Chapter 11

Gravitation

In the chapter of force and motion, you have come across several such examples where an object moves towards the surface of earth. Like when a stone is thrown upwards, away from the surface of earth, it comes back to the earth's surface. Drops of rain, dry leaves, dust particles, everything falls back on the surface of earth. Have you ever thought why does every object fall back on earth?

Why does the velocity of a pebble increase on reaching the surface of earth when its thrown from a height above the earth's surface?

You learnt in earlier classes that several earth-like planets in solar system revolve around the sun and moon-like satellites revolve around the planets. In such a situation, why does earth not fall on the sun or moon does not fall on the earth?

Activity-1

Tie a wooden block with a thread. Hold the free end of the thread with your hands while you drop down the other end which is tied to the block. What happend?

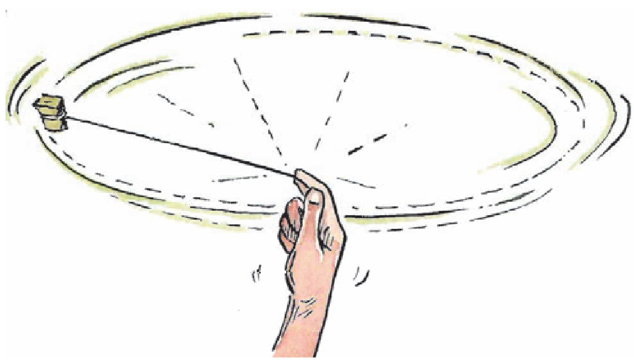


Fig. 1 : circular motion of the wooden block

Now slowly move the block in a circular motion, as shown in the fig.1. Move it faster and see what happens. Do you feel more pull on your finger?

If you drop the thread while moving the block fastly or if the thread breaks off, to which direction does the block go? Does the block keep moving in a circular path even after the thread breaks off? Have you thought about the direction of motion of the block? Discuss amongst yourself.

Experiment carefully and find out what happens if we gradually reduce the speed of the motion of the block.

1.1 Concept of Gravitation

In the above activity you saw that a thread holds the block moving in a circular path even when it moves in a very high speed. But there is no such strong thread between the earth and the moon which keeps the moon connected. Then what is the force which causes the moon to revolve around the earth continuously?

For a long time people thought that attracting the moon and other objects is a characteristic property of earth and thats why the moon and all other stars revolve around the earth. But this belief did not agree with various observation of our solar system and other planets. It also did not coincide with the coppernicus theory of sun centric solar system or with kepler's laws which were based on several observations of solar system. According to them, if sun is at the centre and planets are revolving around it just like moon revolves around the earth, then we must believe that the way earth attracts moon, sun must also attract earth towards it.

In this regard, Sir Isaac Newton studied various works of other scientists and made several observations to conclude that the force of attraction does not only exist between the earth, moon and the sun but also between all small-big things of this world. Stones, dust particles, water molecules, planets, stars etc. all exert a force of attraction on each other due to their masses. This property of attraction due to mass is called as gravitational force.

According to Newton, the force of attraction existing between any two bodies of the universe depends upon their masses and the distance between them.

As shown in fig. 2, consider that two bodies A and B are placed at a 'distance r' from each other. They are attracting each other with a force of attraction 'F'. The masses of bodies A and B are 'm_1', and 'm_2' respectively. According to Newton's law the force acting between them must be directly proportional to the product of their masses.

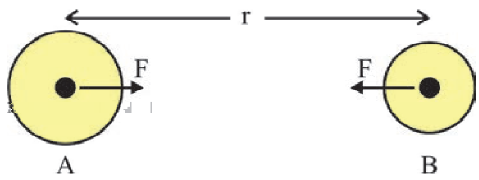


Fig. 2 : Gravitational force between two bodies

That means, $F \alpha\ m_1 \times m_2$ ....(1)

Also, the force between the two bodies is inversely proportional to the square of the distance between them.

$$F \alpha \frac{1}{r^2} \quad ....(2)$$

$$F \alpha \frac{m_1 \times m_2}{r^2} \quad ....(3)$$

$$F = G \frac{m_1 \times m_2}{r^2} \quad ....(4)$$

The value of G was unknown at the time of Newton. In 1797, Cavendish placed two bodies of known masses at a certain distance and found out the force of attraction between them. Using the eq. (4) he then calculated the value of G..

