressed spring, in turn, exerts a force on your hand and you can feel it. But what if the bodies are not in contact? The earth pulls a stone downwards due to gravity. Does the stone exert a force on the earth?

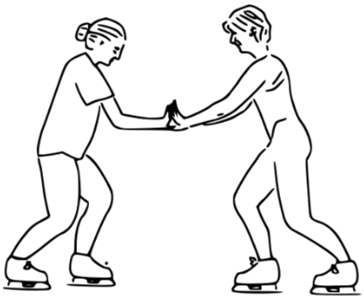
The answer is not obvious since we hardly see the effect of the stone on the earth. The answer according to Newton is:

Yes, the stone does exert an equal and opposite force on the earth. We do not notice it since the earth is very massive and the effect of a small force on its motion is negligible.

Thus, according to Newtonian mechanics, force never occurs singly in nature. Force is the mutual interaction between two bodies. Forces always occur in pairs. Further, the mutual forces between two bodies are always equal and opposite. This idea was expressed by Newton in the form of the third law of motion.

5. FORCES OCCUR IN PAIRS

We have discussed in the first module about external agency which may or may not be in contact with the body.



https://commons.wikimedia.org/wiki/File:Skaters_showing_newtons_third_law.svg

- If you press a coiled spring, the spring is compressed by the force (push or pull) by your hand. The compressed spring, in turn, exerts a force on your hand and you can feel it.

- The earth pulls a stone downwards due to gravity. Does the stone exert
a force on the earth? We hardly see the effect of the stone on the earth. The stone does exert an equal and opposite force on the earth but we do not notice it since the earth is very massive and the effect of a small force on its motion is negligible.
- From Newton's Second Law of Motion: Acceleration = $\frac{Net\ Force}{Mass}$

Thus, from both the above examples we can see that external force on a body always arises due to some other body that forces occur in pairs.

6. NEWTON'S THIRD LAW OF MOTION

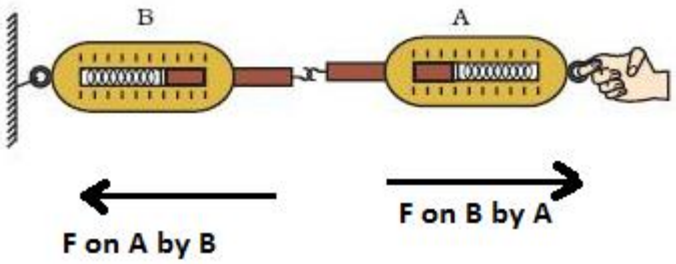
According to Newtonian mechanics, force never occurs singly in nature. Force is the mutual interaction between two bodies and thus forces always occur in pairs.

Further, the mutual forces between two bodies are always equal and opposite. This idea was expressed by Newton in the form of the third law of motion:

"To every action, there is always an equal and opposite reaction."

Some important points about third law of motion:

- Forces always occur in pairs. Force on a body A by body B is equal and opposite to the force on the body B by body A.



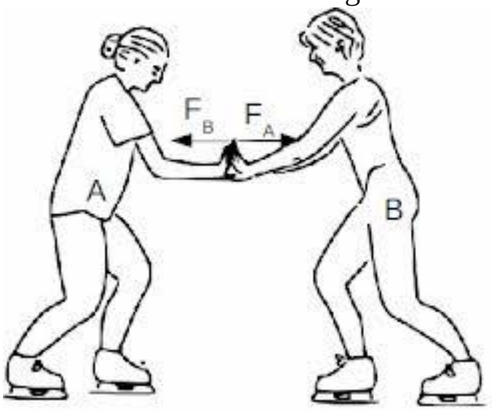
- The terms action and reaction in the third law mean 'force'.

- If we hit a wall with our hand, the hand gets hurt in turn. From a layman's perspective, we always assume that action comes before reaction i.e. action is the cause and reaction the effect.

- But there is no cause-effect relationship implied in the third law. The force on body *A* by body *B* and the force on body *B* by body *A* act at the same instant. By the same reasoning, any one of them may be called action and the other reaction.

- Action and reaction forces act on different bodies, and not on the same body. Consider a pair of bodies *A* and *B*. According to the third law, $F_{AB} = - F_{BA}$
(F on *A* by *B*) = - (F on *B* by A).

