Name: ____ Date: _______

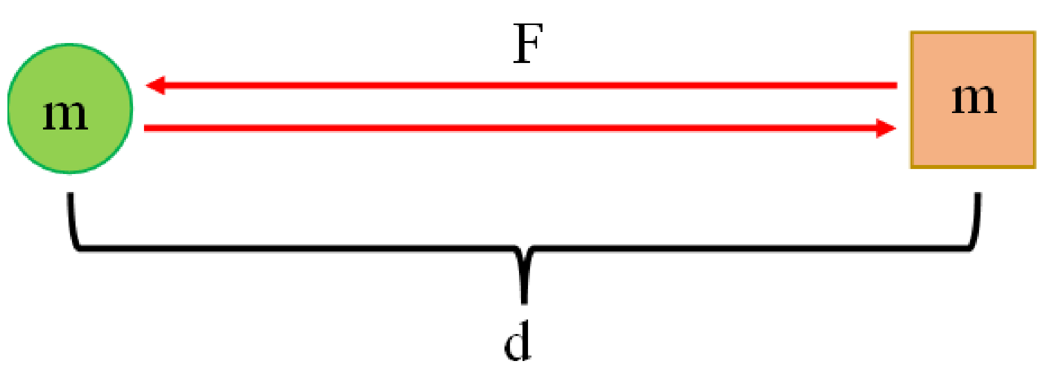
PHYSICS
UNIT 3: APPLIED FORCES & GRAVITY

GRAVITY & GRAVITATIONAL ATTRACTION

Gravity is a **mutual attraction force (pull force) where objects naturally attract all other objects.** Gravitational attraction force is also an **action-at-a-distance force**—objects do not need to be touching each other to pull on each other through gravity. **Gravity is universal**: all objects pull on every other object in our universe by gravity force regardless of the distance separating them. Likewise, the other objects in our universe pull back.

Newton's Law of Universal Gravitation: The gravitational attractive force between two objects is proportional to the products of their masses and inversely proportional to the square of the distance between the object's centers of mass.

Gravitational attraction force depends on two factors: The **masses** (m) of the two objects attracting each other and the **distance** (d) between the objects' centers of mass.



$$F_g = G \cdot \frac{m_1 \cdot m_2}{d^2}$$

$$G = 6.67 \times 10^{-11} N \frac{m^2}{kg^2}$$

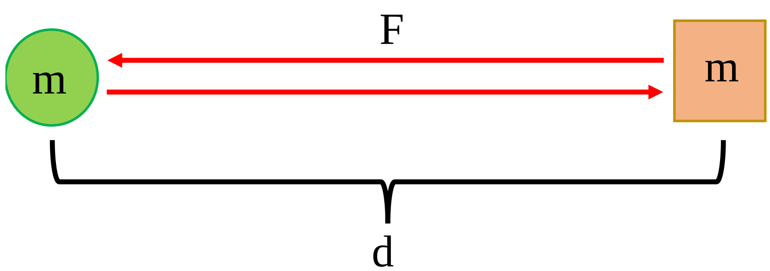
F_g = attractive force due to gravity (N)
m_1 = mass of object 1 (kg)
m_2 = mass of object 2 (kg)
d = distance between centers of mass (m)
G = universal gravitational constant (a number)

The force of gravitational attraction is **proportional to the products of the masses** of the objects attracting each other. Masses are multiplied together. The product of masses are in the numerator of the equation. Larger masses will make stronger attraction force. Smaller masses will make weaker attraction force.

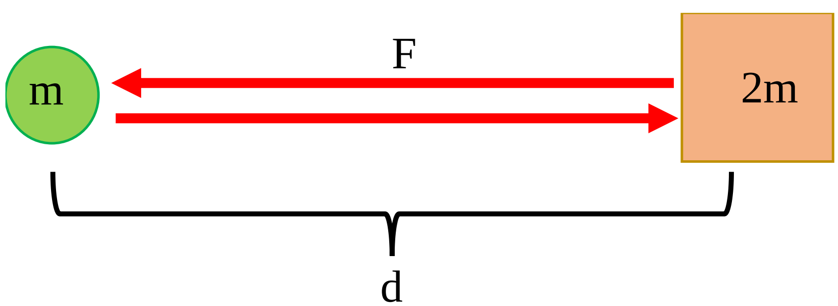
Illustrative Example 1

$$F_g = G \cdot \frac{\mathbf{m_1 \cdot m_2}}{d^2}$$

Two objects (green sphere, orange cube) are kept at constant distance apart. The masses of each object is increased.

