7

Motion and Force

		
Figure 7.1 Parachute landing Perseverance Rover sent from Earth to the planet Mars	*Figure 7.2 Rocket used to send Perseverance Rover*	*Figure 7.3 The International Space Station in orbit about 400 km above Earth (ISS)*

Stones dropped from our hands, fruits falling from trees, etc. move towards the Earth. The earth attracts various objects toward its center. Moon and Earth are also attracting each other. Figure 7.1 shows the parachute being used for the safe landing of the Perseverance Rover sent from Earth to Mars. That means, Mars also attracts objects toward its center.

Gravitation and Newton's universal law of gravitation

When Sir Isaac Newton, a British mathematician/physicist, saw a fruit falling from a tree to the ground, he began to wonder why the fruit did not fall horizontally but only vertically. After doing much study and thinking, he concluded that the attraction between the apple and the earth caused the fruit to fall towards the centerof the earth. Similarly, he wondered how the planets, moon, sun, stars, etc. are stuck in the sky.

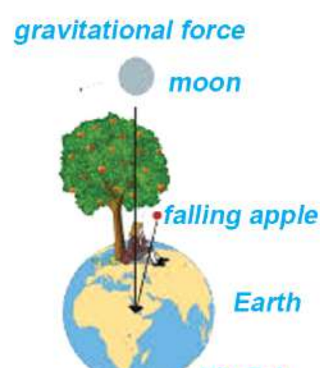


Fig 7.4

After a long study, Newton concluded that there exists a force of attraction between all bodies. He named this force gravitation. In 1687, he propounded the Universal Law of Gravitation.

Activity 7.1

In Figure 7.5, the calculation of gravitational force between two bodies is shown. These values were obtained using the PhET Interactive Simulations on the Internet.To open this activity on your computer, open the internet browser and type https://phet. colorado.edu/sims/html/gravity-force-la latest/gravity-force-lab_en.htmlon the search bar. In the simulation, the mass of the sphere and its distance can be changed through the slider. The two cases of changing the massand changing the distance are presented in the table below. Study them and draw suitable conclusions from thegiven data.

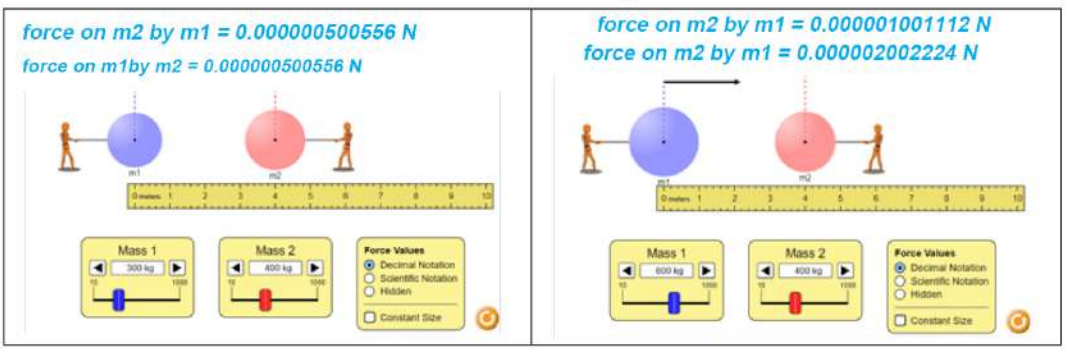


Figure 7.5 Difference in gravitational force between two objects when their mass is changed

(a) First, doubling the mass of the first sphere while keeping the mass of the second sphere and the distance between them the same, and then doubling the mass of both spheres keeping the distance between them constant.

The force between two masses before changing the mass (F_1)	After changing mass		The force between two masses (F_2)	Conclusion
	First mass (m_1)	Second mass (m_2)		
0.000000500556 N	600 kg	400 kg	0.000001001112 N	$F_2 = 2 F_1$
0.000000500556 N	600 kg	800 kg	0.000002002224 N	....

(b) Doubling the distance between two spheres keeping the mass constant.

first mass (m_1)	Second mass (m_2)	Initial distance (d_1)	force (F_1)	Changed distance (d_2)	force (F_2)	Result
300 kg	400 kg	4 m	0.000000500556 N	8 m	0.000000125139 N	

From this activity, when the mass of one sphere and that of both spheres are doubled, the gravitational force is found to be two times and four times the initial force respectively. Here, when the product of two masses increases four times, the gravitational force is also increased by four times. That is, when the distance is kept constant, the gravitational force is directly proportional to the product of the masses of the two objects. Similarly, when the distance between two spheres is doubled, the gravitational force is found to be reduced by four times. That is, when the mass is kept constant, the gravitational force isinversely proportional to the square of the distance between the two objects.

The collective conclusions of activity 7.1 are included in Newton's universal law of gravitation. According to this law, the gravitational force produced between any two objects in the universe is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.

As shown in figure 7.6, let the mass of the objects A and B be m^1andm^2 respectively, the distance between the centers of these two objectsbe d, and the gravitational force produced between them be F. According to Newton's law of gravity, the gravitational force (F) is directly proportional to the product of the mass of these objects m_1 and m_2,

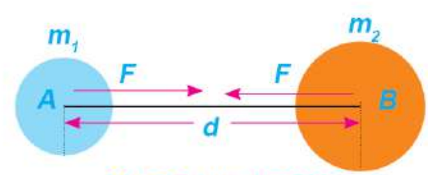


Fig 7.6 two masses

That is, $F \propto m_1 \ m_2$........... (i)

and inversely proportional to the square of the distance d,

That is, $F \propto \frac{1}{d^2}$ .... (ii)

Combining (i) and (ii),

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

$$F = G\frac{m_1 m_2}{d^2} \ldots\ldots\ldots\ldots \text{(iii)}$$

Here, G is the proportionality constant and is also known as the universal gravitational constant. Using equation (iii), the gravitational force between any two objects can be calculated.

The gravitational constant G is the magnitude of gravitational force produced between two unit masses that are separated by unit distance.

