Unit

3

DYNAMICS

CHECK LIST

After studying this unit you should be able to
- ✓ Define momentum, force, inertia, friction, centripetal force.
- ✓ Solve problem using the equation Force= change in momentum/change in time.
- ✓ Explain the concept of force by practical examples of daily life.
- ✓ State Newton's laws of motion.
- ✓ Distinguish between mass and weight and solve problem using F=ma and w=mg.
- ✓ Calculate tension and acceleration in a string during motion of bodies connected by the string and passing over frictionless pulley, using second law of motion.
- ✓ State the law of conservation of momentum.
- ✓ Use the principle of momentum conservation in the collision of two objects.
- ✓ Determine the velocity after collision of two objects using the law of conservation of momentum.
- ✓ Explain the effect of friction on the motion of a vehicle in the context of tyre surface, road conditions including skidding, braking force.
- ✓ List various methods to reduce friction.
- ✓ Explain that motion in a curved path is due to a perpendicular force on a body that changes direction of motion but not speed.
- ✓ Calculate centripetal force on a body moving in a circle using mv^2/r.
- ✓ State what will happens to you while you are sitting inside a bus when the bus
- ✓ 1. starts moving suddenly 2. stops moving suddenly 3. turns a corner suddenly
- ✓ Write a story about what may happen to you when you dream that all frictions suddenly disappeared. Why did your dream turn into night mare?

As discussed earlier mechanics deals with the study of motion of objects. But few questions like why some objects are accelerated and others are not? How and why a moving object changes its direction of motion? These questions can be answered when we extend our discussion of motion of objects to another branch of mechanics known as Dynamics. In this unit we will learn about force, momentum, newton's laws, friction and circular motion.

Kinematics is the "how" of motion and **Dynamics** is the "why" of motion.

Dynamics is derived from the Greek word for force. The branch of physics which deals with the study of motion by analyzing the cause of motion is called dynamics.

3.1 FORCE

A force is a kind of a push or a pull on an object. When we push a stilled car, hit the nail with hammer or drag a chair, we are exerting a force in each case.

We can think of different ways in which we can move this textbook. We can push or pull it, or we can tie a string around it and pull on the string. We often call these *contact forces* because the force is exerted when one object comes in contact with another object. As we are holding this physics textbook right now, our hands are exerting a contact force on it. There are other ways in which we can change the motion of the textbook. We can drop it, as we learned in Chapter 2 Kinematics, it would accelerate as it falls to the ground. This time the gravitational force of Earth (which is not a contact force) is acting on the book which is causing this acceleration. We call such forces as ***non-contact forces, field forces*** or ***action-at-a-distance forces***.

Forces can cause objects to start moving, speed up, slow down, or change direction as they move. In other words, to accelerate an object, a force is needed. But sometimes we apply force and object does not move. For example when we apply force on a wall– wall does not move. At times we

Figure 3.1 Non Contact Forces

Can you think of other kinds of field forces?

If you have ever experimented with magnets, you know that they exert forces without touching.

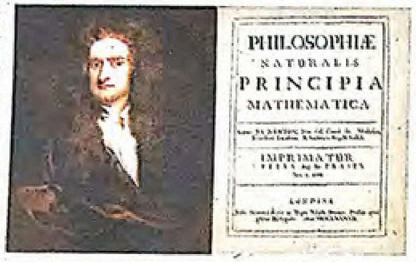
cannot even stop a moving body. For example, we fail to stop a moving truck even if we apply force.

DEFINITION OF FORCE Force is a physical quantity which moves or tends to move a body, stops or tends to stop a moving body.

In other words force is a physical quantity changes or tends to change the velocity (both in magnitude and/or direction – acceleration) of a body. In System International (SI) the unit of force is **newton** (first letter small) and is represented by symbol N. One newton is defined as the force that produces acceleration of **one meter per second square** ($a = 1\ m/s^2$) in a body of mass **one kilogram (1 kg)**.

$$1N = 1kg \times 1m/s^2 \quad \text{or} \quad N = kg\,m/s^2$$

3.2 NEWTON'S LAWS OF MOTION:



Isaac Newton (1642-1727) was born in England, he proposed a theory of the causes of motion. Collectively they are called **"Newton's laws of motion"** and provide the basis for understanding the effect that forces have on an object. This book was written in Latin with title Philosophiae Naturalis Principia Mathematica, as shown in figure. The English title of Newton's 1687 treatise is The Mathematical Principles of Natural Philosophy, which is often referred to as Newton's Principia.

3.2.1 NEWTON'S FIRST LAW OF MOTION:

Statement:

If the net (external) force acting on an object is zero, the object will maintain its state of rest or of uniform motion (constant velocity).

In other words, if there is no net force acting on an object, its velocity will not change. If it is at rest, it will remain at rest; if it is moving, it will continue to move with constant velocity (zero acceleration; no change in speed or direction). Mathematically, first law can be expressed as

$$\vec{F}_{net} = 0 \quad \text{then} \quad \Delta\vec{v} = 0 \quad \text{or} \quad \vec{a} = 0$$

Newton's first law indicates that a state of rest (zero velocity) and a state of constant velocity are equivalent, because both of them does not require a net force to sustain it. The study of first law of motion can be divided into two parts.

Bodies At Rest:

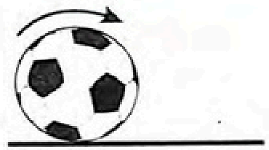
The first part of the law sates that a body at rest will remain at rest if no net force acts on it. This part of first law is easy to understand and goes with our common observation. For example a chair lying in a room will remain stationary and will not start moving or flying around by itself unless some one moves it by applying a net force.

Figure 3.2 Bodies at Rest

Bodies In Motion:

The second part of the law states that a body in motion will continue to move in a straight line with uniform speed if no net force acts on it. However our daily observation is against this. For example if we roll a ball it comes to rest after some time. But careful study of the moving ball shows that there are forces (like friction and air resistance) which oppose the motion of the ball.

Figure 3.3 Bodies in Motion

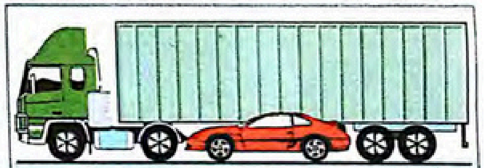


This means that object would continue to move in a straight line for ever, with uniform speed if the forces opposing the motion of the object are removed. In space where there are negligible opposing forces, objects move in a straight line and no applied force has to be maintained by an engine to keep them moving.

Inertia:

A greater net force is required to change the velocity of some objects than of others.

For instance, a net force that is just enough to move a car will cause only a small change in motion of a truck. In comparison to the car, the truck has a much greater tendency to remain at rest.



A larger body (in mass) has a greater resistance to a change in its motion than does a smaller one.

Therefore, we say that the truck has more inertia than a car.

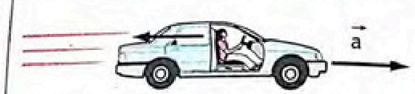
A) Newton's first law is sometimes called the law of inertia:

Using Newton's first law of motion help us to define inertia, therefore it is also called **law of inertia**. Inertia is the natural tendency of an object to remain at rest or in motion at a constant velocity. **The mass of an object is a quantitative measure of inertia.** SI Unit of Inertia and Mass is kilogram (kg). The larger the mass, the greater is the inertia.

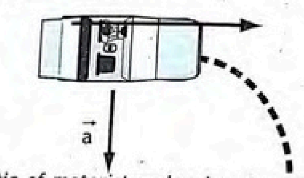
B) We can feel inertia:

When we are in a moving car, we can feel the effects of our own inertia. If the car accelerates forward, we feel as if our body is being pushed back against the seat, because our body resists the increase in speed. If the car turns a corner, we feel as if our body is being pushed against the door, because our body resists the change in the direction of motion. If the car stops suddenly, we feel as if our body is being pushed forward, because our body resists the decrease in speed. These situations are shown in the figure 3.4, where a motorist feel the effects of changing accelerations.

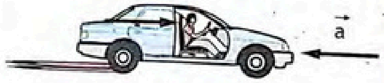
Figure 3.4 Feeling Inertia



Inertia of motorist makes her feel like she is being thrown forward.



Inertia of motorist makes her feel like she wants to continue moving in a straight line.



Inertia of motorist makes her feel like she is being pushed backward.

TID-BIT Using Newton's first law we could remove the cloth without toppling or breaking items placed on it . . .

The trick to keeping the dishes on the table is to use a very smooth tablecloth without any hem and very quickly jerk the tablecloth backward in a slightly downward direction. We suggest that you practice with heavy objects on plastic plates. Remember that the more mass placed on the plates, the greater is the inertia.

ACTIVITY DEMONSTRATION OF INERTIA

Place a card on top of a glass. Then place a coin on top of the card as in Fig (a). Quickly flick the card horizontally. The inertia of the coin tends to keep it at rest horizontally. The force that causes the coin to move is the vertical force of gravity, which pulls it straight down into the glass as in Fig. (b).