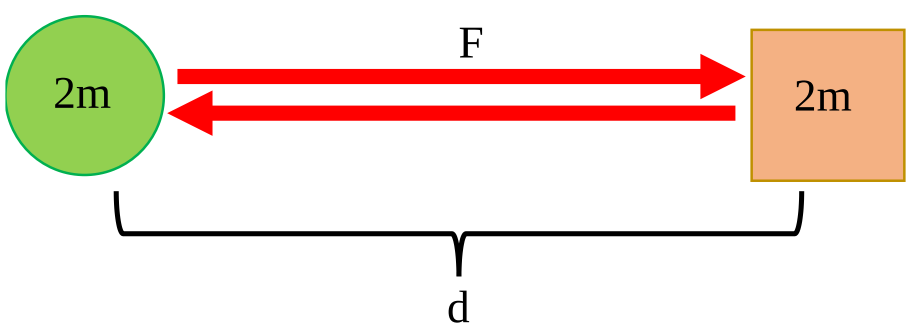


Gravitational attraction force is mutual force. The of the objects pulling on each other is equal in magnitude and opposite in direction.



If the mass of one of the objects is doubled, the attraction force increases to 2-times the original.

1 x 2 = 2



If the masses of both objects are doubled, the attraction force increases to 4-times the original.

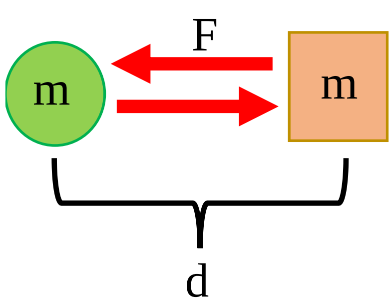
2 x 2 = 4

The force of gravitational attraction is **inversely proportional to the distance squared** between the objects' centers of mass. Distance squared is in the denominator. Objects that are close together have stronger gravitational attraction force. Objects that are farther apart have weaker gravitational attraction force.

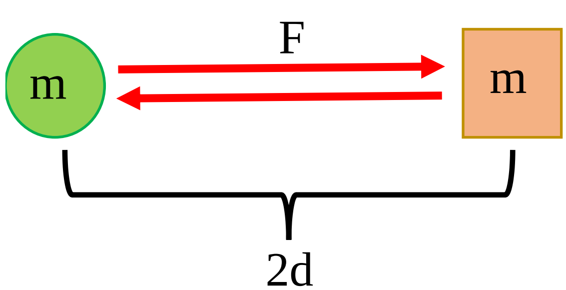
Illustrative Example 2

$$F_g = G \cdot \frac{m_1 \cdot m_2}{\mathbf{d^2}}$$

Two objects (green sphere, orange cube) are moved farther and farther apart. The gravitational attraction force between the green sphere and orange cube gets weaker with increasing distance apart.

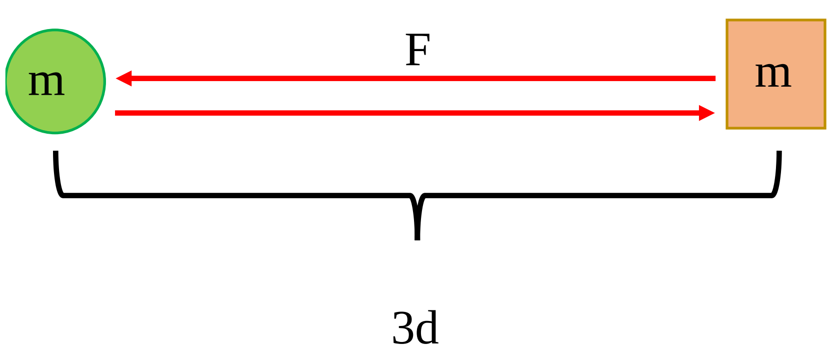


Gravitational attraction force is mutual force. The of the objects pulling on each other is equal in magnitude and opposite in direction.



If the distance between the two objects is doubled (2-times), attraction force decreases to 1/4 the magnitude of the original force.

$1/(2)^2 = 1/4$



If the distance between the two objects is tripled (3-times), attraction force decreases to 1/9 the magnitude of the original force.

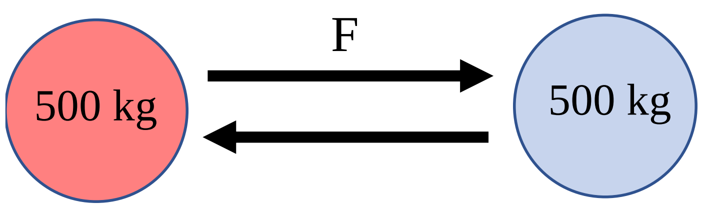
$1/(3)^2 = 1/9$

Gravity is a mutual attractive force (pull force) because it obeys **Newton's 3rd Law of Motion.** Any two objects, regardless of their sizes or masses or distance apart, will gravitationally attract each other with equal and opposite forces. The product of the masses is in the numerator of the force equation. The attraction force depends on the product of forces. Both masses are participating in the force. Both masses pull on each other at the same time.

$$F_g = G \cdot \frac{m_1 \cdot m_2}{d^2}$$

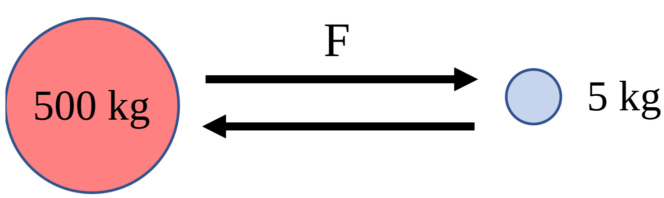
Illustrative Example 3

Two objects of equal mass will attract each other with an equal and opposite force.