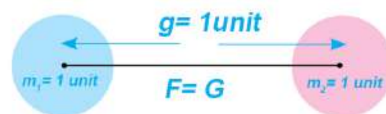


Figure 7.7 Definition of G

As shown in the figure, when $m_1 = m_2 = 1$ kg and $d = 1$ m

$$F = \frac{Gm_1 m_2}{d^2} = \frac{Gx1x1}{1^2} = G$$

The value of the gravitational constant was first measured by Henry Cavendish in 1798 using the Cavendish balance. From that experiment, the value of G was found to be 6.67×10^{-11}. Since its value remains the same regardless of the materials and the medium between the bodies, it is called the universal gravitational constant. Its SI unit is $N\ m^2/kg^2$

Example 7.1

The mass of the Earth is 5.97×10^{24} kg and its radius is 6371 km. Calculate the gravitational force between the Earth and a 1 kg iron sphere on its surface.

According to the information given in the question,

Mass of Earth $(m_1) = 5.97 \times 10^{24}$ kg

Mass of sphere on the surface of the earth $(m_2) = 1$ kg

Radius of the earth(R) $= 6371$ km $= 6371 \times 1000$ m $= 6.37 \times 10^6$ m

The gravitational force between two spheres, $F = \frac{Gm_1m_2}{d^2}$

On substituting the values,

$$F = \frac{6.67 \times 10^{-11} \times 5.97 \times 10^{24} \times 1}{(6.37 \times 10^6)^2}$$

$$\text{or } F = \frac{6.67 \times 5.97 \times 10^{-11+24} \times 1}{(6.37 \times 10^6)^2}$$

$$\text{or } F = \frac{39.82 \times 10^{13} \times 1}{40.58 \times 10^{12}} = 0.986 \times 10^{13-12}$$

$$\text{or } F = 0.981 \times 10 = 9.81\ N$$

$$\therefore F = 9.81\ N$$

The gravitational force between the earth and an iron ball of mass 1 kg on its surface is 9.81N

Example 7.2

The mass of the Moon and the Earth is 5.97×10^{24} kg and 7.34×10^{22} kg respectively. The distance between the Moon and the Earth is 3.84×10^5 km. Calculate the gravitational force between the Moon and the Earth.

According to the information given in the question,

Mass of Earth $(m_1) = 5.97 \times 10^{24}$ kg

Mass of Moon $(m_2) = 7.34 \times 10^{22}$ kg

Distance between the earth and Moon (d) $= 3.84 \times 10^5$ km $= 3.84 \times 10^8$ m

The gravitational force between the earth and moon, $F = \frac{Gm_1m_2}{d^2}$

Substituting the given values,

$$F = \frac{6.67 \times 10^{-11} \times 5.97 \times 10^{24} \times 7.34 \times 10^{22}}{(3.84 \times 10^{8})^2}$$

$$\text{Or } F = \frac{6.67 \times 5.97 \times 7.34 \times 10^{-11+24+22}}{14.75 \times 10^{16}}$$

$$\text{Or } F = \frac{292.28 \times 10^{35} \times 10^{-16}}{14.745} = 19.82 \times 10^{35-16}$$

$$\therefore F = 19.82 \times 10^{19}\ N$$

The gravitational force between the Earth and the Moon is $1.982 \times 10^{20}\ N$.

Question for discussion

As calculated in example 7.1, the gravitational force between the Earth and a sphere of mass 1 kg is 9.8N. This force acts on both objects. However, when the ball is dropped from a certain height, the Earth does not move upwards, but only the ball appears to fall towards the Earth. Why? Using Newton's second laws of motion, calculate the acceleration produced by that force on the sphere with a mass of 1 kg and on the Earth with a mass of 5.97×10^{24} kg.

Variation in gravitational force with mass and distance

The change in gravitational force observed in activity 7.1 can be explained mathematically by using the formula used to calculate the gravitational force. Suppose two objects A and B have masses m_1 and m^2 respectively. If the distance d between those objects is d and the gravitational force in the initial condition is F_1.

then, $F_1 = \frac{Gm_1m_2}{d^2}$ .... (i)

When the mass of an object is made double	When the mass of both objects is made double
Putting, $m_2 = 2\ m_2$ in equation (i) $F_2 = \frac{Gm_1 2m_2}{d^2} = 2\ \frac{Gm_1 m_2}{d^2}$ $F_2 = 2F_1$	Putting, $m_1 = 2\ m_1,\ m_2 = 2\ m_2$ in equation (i) $F_2 = \frac{G2m_1 2m_2}{d^2} = 4\ \frac{Gm_1 m_2}{d^2}$ $F_2 = 4F_1$

On Keeping the distance between two objects constant, increasing the mass of an object by 2 times, the gravitational force also increases by 2 times. Similarly, by increasing the mass of both objects by 2 times, the gravitational force increases by 4 times.

When the distance between the objects is made half	When the distance between the objects is doubled
Putting, $d = \frac{1}{d^2}$ in equation (i) $F' = \frac{Gm_1 m_2}{\left(\frac{d}{2}\right)} = 4\ \frac{Gm_1 m_2}{d^2}$ $F' = 4F$	Putting, $d = 2\ d$ in equation (i) $F' = \frac{Gm_1 m_2}{(2d)^2} = \frac{1}{4}\ \frac{Gm_1 m_2}{d^2}$ $F' = \frac{1}{4}\ F$

If the distance between the two objects is halved, while keeping the mass constant, the gravitational force between the two objects increases by 4 times. Similarly, if the distance between two objects is increased by two times, the gravitational force between those two objects decreases by four times.

Consequences of gravitational force

Some of the consequences of gravitational forces are presented below:

(a) Gravitational force has made the existence of the universe including the solar system possible. The gravitational force between the sun and the planets causes the planets to revolve around the sun.

(b) Since the Moon is closer than the Sun to the Earth, it is important even though it has a very small mass compared to the Sun. The effect of the moon's gravitation is more visible on seawater than on land, due to which tides are created.

(c) Gravitational forces between the earth and the objects on its surface make the objects stick to the surface of the earth. Also, if an object is thrown vertically upwards, the object will fall back on the surface.

Gravity

Earth and other planets and satellites are pulling their nearby objects towards their centers. The force exerted by the planet or satellite on nearby objects is often called the force of gravity. It is also called the weight of the object. According to Newton's universal law of gravitation, the force of gravity decreases with increasing height from the planet and becomes negligible at a certain distance. Therefore, Earth and other planets/satellites have a definite gravitational field.