3.2.2 NEWTON'S SECOND LAW OF MOTION

Statement:

The net force 'F' on a body is equal to the product of the body's mass m and its acceleration a.

OR

A net force (unbalanced force) applied on the body produces an acceleration 'a' in the body. This acceleration is directly proportional to the magnitude of the net force and inversely proportional to the mass of the object.

$$a \propto F \quad \text{--- (1)}$$

$$a \propto \frac{1}{m} \quad \text{--- (2)}$$

The acceleration is in the same direction as that of the net force. Combining equation 1 and 2 we get

$$a \propto \frac{F}{m} \quad \text{or} \quad a = k\frac{F}{m}$$

If m = 1 kg and a = 1 m/s^2, then F = 1 N.

Substituting in F = kma, we get k = 1 and so we can write

$$a = 1\times\frac{F}{m} \quad \text{or} \quad a = \frac{F}{m} \quad \text{therefore } F = ma \quad \text{--- (3.1)}$$

Newton's second law tells us that acceleration 'a' will be largest when force 'F' is large and mass 'm' small.

POINT TO PONDER

Kilogram of Cotton and Gold: Which has more mass: as kilogram of cotton balls or a kilogram of gold?

POINT TO PONDER

In Pakistan the bus does not halt completely for male passengers on bus stop. They momentarily reduce speed and we are told to step down the bus in the direction in which the bus is moving. Why?

TIP

When two things are directly proportional to each other, as one increases, the other increases also. However, when two things are inversely proportional to each other, as one increases, the other decreases.

To change proportionality into equality usually a constant is used.

Example 3.1 FORCES ON SPORTS BALLS

What force is required to produce an acceleration of $6.00\ m/s^2$ in a cricket ball of mass m_c 0.16 kg and metal ball for women shot-put game with mass $m_s = 4$ kg .

SOLUTION

GIVEN:

Mass of cricket ball $m_c = 0.16$ kg

Mass of Metal Ball $m_s = 4.00$ kg

Acceleration $a = 6.00\ m/s^2$

REQUIRED:

Force on cricket ball $F_c = ?$

Force on metal ball $F_s = ?$

By Newton's second law $F_C = m_C a$

putting values $F_C = 0.16\,kg \times 6.00\,m/s^2$ or $F_C = 0.96\,kg\,m/s^2$

since $N = kg\,m/s^2$

therefore $F_C = 0.96\,N$ — Answer

By Newton's second law $F_S = m_S a$

putting values $F_S = 4.00\,kg \times 6.00\,m/s^2$

or $F_S = 24\,kg\,m/s^2$

since $N = kg\,m/s^2$ therefore $F_S = 24\,N$ — Answer

EXTENSION EXERCISE 3.1

What will be accelerations if you apply the same net force N= 10 N on both cricket ball and metal ball in this example?

This example shows us that for same acceleration a large force is required for large mass, and small force is required for small mass.

Assignment 3.1 TRUCK AND CAR ACCELERATIONS

Find the acceleration produced in engine force of 3500 N in car of mass 600 kg and truck of mass 2400 kg.

3.2.3 NEWTON'S THIRD LAW OF MOTION

Statement:

When one object exerts a force on a second object, the second object exerts a force of the same magnitude and opposite direction on the first object. When an object A exert force on object B written as F_{AB}, object B also exert equal force on object A written as F_{BA} but in opposite direction

$$\vec{F}_{AB} = -\vec{F}_{BA} \qquad (3.2)$$

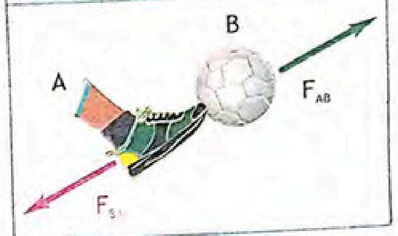
Here the negative sign shows that force F_{BA} is opposite to force F_{AB}.

When a football is kicked, the foot exerts the force F_{AB} on the football and as a reaction to that a foot ball exerts an equal and opposite force F_{BA} on the foot.

$$F_{AB} = -F_{BA}$$

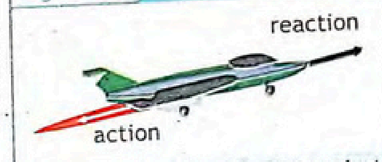
The force of A on B is equal in magnitude and opposite in direction of the force of B on A.

Figure 3.5 Third Law of Motion



Sir Isaac Newton described these two forces as action - reaction pair. To every action there is an equal and opposite reaction. Action reaction cannot neutralize each other because they act on different bodies (action on one body and reaction on another body).

Figure 3.6 Action-Reaction

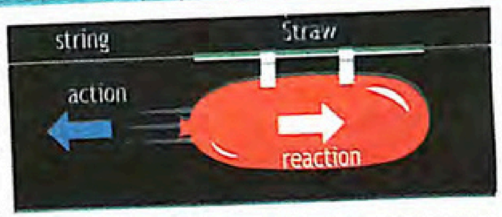


For example, the jet plane eject gases at high speed as an action, and air as reaction apply force on the plane to make it move forward.

We can feel reaction:

When we push against the edge of a table (action). Our hand's shape is changes, this shows that a force is being exerted on it (reaction). We can see the edge of the table pressing into our hand. The harder we push against the desk, the harder the desk pushes back. (We only feel forces exerted on us; when we exert a force on another object, what we feel is that object pushing back on us.)

ACTIVITY BALLOON FORCING AIR OUT



- Tie one end of the string to a chair. Thread the other end of the string through the straw.
- Pull the string tight and tie it to another support in the room.
- Blow up the balloon, but don't tie it. Pinch the end of the balloon and tape the balloon to the straw as shown in figure.
- You're ready for launch. Let go and watch your balloon rocket fly!

3.3 WEIGHT

You know from unit 2: Kinematics that when an object is dropped, it accelerates toward the center of Earth. Newton's second law states that a net force on an object is responsible for its acceleration. If air resistance is negligible, the net force on a falling object is the gravitational force, commonly called its weight w. Since weight is a force as have the same units as force newton (N). Weight can be denoted as a vector w because it has a direction.

Consider an object with mass 'm' falling downward toward's Earth. It experiences only the downward force of gravity, which has magnitude 'w'. Newton's second law states that the magnitude of the net external force on an object is 'F = ma'. Since the object experiences only the downward force of gravity, 'F = w'. We know that the acceleration of an object due to gravity is 'g', or 'a = g'. Substituting these into Newton's second law gives

$$w = mg \qquad (3.3)$$

Since $g = 9.80\ m/s^2$ on Earth, the weight of a 1.0 kg object on Earth is 9.8 N, as we see: $w = mg = (1.0\ kg)(9.80\ m/s^2) = 9.8\ N$.

The acceleration due to gravity g varies slightly over the surface of Earth (we will discuss it in detail in chapter 5; gravitation). So that the weight of an object depends on location and is not a property of the object. Weight varies on large scale if one leaves Earth's surface. On the Moon, for example, the acceleration due to gravity is only $1.67\ m/s^2$. A.1 .0-kg mass which has a weight of 9.8 N on Earth is only about 1.7 N on the Moon.

POINT TO PONDER

Why does a hose pipe tend to move, backward when the fireman directs a powerful stream of water towards fire?

Common Misconception

Mass vs Weight:

In our daily life we use the term mass and weight in almost the same meaning. For example when we ask a shopkeeper to give 5 kg of rice, it is usually considered as the weight of rice. But in fact 5 kg is the mass of rice. From scientific point of view weight and mass are two different quantities. The mass of an object will remain the same, regardless of its location. However, because weight depends on the acceleration due to gravity, the weight of an object can change when the object enters into a region with stronger or weaker gravity.

Example 3.2 WEIGHT OF GIRL ON EARTH AND MOON

The mass of a girl is 60 kg. How much will she weigh on the **(a)** Earth? **(b)** Moon? [take acceleration due to gravity for earth as $g_E = 9.8\ ms^{-2}$ and for moon as $g_M = 1.6\ ms^{-2}$]

SOLUTION

GIVEN:

Mass m = 60 kg

Acceleration due to gravity on earth $g_E = 9.8\ ms^{-2}$

Acceleration due to gravity on moon $g_M = 1.6\ ms^{-2}$

REQUIRED:

weight on Earth w_E = ?

weight on moon w_M = ?

