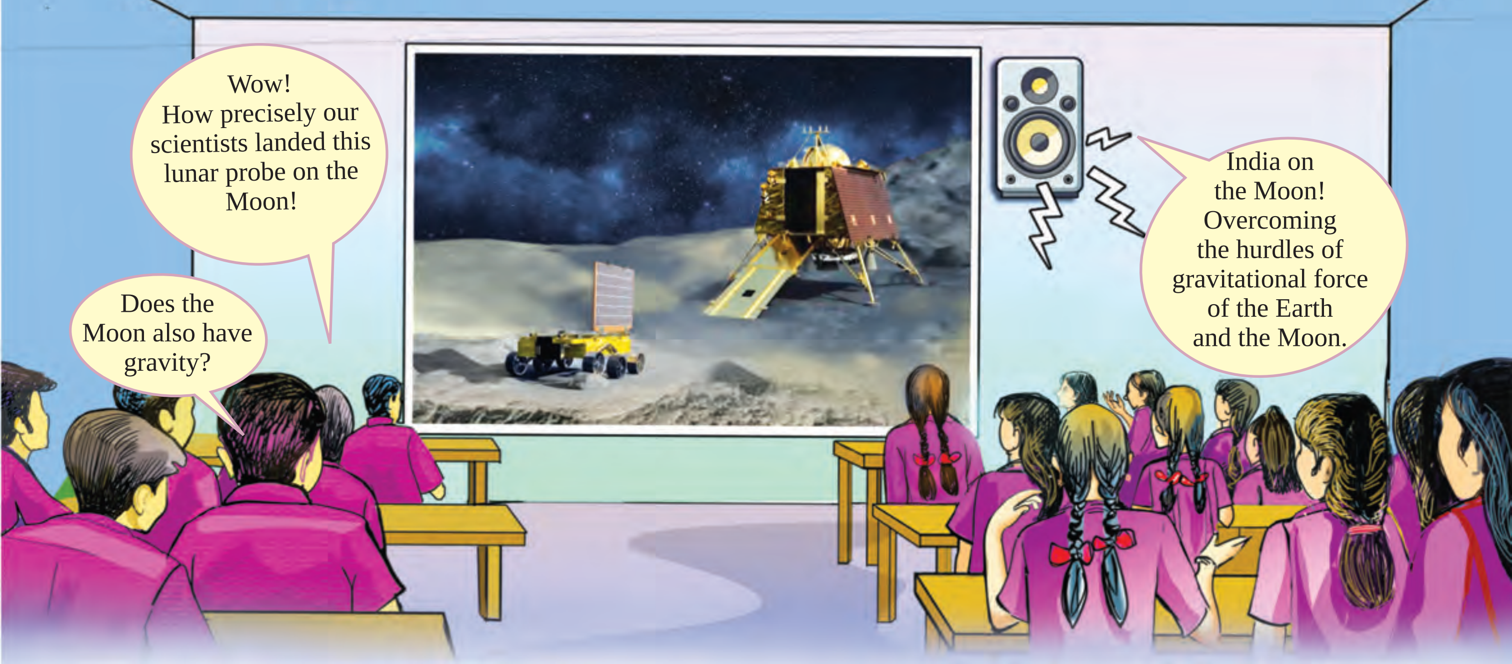
4 Gravitation



You may have noticed that fruits and leaves fall to the ground from the trees around us. Have you ever wondered why a stone thrown up and a bird's feather fall to the ground?

- From where did the stone and the feather get the force they needed to fall?
- Imagine dropping stones in wells at various places around the Earth. Aren't stones attracted to the bottom of the well?
- Do the people standing on the opposite hemisphere of the Earth fall down? Isn't this due to the attraction of the Earth?

Fig. 4.1

Fig. 4.2

Can we measure this force of attraction?

Earth attracts all objects. The direction of this force is towards the centre of the Earth. This force of attraction is the force of gravity.

Let's do an activity.

Fasten a spring balance to the grill of a window.

Pull its hook with your hand.

- Why did the spring stretch?

The spring is stretched due to the force applied by the hand.

- What is the reading on the spring balance?
- Isn't this the force that we applied?
- What is the unit of force?


Fig 4.3

Suspend a mass of 100 g from a spring balance.

- Why did the spring stretch?
- Which is the force that pulled down the 100 g mass?
- What is the reading on the spring balance?