We observe many effects of Earth's gravity in our daily life. Some of these effects are mentioned below:

(a) All objects have the weight due to gravity.

(b) Earth is surrounded by the atmosphere due to gravity.

(c) Objects dropped from a certain height fall towards the center of the Earth due to its gravity.

(d) Due to the effect of gravity, water in rivers and streams flows downwards.

(e) Force of gravity causes acceleration in a falling object.

Acceleration due to gravity

Activity 7.2 Calculation of acceleration due to gravity

Take a small stone and a stopwatch. Drop the stone from different heights (e.g., first floor, second floor of a building). Drop the stone in such a way that no downward force is applied by the fingers on the stone,i.e.,just release the stone from the hand by loosening the fingers. Tell a friend to record the time taken by the stone to reach the ground using a stop watch.

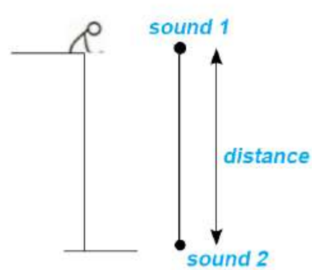


Figure 7.8 Measurement of acceleration due to gravity.

Using the data so obtained and equations of motion ($h=ut+\frac{1}{2}at^2$, $v^2=u^2+2ah$) calculate the acceleration and velocity (final velocity v) of the stone when it hits the ground.While calculating, take the initial velocity of the stone (u) = 0.

A table like the one below can be used for data collection and necessary calculations.

Data collection	h	t	$a=\frac{2h}{t^2}$	**Average acceleration**	$v=\sqrt{(2ah)}$	**Result**
First time	...	...	$a_1=\cdots$	$=\frac{a_1+a_2+a_3}{3}$	$v_1=\sqrt{(2ah_1)}$	....
Second time	...	...	$a_2=\ldots.$		$v_2=\sqrt{(2ah_2)}$	
Third time	...	...	....		$v_3=\sqrt{(2ah_3)}$	

In activity 7.2, the object released from the hand is set in motion due to the earth's gravity, and it acts constantly throughout the motion. The more the object falls, the faster its velocity will be. Increasing the velocity of the object means it is accelerating. Thus, acceleration gets produced in the body falling freely towards the earth's surface because of gravity. In activity 7.2, the acceleration of a falling stone is 9.8m/$s^2$when the air resistance is negligiblei.e., almost zero. Such acceleration is the acceleration due to the gravity of the earth. The acceleration produced in a freely falling object due to the force of gravity is called acceleration due to gravity. It is denoted by 'g' and its SI unit is meter per second squared (m/s^2).

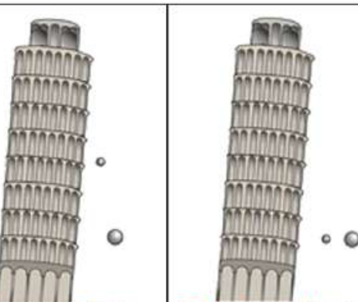
Question to think

Does the acceleration due to gravity vary according to the mass of the falling object?

Activity 7.3

Take a small stone and a sheet of paper. Tear the sheet of paper into two equal parts. Squeeze one of them tightlyinto a ball shape. Drop the sheet of torn paper, a paper ball and a stone together and observe which one reaches the ground first. Do the sheet of paper,the paper ball and the stone fall at different velocities? If this activity was done on the moon, what would be the result?

In this activity, the sheet of paper and the paper ball having the same mass fall at different velocities, but the paper ball and the stone having different masses fall together. Thus, the rate of change in the velocity of an object falling towards the surface of the earth is not related to its mass. When a sheet of paper falls in the air, the air resistance exerts an upward force on it and the velocity decreases, but in the case of paper ball and stone, the air resistance is negligible and they fall together towards the center of the earth only under the influence of gravity.



The perception beforeGalileo's experiment

Confirmation after Galileo's experiment

Figure 7.8 Falling of objects with different masses

Since there is no atmosphere on the surface of the moon, all objects fall freely without obstruction. In such a situation, all objects fall with the same acceleration (acceleration due to gravity). If a sheet of paper and the paper ball, as mentioned in activity 7.3, are dropped together on the surface of the moon, they both fall together

According to the laws of motion propounded by Aristotle, who was born in Greece in 384 BC, heavier objects fall before lighter ones. This law was disproved by Galileo's experiment in the seventeenth century. Around the year 1590 BC, Galileo dropped two balls together from the Leaning Tower of Pisa in Italy and found that both balls hit the ground together. He concluded that all freely falling bodies fall with the same acceleration due to gravity. This was later proved by the feather- and coin experiment.

Feather and coin experiment

In Figure 7.9, a glass cylinder is connected to a vacuum pump. A feather and a coin are placed at its bottom. When the cylinder is turned upsidedown in the presence ofair inside it, the coin falls faster than the feather.If the air is pumped out using the vacuum pump and the cylinder is turned upside down, the coin and the feather are seen to fall together.

Figure 7.9 Featherand coin experiment

The cause of the coin and feathernot falling together the first time is the presence of air resistance inside the cylinder. Since the surface area of the feather is greater than that of the coin, the air resistance acting on the feather is greater than acting on the coin and acceleration is reduced. So the feather falls slower than the coin. The second time, as there is no air inside the cylinder i.e. there is no air resistance, both the feather and the coin fall together. In the absence of air resistance, the acceleration due to gravity is the same for all objects. That is, the value of 'g' does not depend on the mass of the falling body.

Calculation of acceleration due to gravity

Suppose a body of mass 'm' is on the surface of a planet of mass 'M' and radius 'R'. If the force of gravity of the planet acting on the body is 'F', the gravitational force produced between them is,

$$F = \frac{GMm}{R^2} \quad \text{....................} \quad \text{(i)}$$

If this force produces acceleration 'g' in mass 'm', then from the Second law of motion,

$$F = mg \quad \text{......................} \quad \text{(ii)}$$

From the equations (i) and (ii),

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

$$g = \frac{GM}{R^2} \quad \text{......................} \quad \text{(iii)}$$

According to equation (iii) the acceleration depends only on the mass 'M' and radius 'R' of the planet.

