Theme 5: Gravitation

Prior Knowledge

It is recommended that you revise the following topics before you start working on these questions.

- Gravitation - universal law of gravitation, free fall, mass and weight
- Upthrust - buoyancy, Archimedes' principle, relative density

Heliocentric vs Geocentric

Galileo converted a spyglass to a telescope and observed that Jupiter had moons (which he called stars initially), which changed positions within a day or two. He then observed that Venus also had phases the way Earth's moon had.

Based on these two observations, he inferred: (1) Not everything revolves around the Earth. Jupiter's moons revolve around Jupiter. (2) The Sun / Venus do not revolve around the Earth. Instead, the Earth and Venus, both revolve around the Sun. It was already known at that time that Venus is visible either for a few hours after sunset or before sunrise, never in the middle of the night. In the geocentric universe, this is possible only if the Sun and Venus have a similar revolution cycle and Venus is closer to the Sun. However, this does not match with the observation about the phases of Venus because we would never see the full phase of Venus in this arrangement.

Case Study A - Gravitational Force

Five centuries after Gallileo proposed his theory, today we know - based on Newton's Law of Gravitation, which was postulated only a few decades after Galileo's theory - that the gravitational force between any two objects is directly proportional to both the masses and inversely proportional to the square of the distance between the two objects.

Let us represent the mass of the Earth by M_e and that of the Sun by M_s, the distance between the Earth and the Sun by D_{ES} and the universal gravitational constant by G.

Question 1

i. Which of the following options represents the gravitational force of the Sun on the Earth and that of the Earth on the Sun? The value before the comma represents the force imparted by the Sun and the one after the comma represents the force imparted by the Earth. Note that "0 N" in the options here implies that there is no force in that direction.

a. $\frac{GM_eM_s}{(D_{ES})^2}$, 0 N	b. $\frac{GM_s}{(D_{ES})^2}$, $\frac{GM_e}{(D_{ES})^2}$
c. $\frac{GM_eM_s}{(D_{ES})^2}$, $\frac{GM_eM_s}{(D_{ES})^2}$	d. 0 N , $\frac{GM_eM_s}{(D_{ES})^2}$

Answer

ii. What would happen if we somehow swapped the position of the Sun and the Earth, such that the mass and the distance between the two remain unchanged?

a. The Sun would start revolving around the Earth
b. The Earth would continue to revolve around the Sun
c. The Sun's gravitational force will push the Earth away from itself instead of attracting

Answer

Question 2

The Moon revolves around the Earth due to gravitational influences, and the Earth exerts a force on the Moon.

i. How do you think this compares in strength with the force exerted by the Moon on the Earth? The mass of the Earth is 5.972×10^{24} kg and the Moon is only 1.2% of that mass.

a. The Moon does not exert a force on the Earth
b. The Moon exerts the same magnitude of force on the Earth, as the Earth does on it
c. The Moon's force is only around 1.2% of that exerted by the Earth
d. The force is half of that exerted by the Earth

Answer

ii. Which object experiences more acceleration due to the mutual gravitational force between the Earth and the Moon? Pick the option which looks most appropriate to you.

a. The Moon
b. The Earth
c. Both experience equal accelerations
d. Sometimes it's the Earth and other times it's the Moon

Answer

Case Study B - Leaning Tower of Pisa Experiment

As part of Galileo's exploration to understand how the Earth makes objects fall and what impacts the speed with which they fall, he is said to have conducted an experiment where he dropped a heavy and a light object from the same height at the same time. He observed that both objects reached the ground at the same time. The assumption made here was that there is no air resistance.