Thus if we are considering the motion of any one body (*A* or *B*), only one of the two forces is



relevant. We usually add up the two forces and claim that the net force is zero. However, if we consider the system of two bodies as a whole, F_{AB} and F_{BA} are internal forces of the system (*A* + *B*). They add up to give a zero net force.

We have discussed external force in Module-1 about external forces. Here, we will see the examples to differentiate between internal and external forces.

INTERNAL AND EXTERNAL FORCES:

External forces are caused by external agencies outside the system.

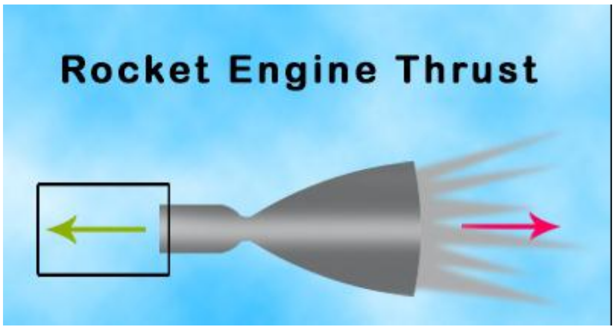
Internal forces are the forces exchanged by the objects inside the system i.e. forces that one part of the system (or an object) exerts on another part of the system (or an object).

7. ILLUSTRATIONS OF NEWTON'S THIRD LAW OF MOTION:

EXAMPLE:

When a rocket launches into outer space, it expels gas backward at a high velocity.

The rocket exerts a large backward force on the gas, and the gas exerts equal and opposite reaction force on the rocket, causing it to launch.



EXAMPLE:

When a person jumps up into the air, the person's feet exert force on the ground and the ground exerts an equal and opposite force on the person's feet.

The force on the feet is sufficient to raise the person off the ground.

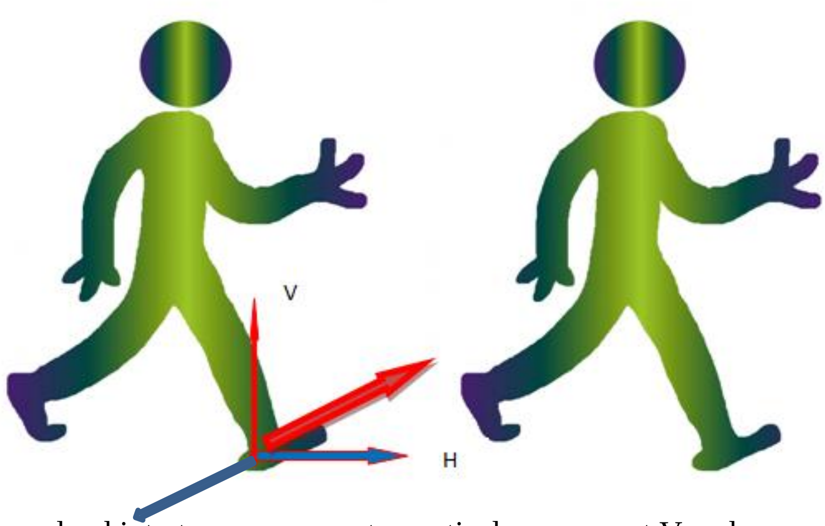
The force on the ground has little effect because the mass of the Earth is so large in comparison to the mass of the person. One of the acceleration of the person is visible but the other of Earth is not visible.

EXAMPLE:

When a person jumps out of a boat, the boat is pushed in the backward direction due to the reaction.

EXAMPLE:

When a man walks, he pushes the ground backwards with a certain force F. The ground exerts a reaction force R in the opposite direction such that R = - F

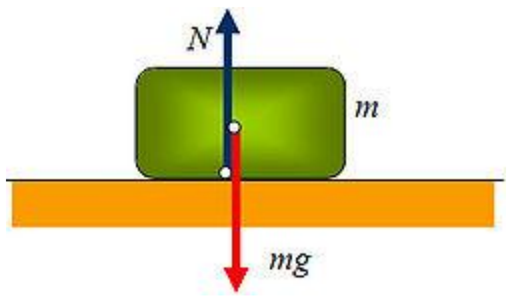


The reaction force R can be resolved into two components: vertical component V and horizontal component H.

The vertical component V supports the weight of the man while the horizontal component H helps the man to walk forward.