Since the mass of the falling object is not included in the equation, it confirms the fact that all the masses have the same acceleration when they fall freely, just like the results of Galileo's activity and feather-coin experiment. In non-spherical planets or satellites like Earth, the value of radius 'R' changes depending on location. In equation (iii) both G and M are constants.

In this case, the acceleration due to gravity is inversely proportional to the square of the radius of the planet or satellite. Hence,

$$g \propto \frac{1}{R^2}$$

Acceleration due to gravity depends upon both the mass and the radius of the planet or satellite. For example, the mass of Jupiter is about 319 times the mass of the Earth, but its acceleration value is only 2.6 times the acceleration due to the gravity of the Earth. The radius of Jupiter has a main role to play in this. The radius of Jupiter is 11 times the radius of the Earth. Since the acceleration due to gravity is inversely proportional to the square of the radius, even though the mass of Jupiter is very large, the net effect on the acceleration due to gravity will be only $\frac{319}{121} = 2.6$ times greater.

On substituting the mass of the earth as 5.972×10^{24} and the radius as 6371 km in equation (iii),

$$g = \frac{6.67 \times 10^{-11} \times 5.972 \times 10^{24}}{(6.371 \times 10^{6})^{2}} = \frac{39.8332 \times 10^{13}}{40.5896 \times 10^{12}} = 9.81 m/s^{2}$$

Since the value of R changes in different places on the earth, the value of acceleration due to gravity is also found to be different.

Variation in acceleration due to gravity of the earth

The earth is not perfectly round. It is slightly flattened at the poles and bulged in the equatorial region. Hence, as shown in Figure 7.10, the radius of the Earth is less towards the poles and more towards the equator. Since the value of the acceleration due to gravity is inversely proportional to the square of the radius of the earth, its value is more at the poles than at the equator. The value of 'g' in the equatorial region is 9.78 m/s^2 and 9.83 m/s^2 in the polar region. As the value of 'g' is higher in the polar region, objects fall faster in the polar region than in the equatorial region.

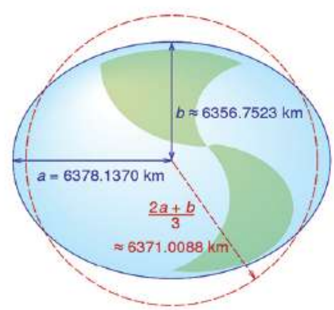
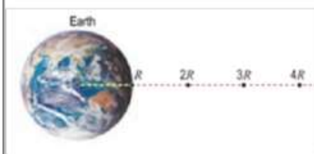


Figure 7.10 Earth's radius

The average value of 'g' on earth is considered to be 9.81m/s^2. This means that the velocity of a freely falling body toward the surface of the earth increases by 9.81 meter per second. In contrast, the velocity of a body projected vertically upwards decreases by 9.81meter per second. The velocity becomes zero at the maximum height that it covers, and then,it returns to the earth.

Height and acceleration due to gravity

Activity 7.4 Comparison of the acceleration due to gravity with increasing distance from the center of the earth

	Distance from the center of the earth (d)	d = 2R	d = 3R	d = 4R
Different distances from center of the Earth	Acceleration due to gravity $g_1 = \frac{GM}{d^2}$	$g = \frac{319}{121} = \frac{319}{121}$ $= \frac{1}{4} \times 9.8 = 2.45\ m/s^2$	....	....

As shown in Figure 7.11, when d = R is the distance from the center of the earth, the value of the acceleration due to gravity, $g_1 = \frac{GM}{d^2}$ = 9.8 m/s^2 Other distance d = 2R, 3R, 4R from the center of the earth are also shown in the same figure. In the table along with the figure, the value of acceleration due to gravity at a distance d = 2R is calculated. Likewise, calculate andcompare the values of acceleration due to gravity that occurs as the distance from the center of the earth goes on increasing.

As the height above the surface of the earth increases, the value of the acceleration due to gravity decreases. Suppose, a satellite at a height h from the surface of the earth is orbiting the earth. The value of the acceleration due to the gravity of the earth at that height h is $g_1 = \frac{GM}{(R+h)^2}$ The value of acceleration due to the gravity of the earth's surface is $g = \frac{GM}{R^2}$ In this case, the distance of the satellite from the center of the earth is d= R+h. Since the value of $(R+h)^2$ is greater than the value of R^2, the value of g1 is less than that of g.

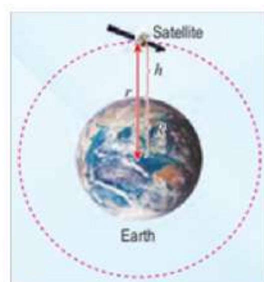


Figure 7.12

Example 7.3

The mass of the earth is 5.97×10^{24} kg and its radius is 6371 km. Calculate the acceleration due to the gravity of the International Space Station situated at an altitude of 400 km above the surface of the earth.

According to the information given in the question,

Mass of Earth (M) $=5.97 \times 10^{24}$ kg

Radius of Earth (R) = 6371 km=6371000 m

Height of International Space Station above the surface of Earth (h)= 400 km = 400000 m

The acceleration due to gravity at that height,

$$g = \frac{GM}{(R+h)^2}$$

$$\text{or,} \quad g = \frac{6.67 \times 10^{-11} \times 5.97 \times 10^{24}}{(6.371000 + 400000)^2}$$

$$\text{or,} \quad g = \frac{39.82 \times 10^{13}}{(6771000)^2} = \frac{39.82 \times 10^{13}}{4.60 \times 10^{13}}$$

$$\therefore \quad g_1 = 8.66\ m/s^2$$

Therefore, the acceleration due to the gravity of the International Space Station at an altitude of 400 km is 8.66m/s^2.

Since, the distance of the top of a hill from the center of the earth is greater than the distance (radius, R) of its bottom from the center of the earth, the value of 'g' is less at the top of the hill than that at its bottom. But such a difference is very small. For example, the height of Mt. Everest is 8848.86 m. The distance from the center of the earth to the peak of Mt. Everest, d= R + h = 6371×1000 m + 8848.86m = 6379848.86 m हुन्छ ।

Putting this value, $g = \frac{GM}{(R+h)^2}$

$$g_1 = \frac{6.67 \times 10^{-11} \times 5.97 \times 10^{24}}{(6.379848.86)^2} = \frac{39.82 \times 10^{13}}{4.07 \times 10^{13}} = 9.78\ m/s^2$$

At the height of Mount Everest, the value of the acceleration due to gravity is only 0.03 m/s2 (9.81-9.78=0.03) less than that on the Earth's surface. So for a small change in the distance from the center of the earth like: (R+ h = 6371 km+8.85 km = 6379.85 km), the velocity also changes by a very small value.