Isn’t this the force that attracted the object to the Earth?

Let’s see the factors on which this force of attraction depends.

Repeat the experiment using a 200 g mass instead of a 100 g mass.

- Why does the spring balance experience more stretching force?
- What happens to the force of attraction as mass increases?

  (increases /decreases)

- If so, write down a factor that influences the force of attraction.

Is mass the only factor that influences the force of attraction?

The force of attraction on an object at different positions on the Earth is given in the table.

Mass of the object (kg)	Height from the surface of the Earth (m)	Attractive Force (N)
100	On the surface (0)	980
100	1,00,000	950
100	10,00,000	730

Table 4.1

Analyse the table and answer the following questions.

- Where did the object of mass 100 kg experience a greater force of attraction?

  (on the surface /at a height of 1,00,000 m / at a height of 10,00,000 m)

- As the distance from the Earth to the object increases, the force of attraction exerted by the Earth

  (increases / decreases)

Record what you have learnt about gravity in your science diary.

- Earth attracts all objects to its centre.
- As the mass of the object increases, the force of attraction increases.
- As the distance from the object increases, the force of attraction decreases.

Is Earth alone exerting such a force of attraction?

Thanu Padmanabhan

Life time : 1957 - 2021
Birth Place: Thiruvananthapuram

He won gold medals in BSc and MSc from University College, Thiruvananthapuram. He gave fundamental contributions in the field of cosmology and gravitation. He introduced a new approach to the gravitational cosmology which is different from that of Newton and Einstein. He received many honours like Padma Shri, Kerala Shastra Puraskaram etc.

Have you heard about high tides and low tides that occur on the Earth? Aren't tides caused by the influence of gravitational force on the Earth by the Moon and the Sun?

- If the Sun and the Moon exert a force on the Earth, wouldn't the other celestial bodies of the universe also exert a mutual force of attraction between them?

Universal Law of Gravitation

Sir Isaac Newton was the first to formulate a comprehensive law of the force of attraction between objects in the universe. This is the Universal Law of Gravitation.

Universal Law of Gravitation

All objects in the universe attract each other. The force of attraction between two objects is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.

If F is the force between two objects of masses m_1 and m_2, separated by a distance d, then,

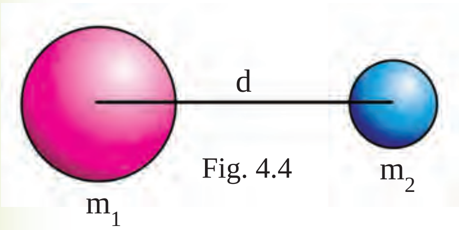


Fig. 4.4

$F \propto m_1 \times m_2 \qquad F \propto \frac{1}{d^2}$

therefore, $F \propto \frac{m_1 m_2}{d^2}$

ie., $\mathbf{F = G\frac{m_1 m_2}{d^2}}$

PhET→ Gravity Force Lab

G is known as gravitational constant. The value of G is 6.67×10^{-11} Nm^2/kg^2. The value of G is constant everywhere in the universe. The scientist, Henry Cavendish later on determined the value of G through experiments.

When two objects of mass 1 kg each are separated by a distance of 1 m, the force of attraction between them will be G newton.

Complete the table 4.2 based on Newton's Universal Law of Gravitation and answer the questions given below.

Sl.No	Mass of the objects kg		Distance between the objects m	Mutual force of attraction N
1	5	10	2	$\frac{G\times10\times5}{2^2} = 12.5\,G$
2	10	10	2	G × ---------- = ----------
3	10	30	2	G × ---------- = ----------
4	5	10	4	G × ---------- = ----------
5	5	10	1	G × ---------- = ----------
6	5	10	$\frac{1}{2}$	G × ---------- = ----------

Table 4.2

- Two mutually attracting objects are placed at a fixed distance between them. If the mass of one of them is doubled, how many times will the force of attraction between them be?
- What if the mass of one object is doubled and the mass of the other tripled?

- What if the distance between the objects is doubled?
- What if the distance between the objects is halved?
- What if the distance between the objects is quartered?
- Calculate the gravitational force of attraction between two children of masses 40 kg and 50 kg when they are 2 m apart.