Question 3

What can you infer from Galileo's experiment about the gravitational pull on the two objects and their acceleration? Is the gravitational force experienced by the heavy object and light object the same or different? The Earth pulls both objects with:

a. The same force but they accelerate differently due to the difference in their mass.

b. Different force but they accelerate with the same rate since the ratio of force and mass is the same for both

c. The same force and hence they accelerate with the same rate

d. Different forces and hence they accelerate differently

Answer

Question 4

Now let us extend our understanding about gravitational force and acceleration caused by this force to other planets. If the gravitational force experienced by a 5 kg rock one metre above the surface of the planet Mercury is 18.05 N, what would be the force experienced by another rock having a mass of 80 kg at the same height? Assume that the acceleration due to gravity is the same on all parts of Mercury.

a. 18.05 N	b. 20.05 N
c. 256.7 N	d. 288.8 N

Answer

Question 5

As an extension to Galileo's experiment, an undergraduate student conducts an experiment in an open field. She climbs to a height of 5 metres above the ground holding a gun loaded with a bullet in one hand and just a bare bullet in the other. She proceeds to fire the gun in the direction she is facing and at the same time, lets go of the bullet in her other hand. The gun is angled carefully so that it fires parallel to the ground (at a zero degree angle), so as to not impart any forces in the up and down directions. She measures the time taken by both the bullets to reach the ground.

i. Which of the following questions do you think she was trying to answer by conducting this experiment?

a. What is the horizontal distance travelled by an object which is thrown at a 0 degree angle with respect to the ground?

b. What happens when a bullet fired from a height of 5 metres impacts the ground?

c. When an object is thrown horizontally, does the horizontal speed impact the vertical distance it travels?

Answer

ii. How much time does the bullet in the gun take to reach the ground?

a. 1/24 seconds	b. 0.5 second
c. 1 second	d. 2.5 seconds

Answer

iii. Which bullet will reach the ground first?

a. Bullet from the gun

b. Bare bullet

c. Both will reach at the same time

d. Depends on the speed at which bullet is fired from the gun

Answer

Firing the bullet upwards!

In the experiment explained in the previous question, the student fired the gun by keeping it horizontal, i.e. by making a zero degree angle with the ground. What will happen if the gun is fired by placing it vertical, i.e. by making it point upwards at an angle of 90 degrees with respect to the ground? Will the bullet enter space or fall back? If you were watching a fiction movie, the hero/heroine may make the bullet enter space or blast a cloud to cause rainfall, but in real life, an object thrown upwards from the surface of the Earth would move up till a certain distance before reaching the speed of 0 and start falling back after that. This is due to the impact of gravity, which continues to slow the object down while it is moving upwards.

Case Study C - Escape Velocity

If the object is thrown at a speed of 11.2km/s or greater, it will manage to escape Earth's gravity. This minimum speed at which an object has to be thrown to escape the gravitational pull of a planet is called the escape velocity of that planet. Note that the escape velocity is different for different planets, since it depends on the mass and diameter of the planet. Recall how the mass and radius of a planet change its gravitational pull. More the pull, more will be the velocity required to escape the planet. The escape velocity of a planet/star S can be expressed using the following formula:

$$\text{Escape velocity, } E_s = \sqrt{\frac{2GM_s}{R_s}}$$

where,

G = Universal Gravitational Constant

= 6.67×10^{-11} m^3/kgs^2

M_s = Mass of the planet/star S

R_s = Radius of the planet/star S

People often talk about rockets requiring a speed equal to the escape velocity to escape Earth's gravity, but note that the case of a rocket is different. It carries fuel with itself and hence has the option of accelerating in the middle of its journey.

Question 6

Table 5.1 provides the escape velocity of the 8 planets of the Solar System. Pluto's data is also included. It also shows the mass and radius of each planet. The mass has been specified relative to the Earth's mass. E.g., if the mass of the Earth was 1 kg, that of Jupiter would be 317.8 kg.

Planet/Planetoid	Escape Velocity (km/s)	Mass Relative to Earth	Equatorial Radius (km)
Earth	11.2	1	6378.1
Jupiter	63.4	317.8	71492
Mars	5	0.11	3396.2
Mercury	4.2	0.06	2439.7
Neptune	24.2	17.2	24764
Pluto	0.3	0.004	1195
Saturn	39.4	95.1	60268
Uranus	21.5	14.5	25559
Venus	10.3	0.82	6051.8

Table 5.1, Data showing escape velocity of different planets along with relative mass and radius

i. Why is the escape velocity on Mercury 4.2 km/s, which is 84% of Mars' escape velocity, while it is only 54% as massive? Write your answer in the space below.