Example 7.4

The value of acceleration due to the gravity of the earth is $9.8 m/s^2$. If the mass of the moon is 7.35×10^{22} kg and its radius is 1.74×10^6 m, what is the acceleration due to the gravity of the moon? Compare the acceleration due to the gravity of the Earth and thatof the Moon.

According to the information given in the question,

Value of acceleration due to gravity of the earth, $g_e = 9.8 m/s^2$

According to the formula for calculating the acceleration of gravity of the moon,

$$g_m = \frac{GM_m}{R_e^2}$$

$$g_m = \frac{6.67 \times 10^{-11} \times 7.35 \times 10^{22}}{(1.74 \times 10^6)^2}$$

$$g_m = 1.62\ m/s^2$$

Taking the ratio of the acceleration of gravity of the earth to the acceleration of gravity of the moon,

$$= \frac{g_e}{g_m} = \frac{9.8}{1.62} = 6.05$$

The value of the acceleration of gravity of the moon is about 6 times less than that of the earth.

Mass and weight

The weight of an object is related to the acceleration due to gravity. The total quantity of matter present in an object is its mass. This is a scalar quantity. Its SI unit is the kilogram (kg). No matter wherever a 1 kg mass of iron is kept either on Earth orthe International Space Station or the Moon or Mars, etc., the quantity of iron in it is always 1 kg. Therefore, the value of the mass of an object does not change according to the place. Like the smallest particle, an electron also has a definite mass. The value of mass is not zero. Similarly, even the smallest mass experiences the force of gravity.

Earth's gravity pulls objects on its surface toward its center.

Weight is the measure of the force of gravity acting on an object. Since weight is the force exerted on an object, its SI unit is the newton (N). This is a vector quantity. Weight is always directed towards the center of the planet/satellite because it is the force of gravity.

Figure 7.13: Measurement of weight by a spring balance

According to Newton's second law of motion, the force of gravity acting on an object of mass 'm', i.e., weight, is $W = mg$. where g is the acceleration due to gravity. The weight of an object dependson the object's mass and acceleration due to gravity.

Since the earth's gravity pulls every object towards its center, a force atleast equal to the force of gravity is to be applied in the upward direction to lift any object from the surface. Depending on the relationship between mass and weight, different forces are required to lift small and large objects. Since the value of acceleration due to gravity at a place remains constant, the weight of the object varies according to its mass. In this case, the weight of the object (W) is directly proportional to its mass (m), i.e.,Weight (W) $\propto$ Mass (m) [Keeping the value of g constant].

Therefore, objects with greater mass weigh more than objects with lesser mass. Hence, more force must be applied to lift an object with a greater mass than an object with a smaller mass. Also, it is easier to lift small stones thanbig ones.

Variation in weight due to change of acceleration due to gravity

The difference in weight for a definite mass depends on the force of gravity. Thus, the weight of an object is directly proportional to the acceleration due to gravity, i.e., Weight (W) $\propto$ Acceleration due to gravity(g) [Keeping mass constant]

Since the value of 'g' on Earth changes according to the location, the weight of the object also changes.

Activity 7.5: Comparison of the weight of an object at different places

As given in the table below, find the pairs of places where the acceleration due to gravity is less/more and mention the difference in the weight of an object at those places:

Pairs of places	place value of the acceleration of gravity is less	place value of the acceleration of gravity is more	Remark
Equatorial and polar regions	Equatorial region	Polar region	The weight of an object is lesser in the equatorial region than that in the polar region.
Base and top of the mountain	....	....	....

The value of the acceleration due to gravity is inversely proportional to the square of the distance from the center of the earth, i.e., $g \propto \frac{1}{R^2}$ Similarly, weight is directly proportional to acceleration due to gravity (W) $\propto g$ .As the value of acceleration due to gravityat placesfar away from the center of the earth such as hilltops, mountains, etc.is less, the weight of an object at those places is also less. At a place on the earth's surface where the value of acceleration due to gravity is maximum, the weight of an object is also maximum at that place. Acceleration due to the gravity of the moon (gm) is six times that of the earth (ge), i.e. $g_m \propto \frac{1}{6} g_e$ Therefore, the weight of an object of a definite mass on Earth is almost 6 times the weight of the same object on the moon. Therefore, one can jump about 6 times higher on the moon than on the Earth. On the moon, a person should be able to lift about 6 times the massas much as he/she can on the earth. Therefore, while comparing the acceleration due to the gravity ofthe Earth and other planets/ satellites, it can also be concluded that the weight of an object on those planets/ satellites is also different. Some examples are presented in the table below.

Mass of an object (m)	acceleration due to gravity (g) m/s^2 and weight (W = mg) in newton on different heavenly bodies									
	moon		mercury		mars		venus		earth	
50 kg	g_1	W_1	g_2	W_2	g_3	W_3	g_4	W_4	g_5	W_5
	1.63	81.5	3.61	180.5	3.75	187.5	8.83	441.5	9.81	490

Example 7.5

Calculate the mass that a person can lift on the moon if he/she can lift a mass of 100 kg on Earth. (Acceleration due to gravity of the moon $g = 1.63\ m/s^2$)

According to the information given in the question,

Mass that a person can lift on earth (M) = 100 kg

Acceleration due to gravity of the earth (g) = $9.8 m/s^2$

Acceleration due to the gravity of the moon (g^1) = $1.63\ m/s^2$

Mass that a person can lift on the moon (m) = ?

The force that human muscles can exert against gravity on the Earth and Moon is the same.

The weight that can be lifted on the moon = Weight that can be lifted on the earth

$$\text{Or } m \times g' = M \times g$$

$$\text{Or } m = \frac{M \times g}{g^1} = \frac{100 \times 9.8}{1.63}$$

$$\therefore \quad m = 601.23 \text{ kg}$$

Therefore, a person who can lift 100 kg on Earth can lift 601.23 kg on the surface of the Moon.