$m_1 = 40$ kg $\quad m_2 = 50$ kg $\quad d = 2$ m

$$F = G\frac{m_1 m_2}{d^2} = \frac{6.67 \times 10^{-11} \times 40 \times 50}{(2)^2} \text{ N}$$

$$F = 500 \times 6.67 \times 10^{-11} \text{ N}$$

$$= 3335 \text{ x } 10^{-11} \text{ N}$$

$$F = 3.335 \times 10^{3} \text{ x } 10^{-11} \text{ N}$$

$$F = 3.335 \text{ x } 10^{-8} \text{ N}$$

$$F = 0.00000003335 \text{ N}$$

Fig. 4.5

Haven't you realised that the force of attraction between the children is not felt because it is very feeble? This force is very small that it cannot even be compared to other forces like frictional force, magnetic force etc. Therefore, this force is not experienced in everyday life!

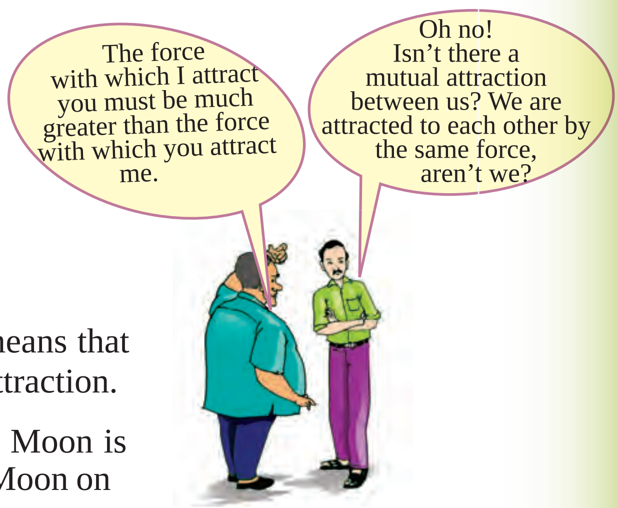


Fig. 4.6

Here, the children of mass 40 kg and 50 kg attract each other with a force of $3.335 \text{ x } 10^{-8}$ N. This means that both of them are experiencing the same force of attraction.

? If the force of attraction of the Earth on the Moon is F, what will be the force of attraction of the Moon on the Earth?

We know that objects accelerate due to continuous application of force. If so, will there be an acceleration due to the force of gravity?

Acceleration due to Gravity

Isn't it the gravitational force that causes the detached coconut to fall from a coconut tree? The coconut falls down because of the downward acceleration produced by the unbalanced force exerted by the Earth on the coconut.

Fig. 4.7

A heavy body and a light body are dropped down together from a certain height.

- Which one reached first?
- Which one will experience greater acceleration?

According to Newton's second law of motion, F = ma

If F is the force of attraction of the Earth and m is the mass of the object, then a is the acceleration due to the force of attraction of the Earth.

The acceleration of objects by the force of gravity is known as acceleration due to gravity. It is denoted by the letter g.

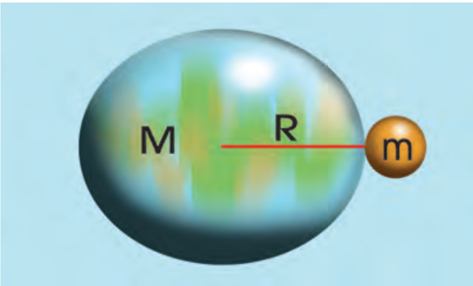


Fig. 4.8

Let's consider the mass of the object as m, mass of the Earth as M and the radius of the Earth as R, then according to the Law of Gravitation, the force of attraction exerted by the Earth is,

$$F = \frac{GMm}{R^2}$$

But, according to the second law of motion, the force required to give acceleration g to an object of mass m is F=mg.

ie., $$mg = \frac{GMm}{R^2}$$

$$\mathbf{g = \frac{GM}{R^2}}$$

- What is the unit of g?
- Is the mass of the object included in this equation?

From this equation it is clear that the acceleration due to gravity is independent of the mass of the object.

Haven't you understood why objects of different masses falling simultaneously from the same height reach the ground at the same time?

- If mangoes and leaves fall down from a mango tree at the same time, will they reach the ground together? What will be the reason?

How to calculate the distance from the centre of the earth to the coconut on the coconut tree.

When we consider the distance between the centre of the Earth and the top of the coconut tree, shouldn't we add radius of the earth and the height of the coconut tree?