(a) Weight of girl on Earth $w_E = mg_E$

putting values $w_E = 60\,kg \times 9.8\,m/s^2$

or $w_E = 588\,kg\,m/s^2$

since $N = kg\,m/s^2$

therefore $w_E = 588\,N$ — **Answer**

(b) Weight of girl on Moon $w_M = mg_M$

putting values $w_M = 60\,kg \times 1.6\,m/s^2$

or $w_M = 96\,kg\,m/s^2$

since $N = kg\,m/s^2$

therefore $w_M = 96\,N$ — **Answer**

Assignment 3.2 WEIGHT OF ASTRONAUT

The weight of an astronaut and his space suit on the Moon is only 250 N. How much do they weigh on Earth? What is the mass on the Moon? On Earth? [take acceleration due to gravity for earth as $g_E = 9.8\ ms^{-2}$ and moon as $g_M = 1.6\ ms^{-2}$]

CHECKPOINT (NEWTON LAWS)

Q1: What is the acceleration produced by a force of 12 N exerted on an object of mass 3 kg? **(Answer: 4 ms^{-2})**

Q2: Calculate the mass of a body when a force of 700 N, produces an acceleration of 12.5 ms^{-2}. **(Answer: 56 kg)**

3.4 LINEAR MOMENTUM:

The linear momentum 'P' of an object is the product of the object's mass 'm' and velocity 'v'. Mathematically

$$\vec{P} = m\vec{v} \qquad (3.4)$$

Linear momentum is a vector quantity that points in the same direction as the velocity. SI Unit of Linear Momentum is kilogram-meter per second (kgm/s or kgms^{-1}), or simply newton-second (Ns).

Momentum measure the quantity of motion in a body. It is our common observation that large force will be required to stop a truck than a car moving at same speeds. Because truck has a large mass than a car. Similarly it is easy to stop a rolling drum of coal tar of mass 50kg moving at a speed of 0.1 m/s but it is difficult to stop it if it is moving at 5 m/s.

Example 3.3 MOMENTUM OF AIRGUN SHOT

An iron shot of mass 6 g is fired with an airgun. If the velocity of the shot is 62 ms^{-1}, what is the magnitude of momentum?

SOLUTION

GIVEN:
Mass m = 6 g = 0.006 kg
velocity v = 62 ms^{-1}

REQUIRED:
magnitude of Momentum P = ?

by definition of momentum $\vec{P} = m\vec{v}$

in magnitude $P = mv$

putting values $P = 0.006\,kg \times 62\,m/s$

therefore $P = 0.372\,kg\,m/s$

Hence $P = 0.372\,Ns$ —— Answer

Assignment 3.3 FASTEST RECORDED BALL SPEED IN ANY GAME

The fastest recorded speed for a golf ball hit by a golfer is 75.8 m/s (273 km/h). If mass of golf ball is 46 g, what is the magnitude of its momentum?

3.4.1 FORCE AND CHANGE IN MOMENTUM

When a force 'F' produces acceleration 'a' in a body of mass 'm'. By Newton's second law of motion it is written as

$$\vec{F} = m\vec{a} \quad \text{—— (1)}$$

The acceleration produced changes the velocity of the body from initial velocity 'v_i' to final velocity 'v_f' during time interval 'Δt'. Then by Definition of acceleration

$$\vec{a} = \frac{\vec{v}_f - \vec{v}_i}{\Delta t} \quad \text{—— (2)}$$

Putting equation 2 in equation 1

$$\vec{F} = m\left(\frac{\vec{v}_f - \vec{v}_i}{\Delta t}\right) \quad \text{or} \quad \vec{F} = \left(\frac{m\vec{v}_f - m\vec{v}_i}{\Delta t}\right) \quad \text{or} \quad \vec{F} = \left(\frac{\vec{P}_f - \vec{P}_i}{\Delta t}\right)$$

since $\Delta\vec{P} = \vec{P}_f - \vec{P}_i$

therefore $\vec{F} = \dfrac{\Delta\vec{P}}{\Delta t}$ —— 3.5

The time rate of change of linear momentum of a body is equal to the net force acting on the body. This means that for sudden change in momentum force is large and vice versa.

INTERESTING INFORMATION FRAGILE OBJECTS

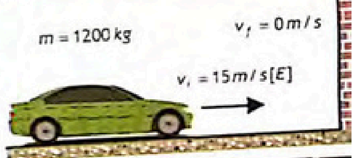
Different safety techniques are used in the packaging of fragile objects.

Example 3.4 IMPACT CRUMPLE OF CAR

To improve the safety of motorists, modern cars are built so the front end crumples upon impact. A 1200-kg car is traveling at a constant velocity of 15.0 m/s [E]. It hits an immovable wall and comes to a complete stop in 0.25 s.

a) What is the average net force exerted on the car ?

b) What would be the average net force exerted on the car if it had a rigid bumper and frame that stopped the car in 0.040 s?



GIVEN:
Mass of car m = 1200 kg
initial velocity v_i = 15.0 m/s [E]
final velocity v_f = 0.0 m/s
a) time interval (deforming) Δt = 0.25 s
b) time interval (rigid) Δt = 0.040 s

REQUIRED:
(a) Average net forc (deforming) F = ?
(b) Average net force (rig F = ?

SOLUTION

a) by Newton's second law in terms of momentum $\vec{F} = m\left(\frac{\vec{v}_f - \vec{v}_i}{\Delta t}\right)$

putting values $\vec{F} = 1200\,kg\left(\frac{0 - 15.0\,m/s[E]}{0.25\,s}\right)$

or $\vec{F} = \frac{-18000\,kg\,m/s[E]}{0.25\,s}$

or $\vec{F} = -72000\,kg\,m/s^2\,[E]$

or $\vec{F} = -72000\,N[E]$

or $\vec{F} = 72000\,kg\,m/s^2\,[W]$

therefore $\vec{F} = 72000\,N[W]$ —— Answer

b) by Newton's second law in terms of momentum $\vec{F} = m\left(\frac{\vec{v}_f - \vec{v}_i}{\Delta t}\right)$

putting values $\vec{F} = 1200\,kg\left(\frac{0 - 15.0\,m/s[E]}{0.040\,s}\right)$

or $\vec{F} = \frac{-18000\,kg\,m/s[E]}{0.040\,s}$

or $\vec{F} = -450000\,kg\,m/s^2\,[E]$

or $\vec{F} = -450000\,N[E]$

or $\vec{F} = 450000\,kg\,m/s^2\,[W]$

therefore $\vec{F} = 450000\,N[W]$ —— Answer

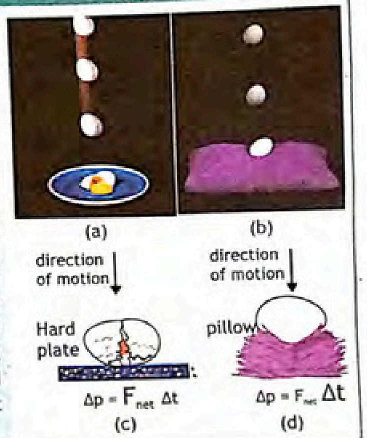
The average net force exerted by the wall on the car is (a) 7.2×10^4 N [W] when it crumples, and (b) 4.5×10^5 N [W] when it is rigid. The change in momentum is the same in both parts is -18000 kgm/s, but the time intervals are different. So the average net force is different in both situations. The magnitude of force on the car with the rigid frame is more than 6 times greater than when the car crumples.

Assignment 3.4 FORCE REQUIRED TO STOP A TRUCK AND CAR

Calculate the force required to stop a car of mass 1200 kg and a loaded truck of mass 9,000 kg in 2 second, if they are moving with same velocity of 10 ms^{-1}.

ACTIVITY FALLING EGG

Consider a falling egg. When the egg hits a hard surface, like the plate in Figure (a), the egg comes to rest in a very short interval of time. The force the hard plate exerts on the egg due to the collision is large. When the egg hits a floor covered with a pillow, as in Figure (b), the egg undergoes the same change in momentum, but over a much longer time interval. In this case, the force required to accelerate the egg to rest is much smaller. By applying a small force to the egg over a longer time interval, the pillow causes the same change in the egg's momentum as the hard plate, which applies a large force over a short time interval. Because the force in the second situation is smaller, the egg can withstand it without breaking.



ISOLATED SYSTEM

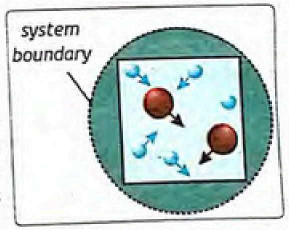
POINT TO PONDER

How rockets move and accelerate in space where there is no air for them to push against.

We are often interested in the behavior of a collection of particles that interact only with each other. We can draw an imaginary boundary around the particles, but complications can arise, if some of the particles experience net forces that originate outside the "system" boundary. In order to effectively study interactions between particles, we must limit our focus to isolated systems of particles.

An isolated system is a collection of particles that can interact with each other but whose interactions with the environment outside the collection have a negligible effect on their motions.

For example, the molecules of a gas enclosed in a vessel can be considered as an isolated system of interacting bodies. Gas molecules interact with each other and with the walls of their container. Other forces, such as those of the table holding up the container and the gravitational force, are considered to have a negligible effect on the motions of the molecules and container.