Free fall

As observed in activity 7.3, a sheet of paper and a falling stone can be considered as free fall when the air resistance on them is negligible. In that case, the acceleration of the stone is equal to the acceleration of gravity ($9.8\ m/s^2$) ofthe earth. Thus, an object falling under the influence of gravity alone without any obstruction is said to be in free fall. The acceleration of an object in free fall is equal to the acceleration due to gravity (g).

According to the structure of the objects falling into the earth's atmosphere, the frictional force on them creates a resistanceto their motion. The upthrust on a falling object also helps reduce the effect of the force of gravity. Thus, the actual free fall is possible only in a vacuum. Since there is no resistanceof the atmosphere to a falling body on the moon, free fall is possible.

Activity 7.6 Making a model of a parachute

Take scissors, a thin plastic sheet and thread. Stretch the plastic in different steps and cut it into a circular shape as shown in Figure 7.16. Tie equal pieces of thread at equal distances around the edges of the circular plastic. Tie the open section of the threads in a single knot and attach a toy or stone to it. Drop the prepared parachute model from a height. Observe its fall. Does the parachute fall at a high speed at the beginning and with a uniform speed at the last?

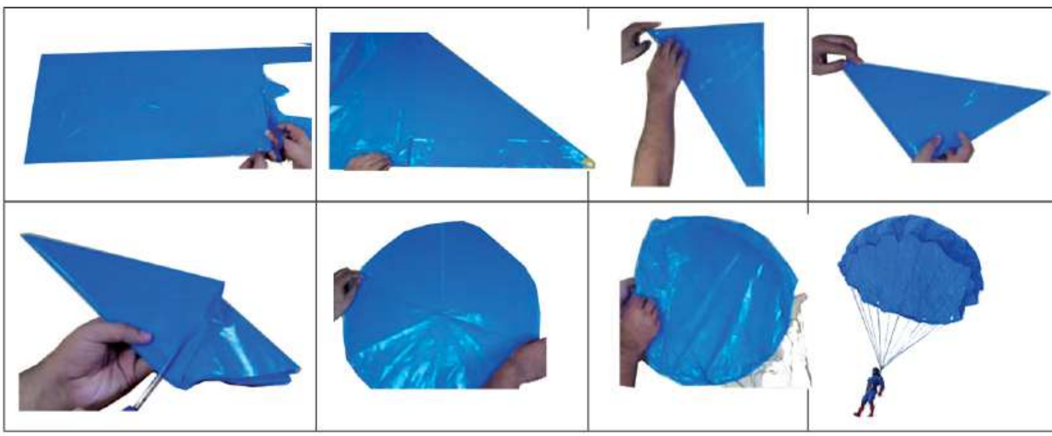


Figure 7.14 Construction of a model of a parachute

Question to think

Is it possible to land safely on the moon using a parachute like on the Earth?

Figure 7.15 Landing of parachute

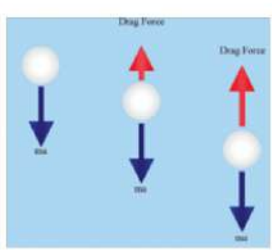


Figure 7.16 Resistance during a hail

Figure 7.17 Dispersion of seeds by wind

While jumping with a parachute, the air resistance increases with the speed of the parachute. This process leads to a situation where weight and air resistance become equal. In such conditions, the acceleration of the falling parachute becomes zero. Then the parachute falls towards the ground with a uniform speed. A safe landing on the ground is possible due to the uniformspeed of the parachute. This kind of parachute fall is not a free fall.

Atmospheric resistance is necessary for a safe landing with a parachute. Since the moon does not contain such resistance,jumping towards its surface with a parachute isa free fall. As a result, the speed increases continuously and lands on the surface at high speed. Thus, a safe landing on the moon using a parachute is not possible.

When hail falls on the earth's surface from a certain height, it falls ata certain constant speed instead of increasing continuously. It is due to the resistance offered by the air. It reduces the damage caused by hail on the earth's surface. The resistance or friction caused by the wind on the hail creates an upward drag force. The faster the hail falls, the greater the resisting force acting on it. When the force of gravity acting on the hail and the frictional force acting on it become equal, the hail falls at a constant speed.

As shown in Figure 7.17, a wind-dispersed seed contains a structure like a fur and a small fan. They worklike small parachutes. When these types of seeds are dispersed, they fall as if floating in the air due to air resistance and stay in the air for some time. As a result, the seeds are scattered far away. Therefore, due to air resistance, the seeds of the plants such as simal, sal, etc. are dispersed far away.

Activity 7.7 Observation of free fall

Take a 'U' shaped iron frame as shown in Figure 7.18. Tie the open part of the frame with a thread so that it is slack as shown in the picture. Also, tie a stone between the threads. As shown in the picture, hang the hook of the spring balance on the place where the stone is tied and raise the whole frame. What is the weight shown by the spring balance? Then release the frame from the hand and observe the condition of the stone tied to the rope attached to the frame and the reading of the spring balance. Lay a foam or cardboard on the floor to protect the spring balance during this activity. If possible, take a video of the falling spring balance and pause it.

In this activity, when the frame is released from the hand, then the spring balance, the stone and the iron frame fall downwards with the same speed. Although the stone-bound thread is tied in such a way that it is slack, it does not stretch downwards. This makes it look like the stone is flying in the air. This is possible with free fall. Since both the spring balance and the frame are in the state of free fall, there is no downward force on the spring of the spring balance and it shows zero weight. Thus, the weight of an object in free fall is zero, and hence, it is called weightlessness.Astronauts inside the artificial satellites orbiting the earth and space station are in a state of free fall. In such a situation, passengers inside the vehicle experience weightlessness.

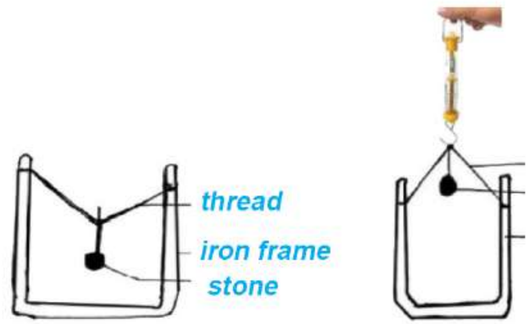


Figure 7.18 Observation of free fall

Equation of motion for free fall

The equations of motion are used to calculate the final velocity and acceleration of a freely falling stone in activity 7.2. In this way, the speed with which a freely falling body dropped from a height reaches the surface, the time taken to reach the surface, and the height can be calculated by using the equation of motion.