As the height of the coconut tree is very small compared to the radius of the Earth, the addition of this distance with the radius of the Earth will not change the value significantly.

- A piece of paper and a coin are dropped down together from the same height. What do you observe?
- Repeat the above activity after crumpling the paper. What difference do you observe now?

It is due to the influence of air that objects like leaves, feather, paper, etc., fall down slowly.

With the advent of technology to create vacuum, this inference was proved by experiments. Feather and coin experiment is one of them.

Feather and Coin Experiment

A coin and a feather are placed in a long transparent tube. When it is held vertically and then suddenly turned upside down, it is seen that the feather reaches the bottom shortly after the coin. If the air inside the tube is removed and the experiment is repeated, it can be seen that both the feather and the coin reach the bottom simultaneously.

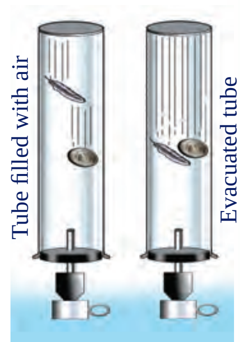


Fig. 4.9

Based on this experiment, are you able to explain why feather, leaf, paper, etc., fall slowly on to the ground?

Let's calculate the value of g on the Earth.

Mass of the Earth M $= 6 \times 10^{24}$ kg

Radius R $= 6.4 \times 10^{6}$ m

$$g = \frac{----------}{----------} = \frac{----------}{----------} = 9.8\ m/s^2$$

Is the acceleration due to gravity the same everywhere on the Earth?

Observe the figure.

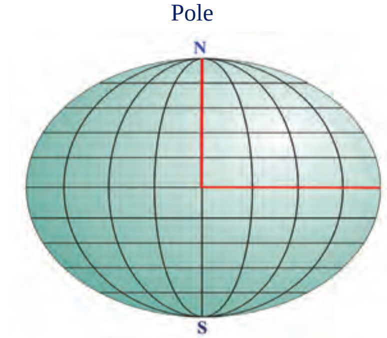


Fig. 4.10

- Does the Earth have a perfect spherical shape?
- Which region of the Earth is the farthest from its centre?

  (polar region / equatorial region)
- Which region lies closer to the centre of the Earth?
- How does the value of g vary as the distance from the Earth's centre to the surface changes?

  Verify your answer using the equation, $g = \frac{GM}{R^2}$
- Where is the value of g maximum?

  (at the polar region /at the equatorial region)
- The forces of attraction on an object at the centre of the Earth, from all sides of the Earth are equal. If so, what will be the value of g at the centre? Discuss and record.

Approximate value of g in the equatorial region = 9.78 m/s^2.

Approximate value of g in the polar region = 9.83 m/s^2.

Fig. 4.11

Gravitational force is a force of mutual attraction. When the engine ceases working, the aeroplane falls down to the Earth. But the Earth does not move towards the aeroplane even though the aeroplane attracts the Earth. Why? Let's examine.

Let's calculate the gravitational force between an aeroplane and the Earth when the aeroplane of mass 10000 kg is at a height 10 km above the surface of the Earth.

m = 10000 kg = 10^4 kg

Height from the surface of the earth, d = 10 km = 10000 m = 10^4 m

$$F = \frac{GMm}{R^2}$$

$$F = \frac{G \times 6 \times 10^{24}\text{kg} \times 10^4\ \text{kg}}{(6.4 \times 10^6 + 10^4\text{m})^2}$$

$$= \frac{(6.67 \times 10^{-11} \times 6 \times 10^{28})}{(6.41 \times 10^6)^2}\ \text{N}$$

$$= 97400\ \text{N}$$

Let's find the acceleration of the aeroplane produced by the above force.

F = mg

$$g = \frac{F}{m} = \frac{97400}{10000} = 9.74\ \text{m/s}^2.$$

Isn't the aeroplane exerting the same force on the Earth as that exerted by the Earth on the aeroplane?

Let's calculate the acceleration of the Earth due to the force exerted by the aeroplane

$$g = \frac{F}{M} = \frac{97400}{6 \times 10^{24}} = 1.6 \times 10^{-20}\ \text{m/s}^2 = 0.000000000000000000016\ \text{m/s}^2.$$

The acceleration of the Earth is almost zero. Although the forces of attraction between the aeroplane and the Earth are equal, the Earth will not experience any considerable acceleration. This is due to the enormous mass of the Earth, as compared to the aeroplane.