8. MISCONCEPTION IN APPLYING THIRD LAW OF MOTION:

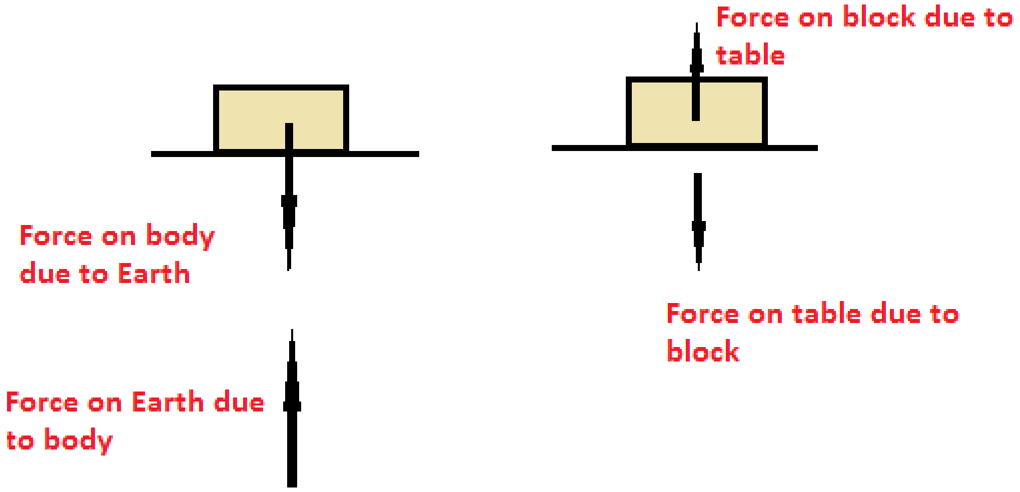
Consider a block placed on the table. The force of Earth's gravity (mg) on the block and the force of the table on the block (N) are equal and opposite. These pair of forces being equal and opposite obeys third law of motion.



But these are not third law pair of forces, because here both the forces are acting on the same object (block). Whereas, according to third law, pair of forces must be exerted on two different blocks.

The correct pairs of third law forces are:

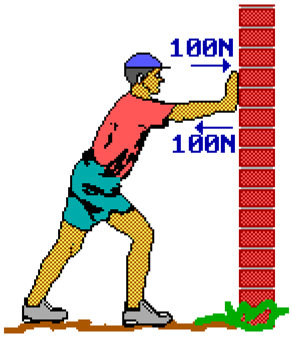
- Earth's gravity on the block and block's gravity on Earth.
- Block pushing the table down and table exerting pushing force on the block in the opposite direction.



Therefore, third law pair of forces must obey the following rules:

- ❖ The force pairs must be of the same type of force.
- ❖ The force pairs should be exerted on two different objects.
- ❖ The force pairs must be equal in magnitude and opposite in direction.

9. DESCRIBING A SYSTEM OF PARTICLES



We are again and again using the terms system and isolated system. Let's understand the meaning of two terms:

A system is a collection of two or more objects.

A system in which no net external force acts on the objects is called as an isolated system. Net external force implies the forces that originate from sources other than the objects of the system.

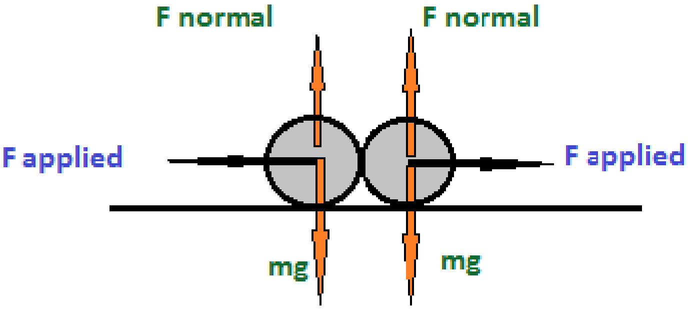
FOR EXAMPLE:

Consider the collision of billiard balls. If the frictional force is small enough to bring the change in momentum of the balls, the only forces acting upon the two balls are the contact forces they exert on one another.

These contact forces which bring the change in momentum of the balls are considered internal forces since they originate from within the system. i.e. When the cue hits a ball, the momentum from the first ball is transferred to the second ball, sending it rolling across the table.

In the absence of friction (negligible friction) from the table, the two balls are part of an isolated system because there are no external forces at work. Such a system is called as an isolated system, and its total momentum is conserved.

Here, the vertically upward and the downward forces are balanced. The only unbalanced forces occur from within the system.