3.4.2 NEWTON'S LAWS AND CONSERVATION OF MOMENTUM

For an isolated system there is no net force acting F = 0, therefore Newton's second law in terms of momentum (equation 3.5) can be written as

$$0 = \frac{\Delta \vec{P}}{\Delta t}$$

or $$0 = \frac{\vec{P}_f - \vec{P}_i}{\Delta t}$$ by cross multiplication $0 = \vec{P}_f - \vec{P}_i$

therefore $$\vec{P}_f = \vec{P}_i \quad \text{—— 3.6}$$

In the absence of an external force (isolated system) the final momentum P_f of the system must be equal to initial momentum P_i. If no net external force acts on a system of particles, the total momentum of the system cannot change.

3.4.3 CHANGE OF MOMENTUM AND COLLISIONS

An event during which particles come close to each other and interact by means of forces is called collision. The forces due to the collision are assumed to be much larger than any external forces present.

Consider a system consisting two objects A and B of masses m_1 and m_2 moving with velocities u_1 and u_2 respectively, such that after collisions their velocities change to v_1 and v_2. The total momentum of the system before collision is

$$\vec{P}_i = m_1u_1 + m_2u_2$$

The total momentum of the system after collision changes to

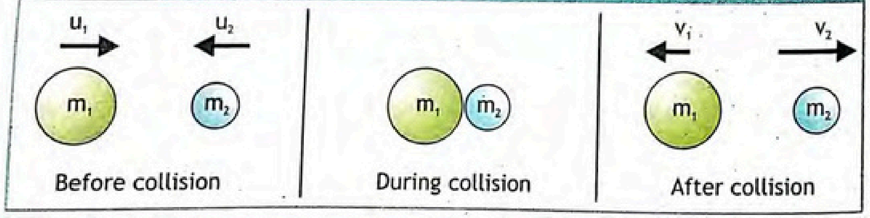
$$\vec{P}_f = m_1v_1 + m_2v_2$$

By law of conservation of momentum

$$\vec{P}_f = \vec{P}_i$$

therefore $$m_1v_1 + m_2v_2 = m_1u_1 + m_2u_2 \quad \text{—— 3.7}$$

Figure 3.7 Collision



Before collision During collision After collision

Example 3.5 BALLS COLLISION

Ball A having mass 0.05 kg moving to the right at velocity of 0.50 m/s makes an head-on collision with ball B having mass 0.20 kg that is initially at rest. After the collision, ball A moves to the left at 0.30 m/s. Find the final velocity of the ball B.

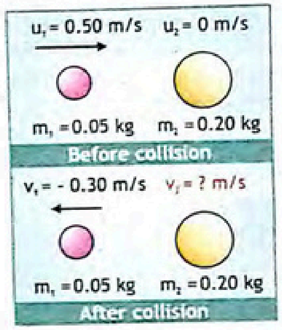
SOLUTION

GIVEN:

Mass of ball A m_1 = 0.05 kg
Mass of ball B m_2 = 0.20 kg
Velocity of ball A before collision u_1 = 0.50 m/s
Velocity of ball B before collision u_2 = 0 m/s
Velocity of ball A after collision v_1 = - 0.30 m/s

REQUIRED:

Velocity of ball B after collision v_2 = ?



By change of momentum and collision between two bodies

$$m_1v_1 + m_2v_2 = m_1u_1 + m_2u_2$$

rearranging $$m_2v_2 = m_1u_1 + m_2u_2 - m_1v_1$$

dividing by m_2 on both sides

$$v_2 = \frac{m_1u_1 + m_2u_2 - m_1v_1}{m_2}$$

putting values

$$v_2 = \frac{0.05\,kg \times 0.50\,m/s + 0.20\,kg \times 0\,m/s - 0.05\,kg \times -0.30\,m/s}{0.20\,kg}$$

or $$v_2 = \frac{0.025\,kg\,m/s + 0\,kg\,m/s + 0.015\,kg\,m/s}{0.20\,kg}$$

or $$v_2 = \frac{0.04\,\cancel{kg}\,m/s}{0.20\,\cancel{kg}}$$

therefore $v_2 = 0.2\,m/s$ —— Answer

Velocity of ball B after collision is 0.2 m/s

Assignment 3.5 CARROM BOARD COLLISION

In carrom board game the striker of mass having mass 0.015 kg sliding to the right at velocity of 0.40 m/s makes head-on collision with a disk having mass 0.005 kg that is initially at rest. After the collision, striker moves to the right along the direction of disk at 0.20 m/s. Find the final velocity of the disk.

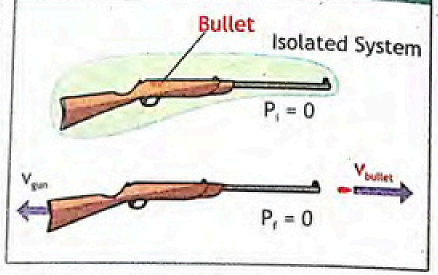
3.7.4 CHANGE OF MOMENTUM AND EXPLOSIVE FORCES

An explosion, where the particles of the system move apart from each other after a brief, intense interaction. Explosion is the opposite of a collision. The explosive forces, which could be from an expanding spring or from expanding hot gases, are internal forces. If the system is isolated, its total momentum during the explosion will be conserved, by the law of conservation of momentum

Firing of rifle:

Consider an isolated system of bullet of mass m and rifle of mass M. Such that before firing the total momentum of the system is zero.

Figure 3.8 Explosive Forces



$$P_i = 0$$

After firing the bullet moves with velocity v_b in one direction and the rifle recoils with velocity v_g in the other direction such that the total momentum is again zero.

$$mv_b + Mv_g = 0 \quad \text{—— } 3.8$$

Due to the large mass of the rifle it recoils with much lower velocity as compared to the bullet.

Example 3.6 RECOIL OF AK47

A bullet of mass 0.008 kg is fired from Ak47 rifle with mass of 4 kg. If the velocity of the bullet is 715 ms^{-1}, what would be the recoil velocity of the gun?

SOLUTION

GIVEN:

Mass of bullet m = 0.008 kg

Mass of rifle M = 4 kg

Velocity of bullet after fire v_b = 715 m/s

REQUIRED:

Recoil velocity of gun after fire v_g = ?

By change of momentum and in terms of rifle and bullet

$$mv_b + Mv_g = 0 \quad \text{or} \quad Mv_g = -mv_b$$

Dividing both sides by M $\quad v_g = -\dfrac{mv_b}{M}$

putting values $\quad v_g = -\dfrac{0.008\,kg \times 715\,m/s}{4\,kg}$

or $\quad v_g = -\dfrac{5.72\,\cancel{kg}\,m/s}{4\,\cancel{kg}}$

therefore $\quad v_g = -1.43\,m/s$ — Answer

The minus sign indicates that the Ak47 rifle's recoil is to the left. The recoil speed is 1.43 m/s.

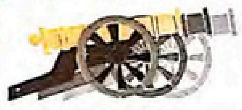
EXTENSION EXERCISE 3.2

Will you want to fire with a rifle of mass 0.008 kg having bullet of 4 kg, ejecting with a muzzle speed of 715 m/s?

Assignment 3.6 CANNON RECOIL

A 200-kg cannon at rest contains a 10-kg cannon ball. When fired, the cannon ball leaves the cannon with a speed of 90 m/s. What is the recoil speed of the cannon?


before firing


After firing

ROCKET PROPULSION AND THRUST

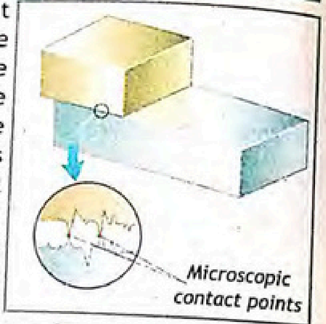
A phenomenon similar to muzzle velocity occurs in rocket propulsion. The rocket ejects gases from its tail at a high velocity, just as a rifle ejects bullets or cannon fires a shell from its barrel. A rocket's mass isn't constant because the fuel it contains is constantly decreasing. Thus giving acceleration to the rocket called thrust. Any space vehicle is maneuvered in empty space by firing its rockets in the direction opposite to that in which it needs to accelerate. When the rocket pushes on the gases in one direction, the gases push back on the rocket in the opposite direction.

3.5 FRICTION

Friction is a force that opposes relative motion or attempted motion between systems in contact. Friction is denoted by letter f, since it is a force therefore it is a vector quantity and has unit as newton (N). Frictional force is around us all the time that opposes motion of one body over another body in contact. When we rub (slide) our hand on a table top, we can feel the friction opposing this motion. We need it to both start and stop a bicycle and a car.