When the same force is applied, objects with a greater mass will experience lesser acceleration.

Will the values of acceleration due to gravity on the Earth and the Moon be the same?

Acceleration due to gravity on the Moon

Mass of the Moon $M = 7.34 \times 10^{22}$ kg

Radius of the Moon $R = 1.74 \times 10^{6}$ m

$$g = \frac{GM}{R^2}$$

$$g_{Moon} = 1.62 \text{ m/s}^2$$

$$\frac{g_{Moon}}{g_{Earth}} = \frac{\text{Value of g on the Moon}}{\text{Value of g on the Earth}}$$

$$= \frac{\ldots\ldots\ldots\ldots\ldots\ldots}{\ldots\ldots\ldots\ldots\ldots\ldots}$$

$$= \text{----------------}$$

That is, the value of g on the Moon is approximately $\frac{1}{6}$th of the value of g on the Earth.

Black hole

Black holes are cosmic matter with such a strong gravity that even light cannot escape from them.

Based on Albert Einstein's theory on gravitation, the possibility of the presence of black holes was predicted in 1916. But proper evidence of its presence was found in 2017. Scientists could create a shadow image of a massive black hole at the centre of a distant galaxy named M 87. Evidence of a giant black hole at the centre of the Milky Way, our galaxy, has been recently established.

Stars which have several times the mass of the Sun are likely to turn into black holes in the last stages of their evolution. There are many such black holes in galaxies.

An artificial satellite of mass 10000 kg stops working and falls down to the Earth. We know that attraction between objects is mutual. The satellite attracts the Earth with the same force with which the Earth attracts the satellite.

Height from the Earth = 5000 m, Radius of the Earth $R = 6.4 \times 10^6$ m

a) What is the acceleration of the satellite?

b) What is the acceleration of the Earth?

(Mass of the Earth = 6×10^{24} kg)

An object of mass 10 kg is allowed to fall to the ground from a height of 20 m.

a) How long will it take to reach the ground?

b) Calculate the time required to reach the ground, if it is on the Moon.

$$g_{Earth} = 10 \text{ m/s}^2, \quad g_{Moon} = 1.62 \text{ m/s}^2$$

A stone is thrown vertically upwards from the lunar surface. If the stone returns in 6 s,

a) what is the initial velocity of the stone?

b) what is the distance that can be covered by the stone?

c) what will be the position of the stone after 4 s?

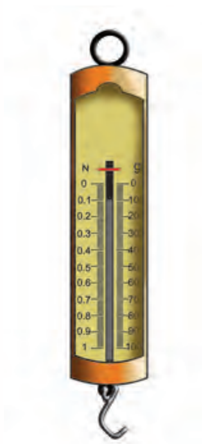
We usually say that a sack of cement weighs 50 kg and a sack of cement has a mass of 50 kg. Do they mean the same? Let's analyse.

Mass and Weight

You have learned that the mass of an object is the quantity of matter contained in it. Which instrument is used to measure mass? Mass of an object is determined by comparing it with the mass of another object using a common balance. What is the unit of mass?

Common balance
Fig. 4.12 (a)

Weight is a force. The weight of the object on the Earth is the gravitational force exerted by the Earth on that object. When an object is on the Moon or other celestial bodies, the weight of the object at that place is the force exerted by those bodies on the object. If the mass of an object is m, then its weight will be mg. Weight is measured using devices such as spring balance, platform balance, etc. The unit of weight is newton (N).



Spring balance
Fig. 4.12 (b)

Another unit of weight is kilogram weight (kgwt). Usually kilogram weight is marked as kg on a spring balance. What is the weight of an object of mass 50 kg?

1 kilogram weight (1 kgwt)

One kilogram weight (1kgwt) is the force of attraction exerted by the Earth on an object of mass one kilogram.

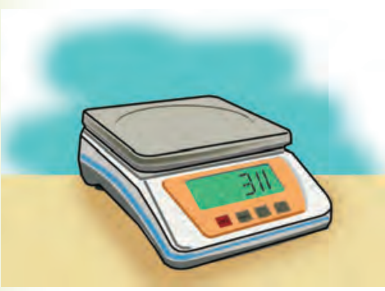
$F = ma = mg$

1 kgwt = 1 kg × 9.8 m/s^2 = 9.8 kgm/s^2 = 9.8 N

ie., 1 kgwt = 9.8 N.