Here G is a universal gravitational constant. The value of G in SI units is 6.67×10^{-11} Nm^2/kg^2.

Suppose that the distance between two bodies is doubled, then what will be the force between the two? And what happens when the distance is trippled? We can see that the value of force decreases with the increase in distance.

- Can you tell what effect will the increase or decrease of the value of G have on our daily lives? What would have happened if there was no gravitational force? Discuss with your friends in a group.

Example 1. The mass of earth is 6×10^{24} kg and the mass of sun is 2×10^{30} kg. If the average distance between the earth and the sun is 1.5×10^{11} m then calculate the force exerted by the sun on the earth. What will be the force exerted by earth on the sun?

Solution : The force exerted by earth on the sun and the force exerted by sun on earth are equal. By calculating one of the two forces we can find the other.

According to eq (4), the force of attraction between the earth and the sun,

$$F = G\frac{m_e \times m_s}{r^2}$$

Where m_e = mass of earth = 6×10^{24} kg;

m_s = mass of sun = 2×10^{30} kg;

r = average distance between earth and sun = 1.5×10^{11} m; G = 6.67×10^{-11} Nm^2/kg^2

Hence;

$$F = \frac{6.67 \times 10^{-11} \times 6 \times 10^{24} \times 2 \times 10^{30}}{(1.5 \times 10^{11})^2} N$$

$$F = \frac{6.67 \times 6 \times 2 \times 10^{-11} \times 10^{24} \times 10^{30}}{(1.5^2 \times 10^{11})^2} N$$

$$= \frac{6.67 \times 6 \times 2 \times 10^{-11+24+30-22}}{1.5^2} N$$

$$= \frac{6.67 \times 6 \times 2}{1.5^2} \times 10^{21} N = 35.57 \times 10^{21} N$$

Therefore the earth and the sun attract each other with a force of 35.57×10^{21} N.

Activity-2

Calculate the force of attraction between you and a friend sitting at a distance of 1 m from you. Do you feel this force? If not then why?

11.2 Gravitational acceleration 'g'

In the chapter on motion you read that when a body is subjected to a force, an acceleration is produced in the body. The acceleration produced in a body due to earth's gravitational force is called as gravitational acceleration. Gravitational acceleration is denoted by 'g'.

From eq. (4) and with the help of Newton's law of motion we can find out the value of 'g'. Suppose that a body of mass 'm' is placed on surface of earth. Earth exerts a force of 'F' on that body.

From eq. (4)

$$F = G\frac{M\times m}{R^2} \quad ....(5)$$

M : mass of earth, R = distance of earth's surface from its centre, m = mass of the body

How much acceleration will be produced in the body due to the gravitational force?

According to second law of motion by Newton, if the acceleration is 'g' then,

$$F = mg \quad ....(6)$$

From eq. (5) and (6), we get

$$mg = G\frac{M\times m}{R^2}$$

$$g = G\frac{M}{R^2} \quad ....(7)$$

With the help of eq. (7) we can calculate the value of 'g'. Mass of earth is $M = 6 \times 10^{24}$ kg and radius is $R = 6.4 \times 10^6$ m.

On calculating, we get the value of $g = 9.81 \text{ m/s}^2$. For simplification we will put the value of g as 10 for all mathematical calculations in this chapter. Is the value of 'g' same at all places on earth?

Does the value of 'g' depend on the mass of the body, volume, nature, density, position above the surface of earth or the distance from the centre of earth? Which all factors amongst these are more important?

Is the value of 'g' on the equator of earth and the poles same? Where will its value be greater? Discuss with your friends.

11.3 Free fall

As shown in the fig. 3, a boy throws a ball upwards from the surface of earth. The path of the ball moving upwards and then downwards is shown as ABCDE. Here A is the initial position of the ball P, C is its maximum height and E is its final position.