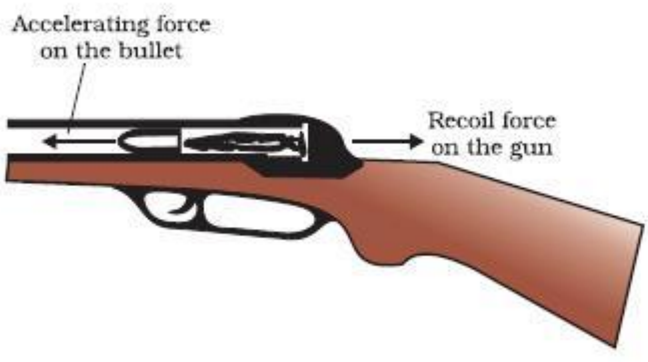


10. CONSERVATION OF LINEAR MOMENTUM AND ITS APPLICATIONS

The second and third laws of motion lead to an important consequence: the law of conservation of momentum.

FOR EXAMPLE:

A bullet is fired from a gun. If the force on the bullet by the gun is F, the force on the gun by the bullet is - F, according to the third law. The two forces act for a common interval of time Δt. According to the second law, F Δt is the change in linear momentum of the bullet



and - F Δt is the change in momentum of the gun. Since initially, both are at rest, the change in

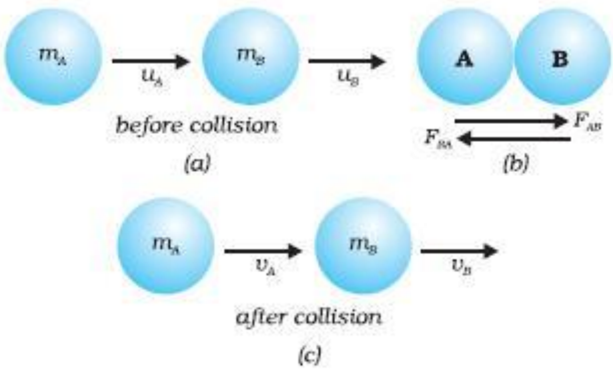
linear momentum equals the final momentum for each.

Thus, if p_b is the momentum of the bullet after firing and p_g is the recoil momentum of the gun, then $p_g = - p_b$ *i.e.* $p_b + p_g = 0$. That is, the total linear momentum of the (bullet + gun) system is conserved.

Thus, in an isolated system (i.e. a system with no external force), mutual forces between pairs of particles in the system can cause linear momentum change in individual particles, but since the mutual forces for each pair are equal and opposite, the linear momentum changes cancel in pairs and the total linear momentum remains unchanged. This fact is known as the law of conservation of linear momentum.

The total linear momentum of an isolated system of interacting particles is conserved.

PROOF OF LAW OF CONSERVATION OF LINEAR MOMENTUM USING NEWTON'S THIRD LAW OF MOTION



Consider two bodies A and B, with initial linear momenta p_A and p_B. The bodies collide; get apart, with final linear momenta p'_A and p'_B respectively.

BY THE SECOND LAW:

$F_{AB}\,\Delta t = p'_A - p_A$ and, $F_{BA}\,\Delta t = p'_B - p_B$ (where we have taken a common interval of time for both forces i.e. the time for which the two bodies are in contact.)

Since $F_{AB} = -F_{BA}$ by the third law

$$p'_A - p_A = -p'_B - p_B$$

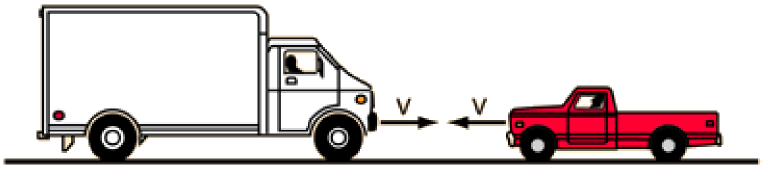
i.e. $p'_A + p'_B = p_A + p_B$

It shows that the total final momentum of the isolated system equals the total initial momentum.

HEAD –ON- COLLISION:

A head-on collision between two trucks could either be an isolated system or not, depending on the forces involved. If the head-on collision occurs between two vehicles travelling on a road that provides large amount of friction, then the trucks are not part of an isolated system because there is an external force of friction acting here.

However, if we assume friction to be negligibly small, then the colliding trucks become a part of an isolated system. This is because the forces they exert on each other cancel out as they collide, and there are no external forces involved.