Answer

ii. **Assertion 1:** Table 5.1 indicates that the more massive a planet is, the higher is its escape velocity.

Assertion 2: It also indicates that the larger a planet is, for a given mass, the higher is its escape velocity.

How would you rate the validity of Assertion 1 and Assertion 2?

a. Both are false

b. Both are true

c. Assertion 2 is true but Assertion 1 is false

d. Assertion 1 is true but Assertion 2 is false

Answer

Case Study D - Black Hole

Pierre Simon Laplace (23 March 1749 – 5 March 1827) was a French scholar and polymath. Among his many contributions to physics and mathematics, was his conception of what he called a dark star (what we now call a black hole). Laplace took the idea of escape velocity to its logical extreme. He reasoned that if a star was dense enough it could reach a point where the escape velocity of the surface would equal or exceed the speed of light.

Such a star would not shine any more, because light would not escape its surface, hence the term dark star. The idea of such objects was largely forgotten till Karl Schwarzschild found an exact solution to Einstein's equations of General Relativity in 1915. This was the first so-called black hole solution. It described an object that was so massive and dense that even light could not escape from the space around it, the physical manifestation of which would look like a 3-dimensional hole in space.

Fig. 5.1, This image of the core of the galaxy M87 was taken by the Event Horizon Telescope, using 1.3 mm radio waves.The central dark spot is larger than the black hole's event horizon, which is the shadow of the black hole M87* itself. Image by Event Horizon Telescope via Wikimedia Commons

Even though the theory indicated such structures exist, their physical existence was debated all through the 20th century. Einstein famously did not believe that black holes existed, even as others like Subrahmanyan Chandrasekar and Roy Kerr expanded on the theoretical models. In 2019, the Event Horizon Telescope made history by publishing the first-ever picture of a black hole (M87*). It's at the centre of a galaxy called Messier 87 and is estimated to have a mass that is billions of times that of the Sun. The glow seen around it is from matter becoming superheated as it clamours to fall into the central hole.

Question 7

The escape velocity of the Sun, whose mass is estimated to be 2.0 x 10^{30} kg and radius is around 700,000 km, is calculated to be 617.6 km/s. Calculate what its radius would have to be for it to become a black hole? Assume the speed of light to be 300,000 km/s.

a. 66 km	b. 3 km	Answer
c. 16 km	d. 900 km	

Recall that the escape velocity of a planet/star S can be calculated as $\sqrt{\frac{2GM_s}{R_s}}$

Floating and Sinking

One of the interesting phenomena we witness in daily life is the effect of interaction between gravity and the resistance of a fluid. When a boat floats on water, gravity pulls it down but water pushes it up. The breakthrough in understanding when exactly the boat (or any other object) floats and when it sinks came through when Archimedes had his Eureka moment.

Here is a simple experiment with a small balloon filled with air and some weight tied below. When this balloon and weight assembly is placed in a closed bottle filled with water and the bottle is pressed, something interesting happens. Look at the pictures - Fig. 5.2 to Fig. 5.9 - with captions to understand the experiment.

Case Study E - Shrink and Sink Experiment

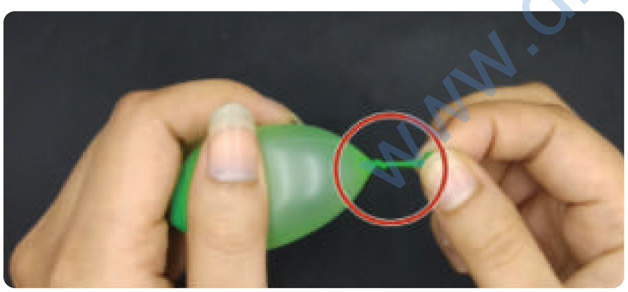


Fig. 5.2, Blow a small amount of air into the balloon and knot it.