Weight of an object of mass 50 kg = mg = 50 kg × 9.8 m/s^2 = 490 N

This is also known as 50 kgwt.



Platform balance
Fig. 4.12 (c)

The mass of an object is 10 kg. Calculate its weight on the Earth. What would be its weight if it were on the moon? (g_{Moon} = 1.62 m/s^2)

Weight on the Earth = mg = 10 × 9.8 = 98 kgm/s^2 = 98 N

$$g_{Moon} = 1.62\ m/s^2$$

Weight on the Moon = mg_{Moon} = 10 × 1.62 = 16.2 N

The mass of an object remains the same everywhere in the universe. Then what about its weight? Compare mass and weight and complete the table.

Mass	Weight
• Measured using common balance •	• Measured using spring balance •

Table 4.3

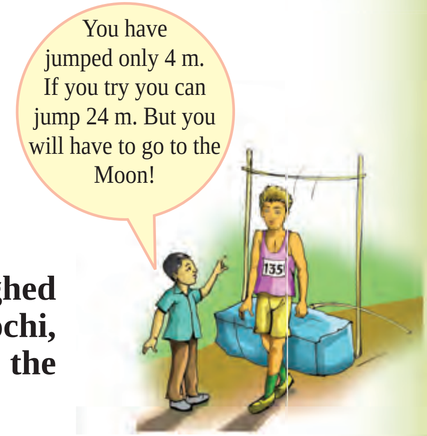


Fig. 4.13

When goods shipped from Kochi to England were weighed in England using the same spring balance used in Kochi, the weight was found to be 20 N more. What could be the reason? Discuss and write it in the science diary.

Is an object heavier at the poles or at the equator? Justify your answer.

What will be the weight of an object at the centre of the Earth?

Does the weight of an object change while falling down to the Earth?

Free Fall and Weightlessness

Hook a 20 g mass on a spring balance and hold it. Bring it down quickly.

- What will be the change in the reading at this time?

  (increases /decreases)

If these are allowed to fall freely, the reading can be seen as zero.

> If an object is allowed to fall freely from a height, it will fall to the ground only under the gravitational force of the Earth. Such a motion is called free fall.

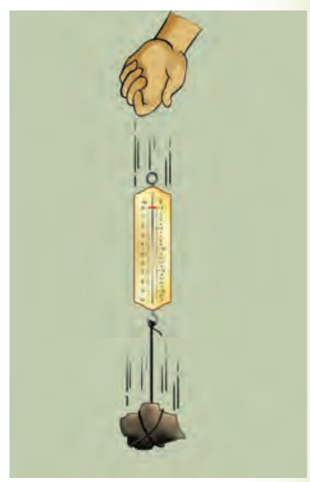


Fig. 4.14

We know that a freely falling object has acceleration. The force required for acceleration is provided by the force of gravity. It is also clear from the experiment that if the entire force of gravity is used to provide acceleration, the object will be weightless.

What are the instances in which weightlessness is experienced?

- For a person who orbits the Earth in space stations
-

Why does a freely falling body experience weightlessness? Write it down in your science diary.

Isn't the motion of a freely falling stone in a straight line? But what type of motion do artificial satellites have? Write down examples for such types of motion.

- Whirling a stone tied to a string
-

Circular Motion


Fig. 4.15

A stone tied to a string is whirled as shown in the figure 4.15. Isn't its motion in a circular path? This is circular motion. If the stone moving along a circular path covers equal distances at equal intervals of time, then it is in uniform circular motion.

- Does this object have uniform velocity though it has uniform speed? Why?
- Does this object experience any force?
- If the string is released from the hand, in which direction will the stone move? Won't it be along the tangent? (figure 4.16).

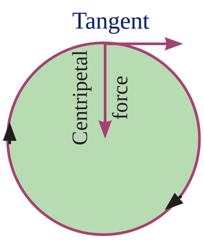


Fig. 4.16

The rate of change of velocity is acceleration. Acceleration of an object moving along a circular path is centripetal acceleration. The force required for this acceleration is centripetal force. Who gave this force? Isn't it our hand?

- If there is no centripetal force, can there be circular motion?

It is due to the centripetal force that electrons revolve around the nucleus of an atom, planets revolve around the Sun, the Moon revolves around the Earth etc.