Physical quantity	For big truck	For small truck
Mass	M	m
Velocity	V	V
Force	F	F
Impulse	F_1	F_1
Change in momentum	$M\Delta v$	$m\Delta V$
Acceleration	Ma	mA

- **The forces are equal in magnitude on the two trucks according to Newton's third law.**
- **Both the trucks experience equal impulse.**
- **Change in momentum of both the trucks should be the same.**
- **The smaller truck experiences greater change in velocity.**
- **The smaller truck experiences greater acceleration.**

According to you, which of the two trucks, the smaller truck or bigger truck, may get more damaged and why?

https://pixabay.com/images/search/truck/

For additional information, follow the links given below:

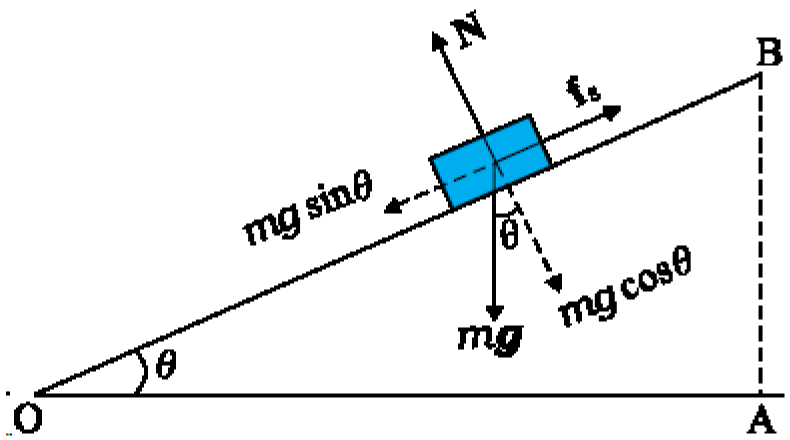
- https://www.youtube.com/watch?v=tz-t_DXk6-c

- https://www.youtube.com/watch?v=hNe8-bg-ojg

Video: http://www.ck12.org/assessment/ui/views/test.detail.new.html?

11. PROBLEMS FOR CONCEPTUAL UNDERSTANDING

1. For each force, marked in the fig. state its reaction pair.



2. A rocket with a lift-off mass 20,000 kg is blasted upwards with an initial acceleration of 5.0 m s^{-2}. Calculate the initial thrust (force) of the blast.

3. Two billiard balls each of mass 0.05 kg moving in opposite directions with speed 6 m s^{-1} collides and rebound with the same speed. What is the impulse imparted to each ball due to the other?

Hint: Impulse on each ball= 0.05 x 12 = 0.6 kg m/s in magnitude. The two impulses are equal and opposite in direction

4. A shell of mass 0.020 kg is fired by a gun of mass 100 kg. If the muzzle speed of the shell is 80 m s^{-1}, what is the recoil speed of the gun?

Hint: Using the principle of conservation of momentum 100 v = 0.02 x 80

V = 0.016 m/s or 1.6 cm/s

5. Explain why

(a) A horse cannot pull a cart and run in empty space

(b) It is easier to pull a lawn mower than to push it,

(c) A cricketer moves his hands backwards while holding a catch.

Hint:

a) The horse - cart system has no external force in empty space. The mutual forces between the horse and the cart cancel. On ground, the contact force between the system and the ground frictional force causes motion from rest.

b) A lawn mower is pulled or pushed by applying force at an angle. When we push the normal force must be more than the weight, for equilibrium in the vertical direction. These results in greater force of friction therefore we have to apply greater force just the opposite takes place when we pull the lawn mower.

c) To reduce the rate of change of momentum and hence to reduce the force necessary to stop the ball.

12. SUMMARY

In this module you have learnt following:

- Forces in nature always occur between pairs of bodies.
- Force on a body A by body B is equal and opposite of the force on the body B by body A.
- A system is a collection of two or more objects.
- A system is isolated if no net external force acts on it.
- Newton's third law of motion: to every action there is an equal and opposite reaction.

- Action and reaction forces are simultaneous forces. There is no cause-effect relationship between action and reaction. Anyone of the two mutual forces can be called action and the other reaction.

- Action and reaction act on different bodies and so they cannot be cancelled out.

- The internal action and reaction forces between different bodies, however, sum to zero.

- Each of the forces in an action- reaction pair cause a change in linear momentum of the body on which they act.

- Law of Conservation of Momentum: The total momentum of an isolated system of particles is conserved. This law follows from the second and third laws of motion.