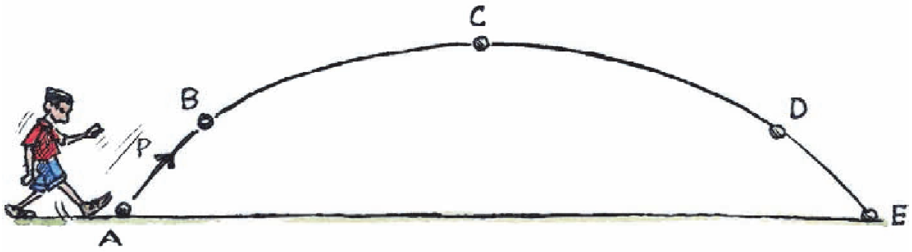


Fig. 3 : The path of the motion of ball P

- Can you state which forces are applied on the ball P at the positions B,C,D and E.
- Other than gravitational force is there any other force working on the ball P which is responsible for the motion of the ball?
- Is the same force exerted on the ball when it is kicked? If yes, then for how long is it applied?
- How much acceleration is produced on the ball due to this applied force? If in this path, the ball P is subjected to only gravitational force by earth then why is the path of the motion of the ball as shown in the figure? All these questions are obvious.

It is always considered that if a body is in motion, there must be a force applied on the body in the direction of motion. But this is not always the case. You have seen in the chapter of force and motion that it is not necessary that if a body is in motion then there must always be a force acting on it. From the second law of motion we also saw that the force exerted on a body is directly proportional to the change in its momentum. But it is not necessary that it is always in the direction of momentum. If it is in the direction opposite to momentum it will decrease the momentum.

In reality, every moving object is subjected to a force exerted by wind in the opposite direction. But this force is very little and therefore it is always negected by us for simplicity.

When we apply a force on an object to throw it upwards, we actually provide it with an initial velocity. This initial velocity and momentum requires force. We exert a force in the beginning while throwing the object, but the question is does this applied force still exist on the object after it leaves our hand?

According to first law of motion, application of force produces motion and due to inertia the body keeps moving upwards. After it leaves our hand, the only force acting on the body is gravitational force. Thus, the acceleration produced in the body is only due to this gravitational force.

That situation in the motion of an object where only the gravitational force exists is called as free fall. Can you think of more such situations where the body is in a state of free fall? Discuss in a group.

You have read about the equations of motion in the chapter on motion. On replacing the acceleration 'a' by 'g' in those equations, we show that this acceleration is produced due to earth's gravitational force.

Equations of motion with gravitational acceleration.

1. $v = u + gt$
2. $v^2 = u^2 + 2gh$, (h = height of object from the surface of earth)
3. $h = ut + \frac{1}{2} gt^2$

Let us understand this using some examples. Suppose you drop down two objects A and B having different masses from a height of 100 m. above the surface of earth. The masses of A and B are 2 kg. and 10 kg. respectively. What will be their speeds after covering a distance of 10 m? After covering the next 10 m what will be their speeds? Calculate their speeds after every 10 m distance and fill in the following table 1.

Table 1 : Position, time and speed of objects during free fall.

Travelled distance	**Speed of object A**	**Speed of object B**	**Time taken by object A to cover the distance (s)**	**Time taken by Object B to cover the distance (S)**
0				
10			$\sqrt{2}$	
20	20 (approx)			
....				
100		$20\sqrt{5}$		$2\sqrt{5}$

On the basis of this table draw a graph between position-time, speed-time and position-speed of the object.

Does the mass of an object affect its speed?

Example 2. A stone is dropped from the top of a 20 m. tower. What will be its velocity just before touching the surface of earth? Calculate time taken by the stone to reach the earth's surface. Take the value of 'g' as $10 m/s^2$.

Solution :(i) Height of tower, $h = 20$ m

initial velocity of the stone $u = 0$

$g = 10 m/s^2$

$$s = ut + \frac{1}{2} gt^2$$

$$\Rightarrow 20 = 0 \times t + \frac{1}{2} 10t^2$$

$\Rightarrow 5t^2 = 20$

$\Rightarrow t^2 = 4$

$\Rightarrow t = 2s$

Hence, time taken by the stone to reach the earth's surface is 2 sec.