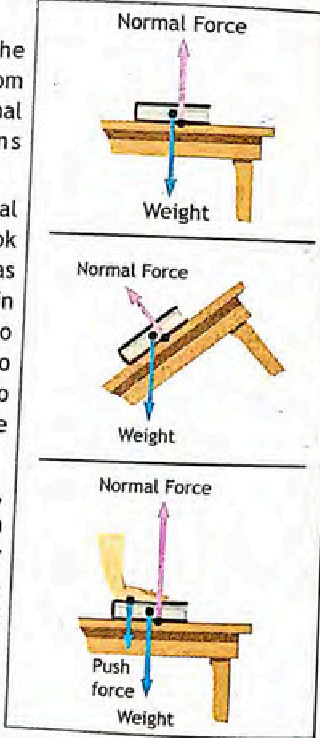
3.5.1 MICROSCOPIC DESCRIPTION OF FRICTION

Every surface is rough, even surfaces that appear to be highly polished can actually look quite rough when examined under a microscope. Some surfaces are more rough than others. Therefore when one surface slide over another, these irregularities bump into one another which gives rise to frictional force. Secondly at these contact points the molecules of the different bodies are close enough to exert strong attractive intermolecular forces on each other, thus opposing motion and result in friction.



NORMAL FORCE

A contact force perpendicular to the contact surface that prevents two objects from passing through one another is called the normal force F_N. (In geometry, normal means perpendicular.)



Consider a book resting on a horizontal table's surface. By Newton's third law the book exert the force on the table due to its weight and as a reaction table exert force on the book, which in this case is a normal force. The normal force due to the table must have just the right magnitude to keep the book from falling through the table. If no other vertical forces act, the normal force on the book is equal in magnitude to the book's weight.

If the surface of the table is not horizontal, the normal force is not vertical and is not equal in magnitude to the weight of the book. Remember that the normal force is perpendicular to the contact surface. Even on a horizontal surface, if there are other vertical forces acting on the book, then the normal force is not equal in magnitude to the book's weight as shown in figure.

3.5.2 TYPES OF FRICTIONAL FORCES:

There are two types of frictional force.

A) Static friction:

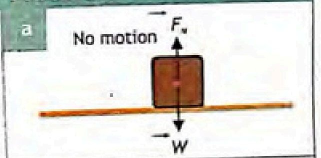
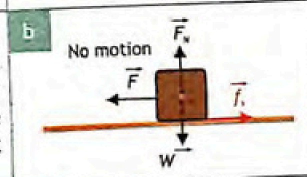
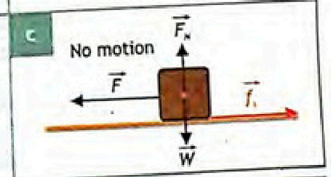
The frictional force that tends to prevent a stationary object from starting to move is called static friction denoted by f_s. For example, when we push horizontally on a heavy crate. The crate does not move. It means that a second force act on the crate to oppose our force, and this force must be directed opposite to our applied force and have the same magnitude to balance our push. That second force is a frictional force. When we push even harder. The crate still does not move. It means that the frictional force can change in magnitude so that the two forces still balance. Now if we push with more strength, the crate begins to slide. So we can say that, there is a maximum magnitude of the frictional force. When we exceeded that maximum magnitude, the crate started to move.

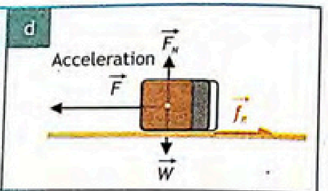
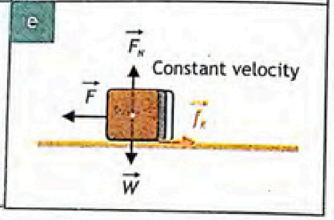
B) Kinetic friction:

The frictional force that acts against during motion of an object in a direction opposite to the direction of motion denoted by f_k.

For example, when heavy crate starts motion, kinetic friction f_k now replaces static friction f_s. If we are applying same force the heavy crate after it has started moving it accelerates, means that kinetic friction is less than static friction ($f_k < f_s$). In order to drag the heavy crate with constant velocity we have to reduce the force to make it equal to kinetic friction. Table 3.2 shows a similar situation.

TABLE 3.2 DESCRIPTION OF FRICTION

A block rests on a tabletop, with the weight W balanced by a normal force F_N. *There is no attempt of sliding. Thus, no friction and no motion.*	a 
We exert a force F on the block, attempting to pull it to the left. In response, a frictional force f_s is directed to the right, exactly balancing our force. The force is called the static frictional force. The block does not move.	b 
As we increase the magnitude of our applied force, the magnitude of the static frictional force f_s also increases and the block remains at rest.	c 

When the applied force reaches a certain level, the block "breaks away" from its contact with the tabletop and accelerates leftward. The frictional force that opposes the motion is now called the kinetic frictional force fk.	
Usually, the magnitude of the kinetic frictional force is less than the maximum magnitude of the static frictional force. Thus, if we wish the block to move across the surface with a constant speed, we usually decrease the magnitude of the applied force once the block begins to move.	

3.5.3 COEFFICIENT OF FRICTION

The maximum static frictional force $f_{s,max}$ between a pair of surfaces has two main characteristics.

- It is independent of the area of contact between the objects, provided that the surfaces are hard or non-deformable.
- Its magnitude is proportional to the magnitude of the normal force F_N.

$$f_{s,\max} \propto F_N \quad \text{or} \quad f_{s,\max} = \mu_s F_N$$

Where μ_s is a constant of proportionality known as the coefficient of static friction and depends on the nature of surfaces in contact before sliding. Coefficient of static friction μ_s is

$$\mu_s = \frac{f_{s,\max}}{F_N} \quad \text{——— } 3.10$$

The magnitude of the force of kinetic friction f_k is assumed to be proportional to the normal force and independent of speed

$$f_k \propto F_N \quad \text{or} \quad f_k = \mu_k F_N$$

Where μ_k is a constant of proportionality known as the coefficient of kinetic friction and depends on the nature of surfaces in contact during sliding. Coefficient of static friction μ_k is

$$\mu_k = \frac{f_k}{F_N} \quad \text{——— } 3.11$$

As μ is the ratio of forces, therefore, it has no units. Coefficient of

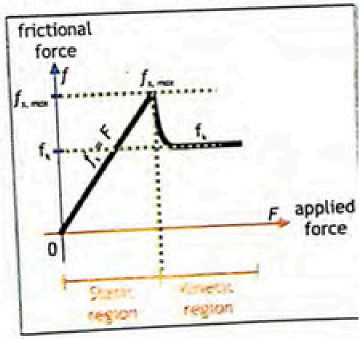
friction is constant for a given pair of surfaces. For a different pair it has a different value. Values for friction of some pair of surfaces (both Static friction and kinetic friction) are given in table 3.3.

TABLE 3.3 APPROXIMATE VALUES OF COEFFICIENTS OF FRICTION

Surfaces	Coefficient of Static Friction, μ_s	Coefficient of Kinetic Friction, μ_k
Glass on glass	0.94	0.4
Ice on ice	0.1	0.02
Rubber on dry concrete	1.0	0.8
Steel on ice	0.1	0.05
Steel on steel	0.78	0.42
Wood on leather	0.6	0.3
Wood on wood	0.35	0.3

Friction is not restricted to solids sliding or tending to slide over one another. Friction occurs also in liquids and gases (both of which are called *fluids)*. Fluid friction occurs as an object pushes aside the fluid it is moving through.

Graphical interpretation of Friction:



The graph is drawn between applied force F and friction f it shows that by increasing the applied force static friction f_s also increases until it reaches a certain maximum value called limiting friction $f_{s,max}$.

At this point the object starts moving and frictional force rapidly decreases to a smaller kinetic friction f_k value, which nearly remains constant.

Advantages of friction:

Friction is desirable in many cases, for example

i) Our ability to walk depends on friction between the soles of our shoes (or feet) and the ground.

ii) Friction holds the screw and nails in wood.

iii) The lighting of a match stick is another useful application of friction.

Disadvantages of friction:

Friction can sometime be a hindrance. for example

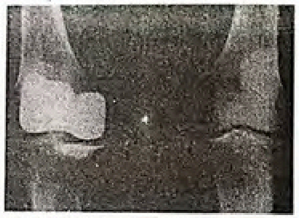
I) It slows down moving objects and causes heating of moving parts in machinery.

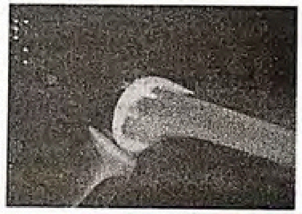
ii) Energy is wasted to overcome friction in machinery.

iii) Produce wear and tear.

We Have Internal Mechanism To Reduce Friction

Many parts of the body, especially the joints, have very small coefficients of friction. A joint is formed by the ends of two bones, which are connected by thick tissues. The knee joint is formed by the lower leg bone (the tibia) and the thighbone (the femur). The ends of the bones in the joint are covered by cartilage, which provides a smooth, almost glassy surface. The joints also produce a fluid (synovial fluid) that reduces friction and wear. A damaged or arthritic joint can be replaced by an artificial joint (shown in lower image). These replacements can be made of metals (stainless steel or titanium) or plastic (polyethylene), also with very small coefficients of friction.