For the objects in linear motion	For the objects in free fall
$v = u+at$	$v = u+gt$
$v^2 = u^2+2as$	$v^2 = u^2+2gh$
$s = ut+ \frac{1}{2} at^2$	$h = ut+ \frac{1}{2} gt^2$

In this way, in the case where the acceleration is generated due to the force of gravity, the value of the acceleration due to gravity is substituted in place of the acceleration in the equation of motion. If the object is thrown vertically upwards, the value of the acceleration due to gravity is negative because the acceleration generated in such a situation is in the opposite direction.

Example 7.6

When a stone is dropped from a bridge over a river into the water, the sound of the stone hitting the surface of the water is heard after 2 seconds. Calculate the height of the bridge above the surface of the water.($g = 9.8\ m/s^2$)

According to the information given in the question,

The initial velocity of the stone (u) = 0 m/s because the stone is dropped from the hand.

Time taken by the stone to hit the water surface (t) = 2s

Acceleration of stone (g) = $9.8 m/s^2$

Using the equation of motion, the height of the bridge above the surface of the water

$$\text{Or } h = ut + \frac{1}{2} gt^2$$

$$\text{Or } h = \frac{1}{2} \times 9.8 \times 2^2$$

$$\text{Or } h = 19.6\ m$$

Therefore, the height of the bridge from the water level is 19.6m.

Example 7.7

A cricket ball thrown vertically upwards into the sky reaches a height of 30m.

Calculate the velocity with which it is thrown and the time taken to reach the maximum height.

As given in the question,

Maximum height of the ball (h) = 30 m

The final velocity of the ball (v) = 0 m/s (since the final velocity at maximum height is zero.

Acceleration of the ball (g) = - 9.8 m/s^2

Using the equations of motion for the initial velocity of the ball

$$0=u^2 + 2gh$$

Or $$0=u^2 + 2 \times -9.8 \times 30$$

Or $$u^2 = 588$$

$$u=\sqrt{588}=24.25 \text{ m/s}$$

For the time taken to reach the maximum height

$$v = u+at$$

Or $$0 = 24.25-9.8 \times t$$

Or $$t= \frac{24.25}{9.8}$$

$$t = 2.47 \text{ s}$$

So, the initial velocity of the cricket ball is 24.25m/s and it takes 2.47s to reach the maximum height.

Project work

Drop a stone from different heights like from the roof of a house or a school building with the help of your parents or teachers. Place a tin or some other sound-producing object on the surface of the ground to know when the stone hits the ground. After this, find the height and the time it takes to hit the ground. Find the height of a house, school building, etc. using the equation of motion. For this, take the average measurement to reduce the probable error. Finally, measure the actual height with a measuring tape and mention the error in the calculated height.

Exercise

1. Choose the correct option for the following questions:

(a) What is the relation between the distance between two objects (d) and the gravitational force (F) produced between them?

(i) $F \propto \frac{1}{d}$ (ii) $F \propto d^2$

(iii) $F \propto \frac{1}{d^2}$ (iv) $F \propto d$

(b) What is the change in the gravitational force between two objects when their mass is doubled?

(i) the force doubles

(ii) the force becomes four-time

(iii) the force is reduced two times

(iv) the force is decreased four times

(c) If the gravitational force between two objects on Earth is 60 N, what is the gravitational force between those two objects on the moon?

(i) 10 N (ii) 6 N

(iii) 9.8 N (iv) 60 N

(d) Whichone of the following statements is correct?

(i) The value of acceleration due to gravity increases as we go deeper from the surface of the earth.

(ii) The value of acceleration due to gravity decreases as the height above the surface of the earth increases.

(iii) The value of acceleration due to gravity is less in the polar region than that in the equatorial region.

(iv) The value of the acceleration of gravity is highest at the highest place on the Earth.

(e) At which of the following places do you weigh the most?

(i) peak of Mount Everest (ii) peak of Api Himal

(iii) Kechnakwal of Jhapa (iv) Chandragiri Hills

(f) The radius of the Earth is 6371 km and the weight of an object on the earth is 800 N. What is the weight of the object at a height of 6371 km from the surface of the earth?

(i) 800N (ii) 1600 N

(iii) 200 N (iv) 3200 N

(g) If the mass and the radius of a celestial body are two times the mass and the radius of the earth respectively, what is the value of acceleration due to the gravity of that body?

(i) 9.8 ms^{-2} (ii) 4.9ms^{-2}

(iii) 19.6ms^{-2} (iv) 10ms^{-2}

(h) What will be the weight of a man on the moon, if his weight on earth is 750 N? (The acceleration due to the gravity of the moon = 1.63 m/s^2)

(i) 124.74N (ii) 125 N

(iii) 126.8 N (iv) 127.8 N

(i) The mass ofplanet B is twice the mass of planet A but its radius is half of the radius of planet A. Similarly, the mass of planet C is half of the mass of planet A, but its radius is twice the radius ofplanet A. If the weight of an object in planets A, B and C is W_1, W_2 and W_3, respectively, which of the following order is correct?

(अ) $W_1>W_3>W_2$ (आ) $W_2>W_1>W_3$

(इ) $W_1>W_2>W_3$ (ई) $W_2>W_3>W_1$

(j) Which one of the following conclusions is correct while observing a freely falling object every second?

(i) the distance covered increases uniformly

(ii) velocity increases uniformly

(iii) acceleration increases uniformly

(iv) translation takes place uniformly

2. Differentiate between:

(a) Gravitational constant G and acceleration due to gravity g

(b) Mass and Weight

3. Give reason:

(a) Acceleration due to gravity is not the same in all parts of the earth.

(b) Jumping from a significant height may cause more injury.

(c) Mass of Jupiter is about 319 times themass of the Earth, but its acceleration due to gravity is only about 2.6 times the acceleration due to gravity of the Earth.

(d) Among the objects dropped from the same height in the polar region and the equatorial region of the earth, the object dropped in the polar region falls faster.