(ii) Velocity of the stone-

$v = u + gt$

$= u + 10 \times 2$ m/s (u=0)

= 20 m/s

Hence, the speed of stone reaching the earth's surface is 20ms^{-1}.

Example 3. A ball thrown upwards vertically comes back to the thrower in 6 sec. Tell-

1. What was the velocity of the ball thrown?
2. What was the maximum height reached by the ball?
3. Position of the ball after 4 sec.?

Solution :(i) initial velocity of ball, u = ?

final velocityof ball, v = 0

Time taken by the ball to reach the maximum height t = 3 sec.

Object goes upwards in first 3 sec., and in next 3 sec. it comes downwards

So, total time taken by the ball to cover the complete distance is = 3s + 3s = 6s

Velocity of the ball

$v = u - gt$

$o = u - 10 \times 3$ m/s

u = + 30m/s

(ii) Maximum height attained by the ball.

$$s = ut - \frac{1}{2}gt^2$$

$$= 30 \times 3 - \frac{1}{2} \times 10 \times 3^2 \text{ m}$$

= 90 – 45 m

= 45 m

(iii) Distance covered by the ball in 1 sec. of returning.

$$s = ut + \frac{1}{2} gt^2$$

$$= 0 + \frac{1}{2} \times 10 \times 1^2 m$$

$= 5$ m

So, position of ball after 4 sec. is 45 m – 5 m = 40 m.

Question

1. An object of mass 'm' is dropped from a height 'h' above the surface of earth. What will be its velocity just before reaching the surface of earth?
2. As shown in the fig. 4. Throw a ball vertically upwards with a speed of 5 m/s. How much height will the ball reach and after how long will it return back to your hands. In which position of the ball, its speed will be minimum and what will be its value?

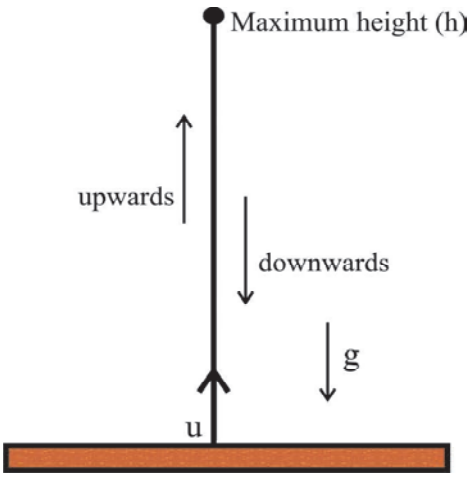


Fig. 4 : Speed of ball

11.4 Mass and Weight

You know that inertia depends upon mass. The total quantity of material in an object is known as its mass. If the total measure of the quantity of the object remains unchanged then the mass of that object remains constant at all positions. Mostly we measure an object on the basis of its mass, for example, 2 kg. of rice, 1 kg. of pulses, 3 kg. of sugar etc. If we take 2 kg. mass of rice to the moon, we will find that the mass of rice will remain 2 kg. on the moon as well. The SI unit of mass is kilogram (kg.)

The force by which an object is attracted towards the earth is called the weight of an object. The SI unit of weight is Newton (N).

From the eq. (6) we know that the earth exerts a force 'mg' on an object of mass 'm' kg. placed at a certain position on earth. That means, the weight of the object having 'm' kg. mass will be 'mg' on that particular position on earth.

Do you think the weight of an object will be same at all positions on earth? Will the weight of the object remain constant on the earth, moon and the sun?

Question

1. Mass of the moon is $M_{moon} = 7 \times 10^{22}$ kg. and its radius is $R_{moon} = 1700$ km. Using the eq. (7), find out the value of acceleration on the surface of moon for an object of mass 'm'.
2. Compare the weight of an object of mass 'm' on the surface of earth and the moon.
3. The distance between the centres of earth and the moon is 3.84×10^5 km. How much force will they exert on each other?

Activity-3

Find out the masses of three of your classmates. Calculate and find the force exerted on them by earth. How will the forces exerted on them change if they were taken to the moon?

11.5 Centre of Gravity

You might have seen a child or a person walking on a thick rope in a fair or somewhere near your house. How does that person balance himself on that rope?