ACTIVITY — ROLLING REDUCE FRICTION

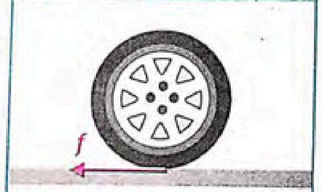
Take the book and slide it on the table now place book on few pencils and roll it you will see that less effort is required.

3.5.4 ROLLING FRICTION

If we set a heavy spherical ball rolling, it experiences an opposing force called rolling friction. ***When a body rolls over a surface, the force of friction is called rolling friction.***

It is a matter of common observation that a body with wheels move easily as compared to a body of the same size without wheels. This is due to the fact that rolling friction overcome the problem of friction by changing contact.

Figure 3.9



Friction resists sliding

METHODS OF REDUCING FRICTION

Some methods of reducing friction are given below

(i) By polishing:

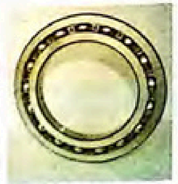
If we polish the rough surfaces, they become smooth and friction is reduced.

(ii) By applying Lubricants (oil or Grease) to surfaces:

Friction of certain liquids is less than that of solid surfaces, therefore, oil or grease is applied between the parts of machinery.

(iii) By using Ball Bearing:

This method converts the sliding friction is converted into rolling friction by use of ball bearings.



Ball Bearing

FUTURE LUBRICANTS

Research into lubricants continues to try to find ways to reduce the coefficient of kinetic friction, μ_k, to a value as close to zero as possible. Modern lubricants include buckyballs – molecules consisting of 60 carbon atoms arranged in the shape of a soccer ball, which were discovered in 1985. These molecules act like microscopic ball bearings.

APPLICATIONS — PHYSICS OF CAR TYRES

A) **The friction between the car tyres and the road is static friction,** because the bottom of the tyre is deformed and comes in static contact with the road.

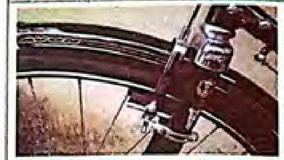
At contact point tyre is deformed and is momentarily at rest

B) **Static friction is more than kinetic friction, therefore we need the tyres of the car to be rolling than sliding to have grip on the road:** The friction during sliding is less than the friction that builds up before sliding takes place. When we slam on breaks the tyres lock, they slide, providing less friction than if they are made to roll to a stop. A rolling tyre does not slide along the road surface, and the friction is static friction, with more grab than sliding friction. But once the tyres start to slide, the frictional force is reduced. Modern cars have an antilock brake system keeps the tyres below the threshold of breaking loose into a slide.

C) **Kinetic friction does not depend upon speed:** It's also interesting that the force of friction does not depend on speed. A car skidding at low speed has approximately the same friction as the same car skidding at high speed. If the friction force on a tyre is 100 newtons at low speed, to a close approximation it is 100 newtons at a higher speed. The friction force may be greater when the tyre is at rest and on the verge of sliding, but, once sliding, the friction force remains approximately the same.

D) Friction does not depend on the area of contact. For a narrower tyre the same weight is concentrated on a smaller area with no change in the amount of friction. So those extra wide tyres you see on some cars provide no more friction than narrower tyres. The wider tyre simply spreads the weight of the car over more surface area to reduce heating and wear. Similarly, the friction between a truck and the ground is the same whether the truck has four ty res or eighteen! More tyres spread the load over more ground area and reduce the pressure per tyre. The stopping distance when brakes are applied is not affected by the number of tyres.

INFORMATION



The brakes of a bicycle use friction to enable the cyclist to control the speed.

E) Tyres have treads not to increase friction but to displace and redirect water from between the road surface and the underside of the tyre: Many racing cars use tires without treads because they race on dry days.

Example 3.7 WOODEN PACKAGE ON WOOD FRICTION

Ayesha pushes a newly bought deep-freezer of mass 120 kg packed in wood across a wooden floor. **(a)** She applies a 400 N force to set it moving, what is the coefficient of static friction? **(b)** Then she makes it move with constant speed by applying force of 350 N, what is the coefficient of kinetic friction?

SOLUTION

GIVEN:

mass = 120 kg

Normal force $F_N = W = mg$

$= 120\ \text{kg} \times 9.8\ \text{ms}^{-2}$

Normal force $F_N = 1176$ N

REQUIRED:

(a) coefficient of static friction $\mu_s = ?$

(b) coefficient of kinetic friction $\mu_k = ?$

(a) Applied force to set the package moving is equal static frictional force, therefore $f_{s,max} = 400$ N, by the relation for coefficient of static friction μ_s

$$\mu_s = \frac{f_{s,\max}}{F_N} \quad \text{putting values} \quad \mu_s = \frac{400\,N}{1176\,N}$$

or $\mu_s = 0.340$ — **Answer**

(b) Applied force to keep it moving at constant speed is equal to kinetic frictional force, therefore $f_k = 350$ N, by equation for coefficient of kinetic friction μ_k

$$\mu_k = \frac{f_k}{F_N} \quad \text{putting values} \quad \mu_k = \frac{350\,N}{1176\,N}$$

or $\mu_k = 0.29$ — **Answer**

These values are close to the approximate values given in the table for the coefficient of friction between wood and wood.

Assignment 3.7 LEATHER AND WOOD FRICTION

A 5 kg heavy leather bag is placed on a horizontal wooden plank. How much force is required to set it in motion if the coefficient of friction between the plank and bag is 0.1.

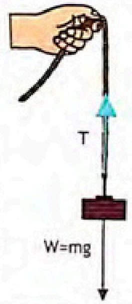
LAB WORK

- Investigate the relationship between force of limiting friction and normal reaction to find the co-efficient of sliding friction between a wooden block and horizontal surface.
- Measure the force of limiting friction by rolling a roller on a horizontal plane.

TENSION

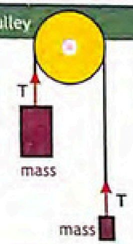
The pulling force exerted by a stretched rope, string, cable or cord on an object to which it's attached is called a tension force. Tension is always a pull force. Hence, the direction of a tension force is always the direction in which one would pull the object with a string or rope.

Suppose a person is holding an object of mass 'm' at rest with the help of a string, the object exerts a force on the hand through the string in the downward direction due its weight. By Newton's third law the force which is exerted by the string on the hand is called the tension in the string and it is usually denoted by T. As the object is at rest the magnitude of tension is equal to that of weight of the object as shown in figure.



ATWOOD MACHINE

Pulleys are often used to redirect a force exerted by a string, as indicated in the figure. In the ideal case, a pulley has no mass and no friction in its bearings. Thus, an ideal pulley simply changes the direction of the tension in a string, without changing its magnitude. **When two objects of unequal mass are hung vertically over a frictionless pulley of negligible mass, the arrangement is called an Atwood's machine.**



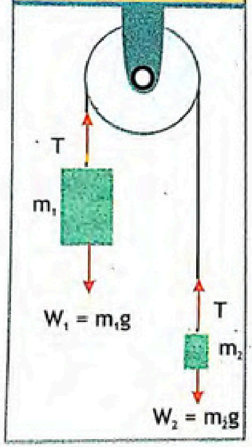
3.6 CONNECTED BODIES

When two objects are connected by a string, applying a force on one of the objects will cause both objects to accelerate at the same rate.

3.6.1 ACCELERATION AND TENSION IN ATWOOD's MACHINE

Consider motion of two objects having masses m_1 and m_2 (with m_1 greater than m_2) suspended by an inextensible string which passes over a frictionless pulley forming an Atwood's machine. In such an arrangement m_1 will move downward under the action of gravity and m_2 will move upward. Tension T and acceleration a will be same for both bodies.

Figure 3.10



Two forces are acting on mass m_1:

i) Its weight $W_1 = m_1 g$, acting downward

ii) Tension of string T, acting upward.

As m_1 is moving downward, the net force F_{net1} acting on it is downward due to which acceleration 'a' is produced in it. Hence,

$$\vec{F}_{net1} = W_1 - T$$

or $$m_1 a = m_1 g - T$$

rearranging $$T = m_1 g - m_1 a \quad \text{——} (1)$$

Similarly two forces are acting on mass m_2:

- Its weight $W_2 = m_2 g$, acting downward
- Tension of string T, acting upward.

As m_2 is moving upward, the net force F_{net2} acting on it is upward due to which acceleration 'a' is produced in it. Hence,

$$\vec{F}_{net2} = T - W_2$$

or $$m_2 a = T - m_2 g$$

rearranging $$T = m_2 a + m_2 g \quad \text{——} (2)$$

Since both equation 1 and equation 2 equal to T, therefore we can write

$$m_2 a + m_2 g = m_1 g - m_1 a$$

rearranging $$m_1 a + m_2 a = m_1 g - m_2 g$$

taking common $$(m_1 + m_2) a = (m_1 - m_2) g$$

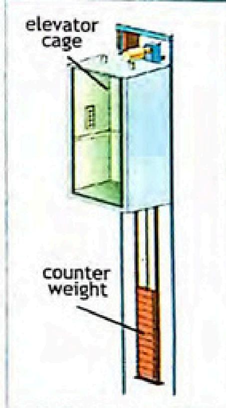
dividing both sides by $m_1 + m_2$ $$\frac{\cancel{(m_1 + m_2)} a}{\cancel{(m_1 + m_2)}} = \frac{(m_1 - m_2) g}{(m_1 + m_2)}$$

therefore $$a = \frac{(m_1 - m_2)}{(m_1 + m_2)} g \quad \text{——} (3.12)$$

This is the value of acceleration at which both masses are moving.