Negotiating a curve

The path travelled by a body should be considered circular even if it is not a full circle and only an arc. That is why we say that vehicles are moving along a circular path while negotiating a curve.

It is due to the centripetal force that vehicles negotiating curves on a road tend to skid or roll off the curve. Mass and speed of the vehicle and curvature of the road are the factors that influence the tendency of the vehicle to roll over.

Will the path followed by the objects moving under centripetal force be circular or curved?

- If so, from where do the artificial satellites orbiting around the Earth get their centripetal force?
- Isn't it the Earth's gravitational force that is acting as the centripetal force?

Chandrayaan-3, which marked a new beginning in India's field of science, overcame the same gravitational force and landed on the moon.

Wouldn't satellites require a lot of energy to overcome Earth's gravity and enter the outer space? Hence large rockets are used to launch satellites. This increases the expense of the mission. The technological advancements used for the launch of Chandrayaan helped it to land on the Moon using less powerful rockets than the lunar missions of other nations. The speed of the lander will increase on reaching the Moon due to the Moon's gravity. Soft landing was done by gradually reducing this increased speed. It was this excellence in technology that the children praised at the beginning of this lesson.

Let's Assess

1. If an object is lifted from the centre of the Earth to its surface, will the mass and weight of the object change? Justify the answer.
2. The weight of an object of mass 5 kg is determined using a spring balance. If the object and the spring balance are dropped down together, what will be the weight of the object while falling down? What is the reason?
3. Will there be a change in the mass and weight of an object brought to the Moon from the Earth? Justify the answer.
4. An object is allowed to fall from the top of a tower of height 100 m. At the same time, another object was thrown vertically up with a velocity 25 m/s in order to collide with the object falling down (g_{Earth} = 10 m/s^2, g_{Moon} = 1.62 m/s^2).
   a) Calculate the time taken by them to collide.
   b) Find out the height from the ground at which they collide.
   c) Would the answers obtained in the above case change, if this activity was carried out on the Moon? Justify.

5) The gravitational force on the lunar surface is approximately $\frac{1}{6}$th that of the Earth.
   a) What is the weight of an object of mass 10 kg on the Earth?
   b) If this object is taken to the surface of the Moon, what will be its mass and weight?

6. Objects with a larger mass are attracted by the Earth more strongly than objects with a smaller mass. So, if an object with a larger mass and an object with a smaller mass are allowed to fall from the same height,
   a) which one will reach the ground first?
   b) Justify the answer.
7. Explain the difference between mass and weight.
8. The masses of a stone and a hydrogen-filled balloon are equal. If both are placed on the same ground, will the force of attraction exerted by the Earth on them be the same? Justify the answer.
9. A stone falling from the top of a tall building reaches the ground in 2 s (g = 9.8 m/s^2).

a) Calculate the height of the building.

b) What will be the velocity of the stone just before touching the ground?

10. Find examples of circular motion from the following and tabulate.

- Electrons revolving around the nucleus
- A child running a 100 m sprint
- Planets revolving around the Sun
- A train running along a railway track with no curves
- Moon orbiting around the Earth

11. What will be the weight of an object of mass 10 kg on a planet having twice the mass and three times the radius of the Earth?

12. The mass of a planet is half of the Earth and the radius is $\frac{1}{4}$ times that of the Earth. The acceleration due to gravity of the planet is ..... times that of the Earth.

a) $\frac{1}{4}$ b) 4 c) $\frac{1}{8}$ d) 8

13. A body falling freely from a certain height takes 50 s to reach the ground. How much time will the same object take to fall from the same height on another sphere having twice the radius and twice the mass of the Earth? (Answer : $50\sqrt{2}$ s).

14. The mass of an object is 100 kg. Calculate its weight at the centre of the Earth, the polar region, the equatorial region, the Moon and the Jupiter (g on the Jupiter = 23.1 m/s^2).

Extended Activities

1. Make a still model of the Solar System and exhibit it in the class. It should include the Moon and an artificial satellite orbiting the Earth.

2. The values of g in various planets are given. There is an object of mass 100 kg. Determine the weight of the object on these planets.

Planet	Acceleration due to gravity in m/s^2 (Approximate value)	Weight(N)
Earth	9.8	
Mercury	3.7	
Venus	8.9	
Mars	3.7	
Saturn	9.00	
Uranus	8.7	
Neptune	11.00	

Table 4.4