While walking on the rope, he spreads both of his hands or takes support from a horizantal stick in his hand. Have you ever wondered why he does this?

Fig. 5

Activity-5

Can you get up from a chair without bending?

Sit comfortably on a chair as shown in the fig.6. Now without bending your legs try to get up from the chair.

- Are you able to do it? If not then why?

Activity-6

Try to balance a long bamboo stick on your palm.

In which situation is this possible?

Here we will introduce you to the concept of 'centre of gravity'.

The average or balanced position of weight distribution is known as centre of gravity. This point where the total weight of the object appears to be concentrated at is called as centre of gravity.

Fig. 6

Activity-7

To find the centre of gravity.

Take a metre scale. Now using your index finger try to balance it horizontally at different points. What do you see? Can you balance the scale at its middle point? Why does this happen?

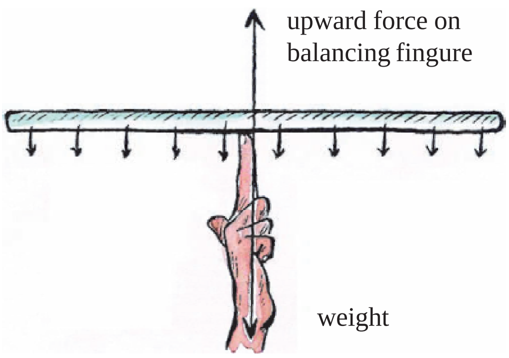


Fig. 7

The centre of gravity of an object having fixed shape is at its centre. The complete weight of the scale is considered to be concentrated at that point. By just giving a support to that particular point, the complete scale can be supported.

We can easily find the centre of gravity of an object by balancing it. The small arrows shown in the figure represent the gravitational forces acting on the scale. the sum of all those forces is equialent to the resultant force at the centre of gravity.

The complete weight of the scale is concentrated at this particular point. Thus a single force acting at this point in upward direction balances out the metre scale.

- How can we find out the centre of gravity of any object?

The centre of gravity of a freely suspended object is right below its suspension point.

If a vertical line passing through the point of suspension is drawn then the centre of gravity would lie somewhere on this line. To know its exact position suspend the object from some other point and draw another vertical line from that point. The point of coincidence of these two lines is the centre of gravity.

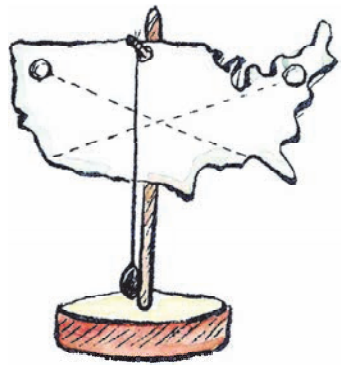


Fig. 8

Similarly the centre of gravity of a person walking on a rope is right in his centre. By taking support from a long wooden stick he tries to shift the centre of gravity downwards (towards his knee or legs) so that he can easily walk on the rope.

Activity-8

To find out the centre of gravity of a ring.

In the above activity it is explained that how to find centre of gravity. On the same basis we can find out the centre of gravity of a ring.

- Where will be the centre of gravity of a ring?

- Can a body have its centre of gravity outside it?
- Can the centre of gravity be somewhere where there is no mass?

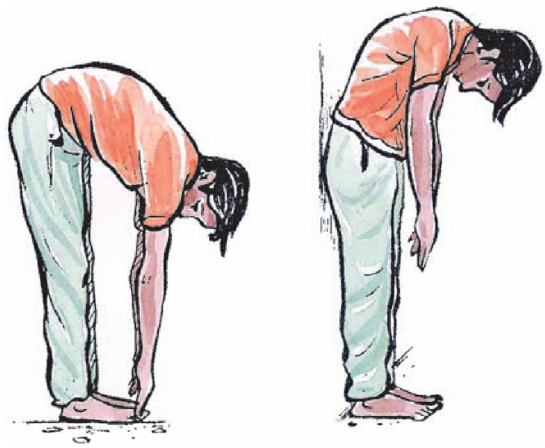
Stability

It is essential to know the centre of gravity for stability. Draw a line vertically downward from the point of centre of gravity for any object having any shape, if the line lies within the base of the object, then the object will remain stable.