(e) Out of two paper sheets, one is folded to form a ball. If the paper ball and the sheet of paper are dropped simultaneously in the air, the folded paper will fall faster.

(f) When a marble and a feather are dropped simultaneously in a vacuum, they reach the ground together (at the same time).

(g) As you climb Mount Everest, the weight of the goodsthat you carry decreases.

(h) It is difficult to lift a big stone on the surface of the earth, but it is easy to lift a smaller one.

(i) Mass of an object remains constant but its weight varies from place to place.

(j) One will have an eerie feeling when he/she moves down while playing a Rote Ping.

4. Answer the following questions:

(a) What is gravity?

(b) State Newton's universal law of gravitation.

(c) Write the nature of gravitational force.

(d) Define gravitational constant (G).

(e) Under what conditions is the value of gravitational force equal to the gravitational constant (F=G)?

(f) Write two effects of gravitational force.

(g) Mathematically present the difference in the gravitational force between two objects when the mass of each is made double and the distance between them is made one forth their initial distance.

(h) What is gravitational force?

(i) Define acceleration due to gravity.

(j) What is free fall? Give two examples of it.

(k) Under what conditions is an object said to be in free fall?

(l) Write the conclusions of the feather and coin experiment.

(m) What is weightlessness?

(n) Mention any four effects of gravitational force.

(o) Prove that acceleration due to the gravity of the Earthis inversely proportional to the square of its radius ($g \propto \frac{1}{R^2}$)

(p) Mention the factors that influence acceleration due to gravity.

(q) The acceleration due to the gravity in the Earth surface is 9.8 m/s2. What does this mean?

(r) Mass of the Moon is about 1/81 times the mass of the Earth and its radius is about 37/10 times the radius of the Earth. If the earth is squeezed to the size of the moon, what will be the effect on its acceleration due to gravity? Explain with the help of mathematical calculation.

(s) The acceleration due to gravity of an object of mass 1 kg inouter space is $2 m/s^2$. What is the acceleration due to gravity of another object of mass 10 kg at the same point? Justify with arguments.

(t) A man first measures the mass and weight of an object in the mountain and then in the Terai. Compare the data that he obtains.

(u) A student suggests a trick for gaining profit in a business. He suggests buying oranges from the mountain selling them to Terai at the cost price.If a beam balance is used during this transaction, explain, based on scientific fact, whether his trick goes wrong or right.

(v) How is it possible to have a safe landing while jumping from a flying airplane using a parachute? Is it possible to have a safe landing on the moon in the same way?Explain with reasons.

(w) The acceleration of an object moving on the earth is inversely proportional to the mass of the object, but for an object falling towards the surface of the earth, the acceleration does not depend on the mass of the object, why?

5. Solve the following mathematical problems:

(a) The masses of two objects A and B are 20 kg and 40 kg respectively. If the distance between their centers is 5 m, calculate the gravitational force produced between them. Ans: 2.134×10^{-9} N

(b) Calculate the gravitational force between the two bodies shown in the figure. Ans: 3.14×10^{-11} N

(c) Mass of the Sun and Jupiter are 2×10^{30} kg and 1.9×10^{27} kg respectively.

If the distance between Sun and Jupiter is 1.8×10^{8} km, calculate the gravitational force between Sun and Jupiter. Ans: 4.17×10^{23} N

(d) Gravitational force produced between the Earth and Moon is 2.01×10^{20} N. If the distance between these two masses is 3.84×10^{5} km and the mass of the earth is 5.972×10^{24} kg, calculate the mass of the moon. Ans: 7.34×10^{22}kg

(e) Gravitational force produced between the Earth and the Sun is 3.54×10^{22} N. If the masses of the Earth and sun are 5.972×10^{24} kg and 2×10^{30} kg respectively, what is the distance between them? Ans: 1.5×10^{11} m

(f) The mass of the moon is 7.342×10^{22} kg. If the average distance between the earth and the moon is 384400 km, calculate the gravitational force exerted by the moon on every kilogram of water on the surface of the earth. Ans: 3.314×10^{-5} N

(g) If the mass of the moon is 7.342×10^{22} kg and its radius is 1737 km, calculate its acceleration due to gravity. Ans: 1.63 m/s^2

(h) Mass of the Earth is 5.972×10^{24} kg and the diameter of the moon is 3474 km. If the earth is compressed tothe size of the moon, how many times will be the change in acceleration due to the gravity of the earth so formed than that of the real Earth? Ans: 13.47

(i) If the mass of Mars is 6.4×10^{23} kg and its radius is 3389 km, calculate its acceleration due to gravity. What is the weight of an object of mass 200 kg on the surface of Mars?Ans: 3.75 m/s^2 and 750 N

(j) The acceleration due to the gravity of the earth is 9.8 m/s^2. If the mass of Jupiter is 319 times the mass of the Earth and its radius is 11 times the radius of the Earth, calculate the acceleration of gravity of Jupiter. What is the weight of an object of mass 100 kg on Jupiter? Ans: 25.83m/s^2 and 2583N

(k) Earth's mass is 5.972×10^{24} kg and its radius is 6371 km. Calculate the acceleration due to the gravity of the earth at the height of the artificial satellite shown in the figure. Ans: 0.56m/s^2

(l) Mass of the earth is 5.972×10^{24} kg and its radius is 6371 km. If the height of Mt. Everest is 8848.86 m from the sea level, calculate the weight of an object of mass 10 kg at the peak of Mt. Everest. Ans: 97.87N

(m) The acceleration due to gravity of the Mars is 3.75m/s^2. How much mass can a weight-lifter lift on Mars who can lift 100 kg mass on the Earth? Ans: 261.33 kg

(d) When a stone is dropped from a bridge over a river into the water, after 2.5 seconds the sound of the stone hitting the surface of the water is heard. Calculate the height of the bridge from the surface of the water. ($g = 9.8$ m/s^2) Ans: 30.62 m.

(n) If a stone is dropped from a height of 15 m, how long will it take to reach the ground? Calculate the velocity of the stone when it hits the ground. Ans: 1.75 s, 17.15 m/s

(o) If a cricket ball is thrown vertically upwards into the sky with a velocity of 15 m/s, to what maximum height will the ball reach? Ans: 11.47 m