ELEVATORS AND ATWOOD's MACHINE

Figure 3.11



The supporting cable in elevators passes up over a pulley and then back down to a heavy, movable counterweight, as shown in Figure 3.11. Gravitational forces acting downward on the counterweight create tension in the cable. The cable then exerts an upward force on the elevator cage. Most of the weight of the elevator and passengers is balanced by the counter-weight. Only small additional forces from the elevator motors are needed to raise and lower the elevator and its counterweight. Although the elevator and counter-weight move in different directions, they are connected by a cable, so they accelerate at the same rate. Elevators are only one of many examples of machines that have large masses connected by a cable that runs over a pulley.

To find tension T, we can put the value of a in either equation 1 or 2

for equation 1 $$T = m_1 g - m_1 \times \frac{(m_1 - m_2)}{(m_1 + m_2)} g$$

taking $m_1 + m_2$ as LCM $$T = \frac{m_1 g \times (m_1 + m_2) - m_1 g \times (m_1 - m_2)}{(m_1 + m_2)}$$

or $$T = \frac{\cancel{m_1^2 g} + m_1 m_2 g - \cancel{m_1^2 g} + m_1 m_2 g}{(m_1 + m_2)}$$

therefore $$T = \frac{2 m_1 m_2}{(m_1 + m_2)} g \quad \text{——} (3.13)$$

Example 3.8 ELEVATOR (AS ATWOOD MACHINE)

Let the elevator is going up with mass of counter weight as 1200 kg Assume the mass of the elevator when carrying passengers is 1000 kg. Calculate a. the acceleration of the elevator and b. the tension in the cable.

SOLUTION

GIVEN:
mass of counter weight m_1 = 1200 kg
mass of elevator m_2 = 1000 kg
acceleration due to gravity g = 9.8 ms^{-2}

REQUIRED:
acceleration a = ?
tension T = ?

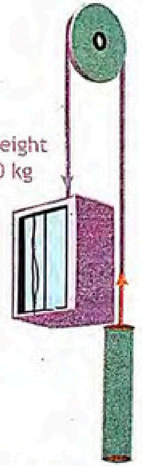
a) From Atwood's machine equation for acceleration

$$a = \frac{(m_1 - m_2)}{(m_1 + m_2)} g$$

putting values $a = \frac{(1200\,kg - 1000\,kg)}{(1200\,kg + 1000\,kg)} \times 9.8\,ms^{-2}$

or $a = \frac{200\,\cancel{kg}}{2200\,\cancel{kg}} \times 9.8\,ms^{-2}$

therefore $a = 0.89\,ms^{-2}$ — Answer



The elevator accelerates downward (and the counterweight upward) at an acceleration of 0.89 m/s^2

b) From Atwood's machine equation for tension

$$T = \frac{2m_1m_2}{(m_1 + m_2)} g$$

putting values $T = \frac{2 \times 1200kg \times 1000kg}{(1200kg + 1000kg)} \times 9.8\,ms^{-2}$

or $T = \frac{2400000kg^{\cancel{2}}}{2200\cancel{kg}} \times 9.8\,ms^{-2}$

or $T = 10691\ kgms^{-2}$ as $N = kgms^{-2}$

therefore $T = 10691\,N$ — Answer

The tension in the elevator cable is 10691 N

EXTENSION EXERCISE 3.3

If both mass of elevator cabin and counter weight are equal as 1000 kg. What is the acceleration and tension in the cable.

Assignment 3.8 SIMPLE ATWOOD MACHINE

Two bodies of mass 3.5 kg and 1.5 kg are tied to ends of string which passes over a pulley. Find a. the acceleration of bodies and b. the tension in string.

LAB WORK

To determine the value of "g" by the Atwood's machine.

3.7 UNIFORM CIRCULAR MOTION

When a body moves in a circle we call it circular motion, for example, a famous amusement ride is Ferris wheel (shown in picture) which makes us move in a circle. Circular motion is of two types - uniform circular motion and non-uniform circular motion. **When the speed of the moving object does not change as it travels in the circular path, it is called uniform circular motion.** However when there are variations in speed, for an object moving in circular path we call it non-uniform circular motion.

3.7.1 CENTRIPETAL ACCELERATION

Acceleration can be produced in a body either by increasing or decreasing its magnitude of velocity (known as speed) or by changing direction of velocity. When an object moves in a circle, it continuously changes its direction. This means that, the object moves at a tangent to the circular path in which it travels. The velocity vector is also directed along the tangent. We can demonstrate this with a simple experiment.

Tie a ball to a string, and rotate it around head by holding one end of the string so that the stone travels in a circle.

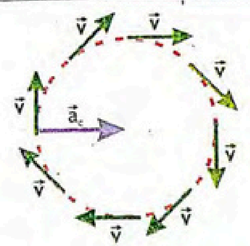
If you let go of the string, the ball will travel in a straight line. This shows that velocity vector is directed along tangent. The same phenomena is used in hammer throw game, when athlete whirl and let the hammer go it travels a straight distance.

However, as there is a continuous change in the direction, an object moving in a circle is always accelerating. This acceleration is directed inwards, towards the center of the circular path, and is known as **centripetal acceleration**. For an object of mass m moving with velocity v, in the circle of radius r, the centripetal acceleration a_c is

$$a_c = -\frac{v^2}{r} \qquad (3.14)$$

The negative sign shows that acceleration is directed towards the center.

Figure 3.12



When a particle moves in uniform circular motion its velocity vector changes direction at every point resulting in centripetal acceleration a_c.

3.7.2 CENTRIPETAL FORCE

To produce an acceleration, a net force has to act on the system. The net force is directed perpendicular to the velocity vector, towards the center of the circular path. This force is called the centripetal force. In the absence of the centripetal force, the object will travel in a straight line. Hence, the effect of the centripetal force is to continuously change the direction of the moving object, forcing it to move in a circle.

The centripetal force F_c by Newton's second law of motion can be written as

$$F_c = ma_c$$

putting value from equation 3.14 , we get

$$F_c = -\frac{mv^2}{r} \qquad (3.15)$$

3.7.3 APPLICATIONS OF CENTRIPETAL FORCE

The following are some daily life application of centripetal force.

A) Banking of Road:

When a car moves along a curve, centripetal force is required. In the absence of this force, the car will skid off the road. The force of friction between the tyre and the road provides this centripetal force and keeps the car moving on the curved path. However if the tyres are worn out or the road is slippery due to some rain, snow or oil spill, the friction will be not be enough to provide necessary centripetal force.

For extra protection level of the outer edge of a round track is kept slightly higher than that of the inner edge known as banking of road. In this case the normal

component of the vehicle increase friction to provide necessary centripetal force for safe turning around the circular track.

That is, roads must be steeply banked for high speeds and sharp curves. Since the race car tracks are designed for high speeds, every turn has its own limiting speeds to pass, depending upon banking provided.

TID-BITS

Race car coming towards a curve. From the tire marks we see that most cars experienced friction force to give them the needed centripetal acceleration for rounding the curve safely. But, we also see tire tracks of cars on which there was not sufficient force—and which unfortunately followed more nearly straight-line paths.

B) Centrifuge:

A centrifuge is a device that separates substances suspended in a liquid by spinning a sample of liquid very quickly around an axle. Any small denser particles found in the liquid travel in a straight line inside the test tube, obeying Newton's first law. The liquid in the test tube applies a centripetal force on these particles to keep them moving in a circle. After running the centrifuge at high speed for a period of time, the particles become clumped together at the bottom of the test tube, which can be collected and the sample is analyzed.

The same Centrifuge principle can be used in these commonly used devices.

(i) Separator:

A separator is a Centrifugal device that separates milk into cream and skimmed milk. In this machine milk is whirled rapidly. Since milk is a mixture of light and heavy particles, when it is rotated the light particles gather near the axis of rotation whereas the heavy particles go away and hence cream can easily be separated from milk.

(ii) Washing Machine dryer:

Washing machine dryer is a kind of centrifuge. The dryer consists of a long cylinder with small holes on its walls. Wet clothes are placed in this cylinder, and then rotated rapidly. Water moves outward to the wall of the cylinder and is drained out through the holes. In this way clothes become dry quickly.

Example 3.9 BUG ON DISK

Suppose this bug has a mass m = 5.0 g and sits on the edge of a compact disc of radius 6.0 cm that is spinning such that the bug velocity is 1.2 m/s. Find **a.** the centripetal acceleration of the bug and **b.** the total force on the bug.