But if the centre of gravity is outside the base of the object than the object will be unstable.

Activity-9

Change in centre of gravity and its affect.



(a) (b)

Fig. 9

Where is your centre of gravity when you are standing straight?

Try touching your toe. Try doing the same while standing close to a wall (as shown in the fig. 9 (b).

- In the position shown in fig. 9 (b) are you able to touch your toe? If not then why?
- In both the cases what difference do you see in the centre of gravity of your body?

Think

- Where will be the centre of gravity of a sphere and a triangular table?
- Can a body have more than one centre of gravity?
- Why does the leaning tower of pisa not fall?
- Why do you bend forward when you lift a heavy load on your back?

What we have learnt

- Due to their masses, all the objects in the universe exert a force of attraction on each other. This property of attraction due to mass is called as gravitational force (It is a central force).
- The universal gravitational constant is denoted by G. The value of G is 6.67×10^{-11} Nm^2/kg^2.
- The value of gravitational acceleration is 9.81 m/s and is denoted by g.
- A freely falling body falls on earth with an acceleration 'g'.
- The mass of a body is constant. But the weight of a body depends upon the gravitational acceleration acting on it.

Keywords :- Gravitation, Universal gravitational constant, Mass, Free path, Centre of gravity..

Exercise

1. Multiple choice questions-

(i) The gravitational force between two bodies does not depend on-

(a) The distance between both the bodies.

(b) Product of their masses

(c) Sum of their masses

(d) Gravitational constant

(ii) The value of G is-

(a) 7.67×10^{11}Nm^2/kg^2 (b) 6.67×10^{11}Nm^2/kg

(c) 6.67×10^{-11}Nm^2/kg^2 (d) 5.67×10^{11}Nm^2/kg^2

(iii) The value of gravitational acceleration on the surface of earth is-

(a) 9.8 m/s^2 (b) 8.8 m/s^2

(c) 4.8 m/s^2 (d) 8.9 m/s^2

(iv) According to universal law of gravitation, the force acting between two bodies of masses m_1 and m_2 placed at a distance R is-

(a) $F = G\dfrac{m_1m_2}{R^2}$ (b) $F = G\dfrac{m_1m_2}{R^4}$

(c) $F = Gm_1m_2/R$ (d) $F = G\dfrac{M}{R}$

(v) A body is moving upwards opposing the gravitational pull of earth. What will be its velocity at the highest point reached?

(a) 0 (b) $u^2/2g$

(c) h/t (d) 2gh

2. Fill in the blanks-

(i) On earth, the weight of a body having 10 kg. mass will be ....

(ii) A body falling from rest from a height h will have a velocity of ....

(iii) Value of universal gravitational constant is ....

(iv) The value of gravitational acceleration in SI units is ....

(v) If two objects of different masses are dropped from a same height, they will reach the surface of earth at .... time.

3. What will be the gravitational force between earth and an object of 1 kg. placed on its surface. Here, the mass of earth is 6×10^{24} kg, and distance from the earth to the earth's surface is 6400 km.

4. What will be the gravitational force between two objects if-

(i) The mass of one object is doubled.

(ii) The distance between the objects is tripled.

(iii) Mass of both the objects is doubled.

5. Why does a sheet of paper fall slower than a ball made up of that sheet.

6. What is the importance of the universal law of gravitation.

7. Why does earth not travel towards the moon, if moon attracts the earth?

8. A ball is thrown vertically upwards with a speed of 49 m/s. Calculate-

(i) Maximum height of the ball

(ii) Total time taken by the ball to reach the earth's surface.

9. If a body is thrown vertically upwards at a speed of 10 m/s then after how much time and with what velocity will it reach back to us?

10. The force of gravitation between two bodies is F. In what situation will the force between the two become 4 F?

11. Why do two objects having different mass reach the surface of earth simultaneously? Is the force of gravitation acting on both of them equal?

12. Derive an equation to find the acceleration produced due to earth on an object of mass 'm'. Also find its value.