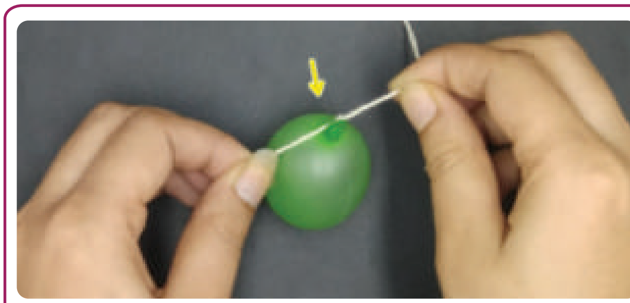


Fig. 5.3, Tie a 6-8 cm piece of cotton thread at the base of the balloon.

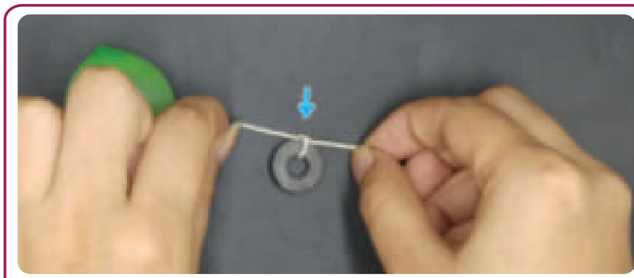


Fig. 5.4, Tie a ring magnet to the other end of the cotton thread. The total length of the balloon-magnet assembly should be less than half the height of the bottle.

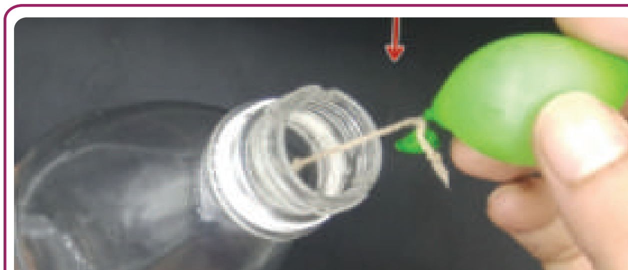


Fig. 5.5, Carefully insert the balloon and magnet into a plastic bottle through its mouth.

Fig. 5.6, Fill the bottle with water to the top.

Fig. 5.7, Screw the bottle cap on tightly and you are ready to play!

Fig. 5.8, Press the bottle from outside and observe that the balloon contracts a little and the assembly sinks.

Fig. 5.9, Once you let go, it floats back up again. You can vary the pressure applied to make it float at various heights in the bottle.

When an object is placed in a fluid (liquid/gas), what will decide whether it will sink or float? If the density of the object is more than that of the fluid, it will sink. If it is less, it will float. Note that density is defined as the ratio of the mass of the object to its volume.

Question 8

i. Explain what makes the balloon and magnet assembly sink when we squeeze the bottle. Write your answer in the space below.

Answer

ii. The experiment was conducted by two students - Joseph and Fareeda. Fareeda filled more air in her balloon than that filled by Joseph. What is a possible effect of this difference which we may see? Will the effort required to bring down the balloon and magnet assembly be more for Fareeda or less?

a. Less effort

b. More effort

c. Same effort

Answer

Question 9

Two more experiments were conducted with the same setup

A. The bottle was placed in hot water for some time and then pressed

B. 90 grams of salt was dissolved in the water. Note that one can dissolve a maximum of 36 grams of salt in 100 ml of water and the bottle used here was a 250 ml bottle

Both the experiments had a visible effect. What do you think is common between the two experiments? Write your answer in the space provided below.