SOLUTION

Given

mass m = 5 g = 0.005 kg

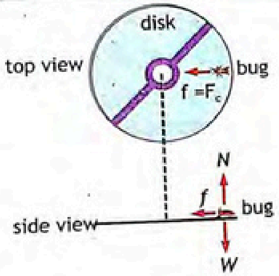
velocity v = 1.2 m/s

radius r = 6 cm = 0.06 m

REQUIRED:

(a) centripetal acceleration a_c = ?

(b) centripetal force F_c = ?



The centripetal acceleration of bug is

$$a_c = -\frac{v^2}{r} \quad \text{putting values} \quad a_c = -\frac{(1.2\,ms^{-1})^2}{0.06\,m}$$

$$\text{or} \quad a_c = -\frac{1.44\,m^2s^{-2}}{0.06\,m}$$

therefore $a_c = -24\,ms^{-2}$ — Answer

The centripetal force on bug is $F_c = m a_c$

putting values $F_c = 0.005\,kg \times 24\,ms^{-2}$ or $F_c = 0.12\,N$ — Answer

Assignment 3.9 MASS OF PLANE

A pilot is flying a small plane at 56.6 m/s in a circular path with a radius of 188.5 m. The centripetal force needed to maintain the plane's circular motion is 1.89×10^4 N. What is the plane's mass?

KEY POINTS

- Dynamics: The branch of mechanics in which we discuss the motion of bodies along with causes of motion of bodies.
- Force: Force is a physical quantity which moves or tends to move a body, stops or tends to stop a moving body or which tends to change the speed and direction of a moving body.
- Newton 1st Law of Motion: This law states that every body continues in its state of rest or uniform motion in a straight line unless an external net force acts upon it.
- Newton Second Law of Motion: This law states that whenever a net force acts on a body, it produces acceleration in the direction of the net force. The acceleration is directly proportional to the net force and inversely proportional to the mass of the body.
- Newton Third Law of Motion: This law states that to every action there is an equal and opposite reaction.
- Mass: The quantity of matter in a body is called its mass.
- Weight: The downward force with which the earth pulls a body towards its center is called weight of the body.
- Momentum: The product of mass and velocity is called momentum. It is a vector quantity.
- Law of Conservation of Momentum: This law states that if there is no external force applied to a system, the momentum of that system remains constant.
- Force of Friction: The force which opposes the motion of an object while in contact with its surroundings is called the force of friction.
- Uniform Circular Motion: If a body moves in a circular path with a uniform speed, it is said to be in a uniform circular motion.
- Centripetal Force: The force which compels a body to move in a circular path is called centripetal force.

PROJECTS

GROUP - A

ROLLER COASTER: Many amusement-park rides utilize centripetal acceleration to create thrills for the park's customers. Choose two rides that involve circular motion and to explain the physics of circular motion creates the sensations for the riders. Prepare a presentation to be presented in physics class.

PROJECTS

GROUP - B

TYRES IN PAKISTAN, ARE PEOPLE AWARE?: Research tyre types used in Pakistan. What type of tyres are better in hot and dry conditions, cold and snowy regions and in wet weather? Interview few people who drive and gather information whether they know the advantages and disadvantages of wide tyres and treads on tyre .

Photograph different types of tyre treads found on cars in your school parking or a local tyre store. Think, to which of the tyres you photographed provides the shortest stopping distance on dry roads, snow, and ice. Use Internet ., electronic and print resources to collect data on the stopping distances for the tyres you have chosen. Compare these results to your predictions. Make a catalogue of your research and place it in school library for reference.

GROUP - C

ROAD BARRIERS: Design an experiment that uses a dynamics cart with other easily found equipment to test whether it is safer to crash into a steel railing or into a container filled with sand. How can you measure the forces applied to the cart as it crashes into the barrier? If your teacher approves your plan, perform the experiment. Write how your research will prove to produce more effective highway barriers.

GROUP - D

CONVEYER BELTS: What are conveyer belts. Research different conveyer belts and their uses. In terms of static and kinetic friction analyze the fabric of different conveyer belts, used in industry. Prepare a presentation, charts and models for conveyer belt.

GROUP - E

GUN TEST: An inventor is testing his new rifles during the target-shooting segment of an event. The new 0.75 kg guns shoot 25.0 g bullets at 615 m/s. The shooting team coach has hired you to advise him about how these guns could affect the accuracy. Prepare figures to justify your answer, display them on chart. Be ready to defend your position.

EXERCISE

MULTIPLE CHOICE QUESTIONS

1. A 30 kg object is supported from rope, such that tension in the rope is equal to its weight. the weight of the object is
   A. 30 kg B. 30 N C. 294 N D. 9.8 N/kg
2. Force needed to produce an acceleration of 10 ms^{-2} in a ball of mass 0.5kg is
   A. 20 N B. 10.5 N C.9.5 N D. 5 N
3. Ball A collide with ball B which is at rest, after the collision which of the following condition is not possible
   A. ball A comes to rest and ball B start moving
   B. both balls move in same direction
   C. both balls move in opposite directions
   D. both balls are at rest
4. What is the mass of a car that is traveling with a velocity of 20 m/s[W] and a momentum of 22000 kg m/s[W]
   A. 440000 kg B. 21980 kg C. 22020 kg D. 1100 kg
5. An object at earth and taken to moon should have
   A. less mass/less weight B. same mass/more weight
   C. same mass/less weight D. less mass/same weight
6. The unit of coefficient of friction is
   A. N B. kg C. μ D. it has no units
7. The centripetal acceleration for an object of mass 1 kg moving with 6 m/s in a circle of radius 3 m is.
   A. 18 ms^{-2} B. 12 ms^{-2} C. 10 ms^{-2} D. 2 ms^{-2}
8. How many times the centripetal force will increase if the mass of a body moving with uniform speed in a circle is doubled?
   A. Six time B. Two times C. Four times D. Eight times
9. Which of the following forces can act as a centripetal force
   A. tension B. friction C. gravitational force D. All of these

⑩ An empty suitcase is placed in the middle of bus on its floor traveling at high speed. When the bus brake suddenly, the suitcase slide

A. backwards B. forward C. jumps up D. remains in place

⑪ In Newton's third law the action reaction pair does not neutralize each other, because they

A. act on same body B. act on different bodies

C. act on third body D. produce friction

CONCEPTUAL QUESTIONS

Give a brief response to the following questions.

1. Why does dust fly off, when a hanging carpet is beaten with a stick?
2. If your hands are wet and no towel is handy, you can remove some of the excess water by shaking them. Why does this work?
3. Why a balloon filled with air move forward, when its air is released?
4. Why does a hose pipe tend to move, backward when the fireman directs a powerful stream of water towards fire?
5. Your car is stuck in wet mud. Some students on their way to class see your predicament and help out by sitting on the trunk of your car to increase its traction. Why does this help?
6. How does friction help you walk? Is it kinetic friction or static friction?
7. The parking brake on a car causes the rear wheels to lock up. What would be the likely consequence of applying the parking brake in a car that is in rapid motion?
8. Why is the surface of a conveyor belt made rough?
9. Why does a boatman tie his boat to a pillar before allowing the passengers to step on the river bank?
10. In uniform circular motion, is the velocity constant? Is the acceleration constant? Explain.
11. You tie a brick to the end of a rope and whirl the brick around you in a horizontal circle. Describe the path of the brick after you suddenly let go of the rope.
12. Why is the posted speed for a turn lower than the speed limit on most highways?

COMPREHENSIVE QUESTIONS

Give an extended response to the following questions.

1. What is force? What are its unit. Distinguish between contact and non-contact forces?
2. State and explain Newton's three laws of motion. Give one example of each.
3. What is weight? Differentiate between mass and weight.
4. Define momentum. Relate force to change in momentum.
5. Define isolated system. Explain the law of conservation of momentum.
6. Define collision and explosion. Explain change in momentum in terms of collision and explosion.
7. What is friction. What are microscopic basis of friction? What is normal force, how it affects friction.
8. Differentiate between static and kinetic friction by giving an example. Find the expression for the coefficient of kinetic and static friction.
9. What are advantages and disadvantages of friction. Also give methods to reduce and improve friction.
10. What is tension? If two connected bodies of masses m_1 and m_2 are hanging from the ends of a string which is passing over a pulley, find the values of tension and acceleration in it.
11. What is uniform circular motion. What are the factors on which magnitude of acceleration (centripetal acceleration) in uniform circular motion depends.
12. What is centripetal force? Explain how centripetal force is used in banking of roads and centrifugation.

NUMERICAL QUESTIONS

1. 1580-kg car is traveling with a speed of 15.0 m/s. What is the magnitude of the horizontal net force that is required to bring the car to a halt in a distance of 50.0 m?
2. A bullet of mass 10 g is fired with a rifle. The bullet takes 0.003 s to move through barrel and leaves with a velocity of 300 ms^{-1}. What is the force exerted on the bullet by the rifle?