Answer

Question 10

Out of idle curiosity, Nisha decides to see if oranges are buoyant. She picks out an almost spherical orange for her test, which has a radius of 4.2 cm and has a mass of 264 grams. She puts this in a bucket of water and notes the result. Then she removes the peel of this orange and finds that the fruit itself has a radius of 3.8 cm and a mass of 254 grams. She then proceeds to test this in the bucket as well. Based on this data, what do you think were the results? Recall that the volume of a sphere can be calculated using the formula:

$$\text{Volume of a sphere of radius } r = \left(\frac{4}{3}\pi r^3\right)$$

a. The whole orange floats, but only the fruit sinks

b. Both the whole orange and the fruit part float

c. The fruit by itself floats but the whole orange sinks

d. They both sink

Answer

Question 11

Let us do a thought experiment. A table tennis ball is dropped in a glass of water on the surface of the Earth and it rests when it is about halfway submerged in the water. Then the same experiment is carried out on the Moon, inside an artificial habitat that has the same temperature and atmospheric pressure as on Earth. How do you think the experiment will be affected?

a. The ball will sink a little deeper into the water

b. The ball will be less than half submerged in the water

c. The ball will sink completely

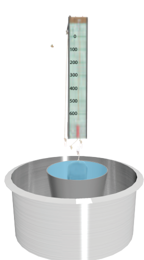
d. It is not affected

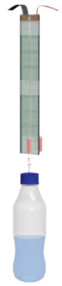
Answer

Exploration Pathway

 Density - Shrink and Sink	The density of an object is nothing but the ratio of its mass to its volume. In a fluid, objects that are less dense than the fluid will float, whereas those denser than the fluid will sink. In this TACtivity, a balloon is partially inflated and a nut is suspended from it with a thread, such that the whole assembly floats in water. This is then inserted into a plastic bottle filled to the brim with water and closed tightly shut. When you squeeze the bottle, the balloon should start to sink! How and why?

 Density - Saline Water	The density of a liquid can be changed quite easily and dramatically by dissolving a soluble solute in the liquid. We observe this property by seeing if a lemon floats or sinks in freshwater and a saline solution.

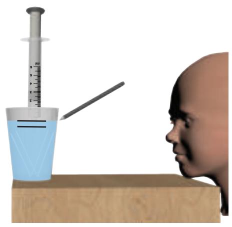
 Archimedes Principle	Archimedes' principle is a fundamental law in physics and states that the upward buoyant force that is exerted on a body immersed in a fluid, is equal to the weight of the fluid that the body displaces. In this TACtivity, we use simple materials and water to demonstrate this law.



DIY Spring Balance

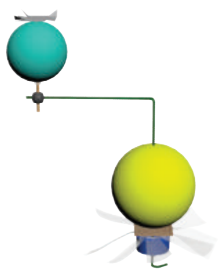
Based on the beautifully fundamental Hooke's Law, which states that the amount by which a spring expands is directly proportional to the force stretching it, the spring balance is a classic tool used to measure weight.

Here, you make your very own spring balance(s), mounted on a cardboard frame, using several kinds of "springs".



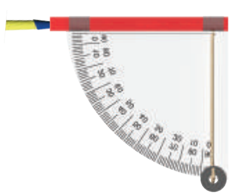
Measure - Density

If I place an eraser or a pencil sharpener in water, will it float or sink? One of the ways to answer this, and similar, questions is to measure the densities of the items from daily life. In this TACtivity, you will use a kitchen scale and a measuring cylinder to find the densities of solids and liquids around you.



Sun and Earth Model

Any rotating object does so because of a force that is pulling the object towards the centre of rotation. In the case of a mass rotating around another mass, that "centre" happens to be the system's centre of mass. For two objects vastly different in mass, the centre of mass is effectively at the location of the heavier mass, as in the case of the Sun and Earth. In this brilliant simulation, we use two balls and a piece of wire, with turbines causing the rotation!



Paper Projectile

What is the path of an object when it is launched? Does it depend on the initial speed of the object? What about the angle of launch? We observe this and much more in this TACtivity. Using a piece of fat straw, a launch-angle measuring device called a sextant, and some paper darts, we launch the paper darts by blowing them through the straw to see what impact they make on a newspaper screen!