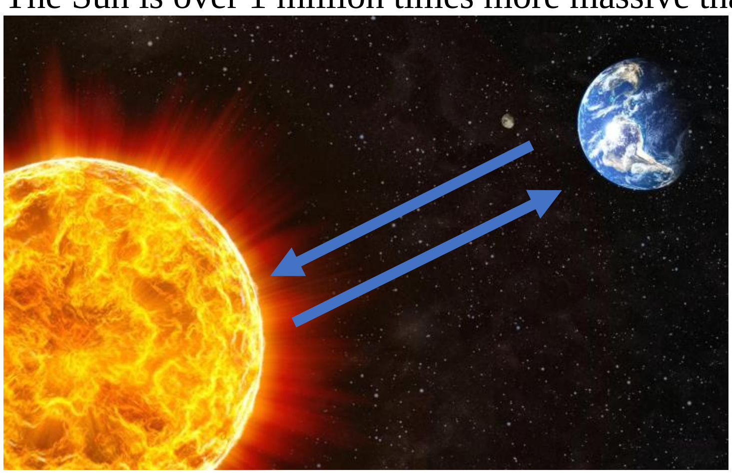
The red object will attract the blue object with a force that is equal in magnitude and opposite in direction of the blue object attracting the red object.

Two objects of unequal mass will attract each other with an equal and opposite force.



Despite the mass difference between the more massive red object and the lesser massive blue object, the force of attraction between them is equal in magnitude and opposite in direction.

The Sun is over 1 million times more massive than the Earth. Despite the difference in mass, the force of the Sun pulling on the Earth is equal in magnitude and opposite in direction to the force of the Earth pulling back on the Sun. Gravity is a mutual force. The forces are equal and opposite regardless of the size or mass difference.



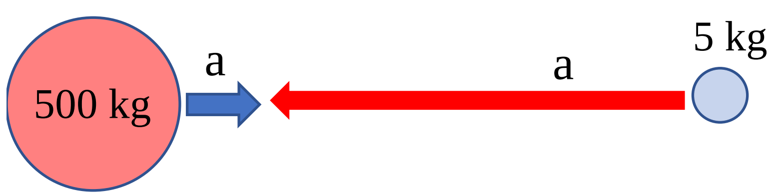
Gravity Force Causes Acceleration

Gravity is a force. Like all forces, **gravity force causes objects to accelerate**. Because gravity is an attraction, the acceleration happens by objects pulling on each other and moving closer together with time. Remember **Newton's 2nd law of motion**: **The acceleration applied to an object is proportional to the magnitude of the force and inversely proportional to the mass of the object.** Falling happens because the Earth and the objects in Earth's gravity field are attracting each other. The objects, however, must go down and fall—little mass means little inertia. In contrast, the Earth relatively does no movement because it is astronomically more massive and has an astronomically large inertia. Things fall down to the Earth, the Earth does not move up to meet the things even through the gravity attraction force between them is equal and opposite.

Illustrative Example 4

Objects of equal masses have equal inertia. Both will resist forces and acceleration equally. If the two objects were in space, away from all other influences and forces, the two objects would pull each other closer and closer. The acceleration at which they move together would be equal in magnitude. Over time, they will approach each other with the same acceleration.

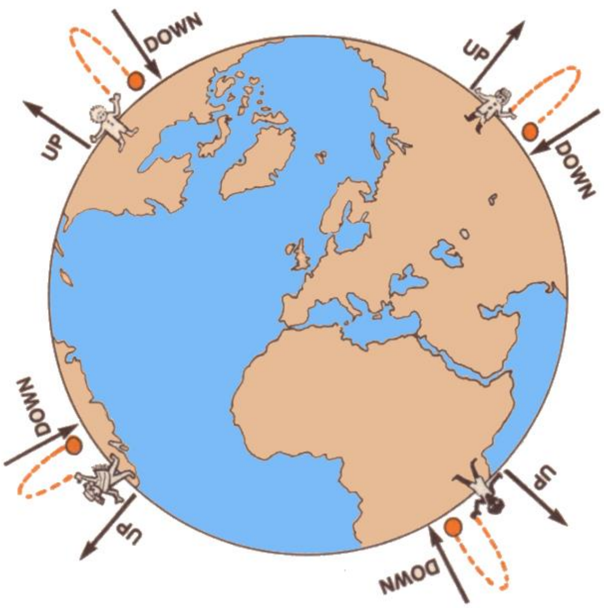
Objects of unequal masses have unequal inertia. Both will resist forces and acceleration, however, the more mass will resist acceleration strongly and the lesser mass will resist weakly. If the two objects were in space, away from all other influences and forces, the two objects would pull each other closer and closer. The smaller object will accelerate more and move much faster inward towards the larger object. The larger object will accelerate less and move slower inward towards the smaller object.



Falling happens because the Earth and the objects in Earth's gravity field are attracting each other. The objects, however, must accelerate down towards the Earth's surface. Their very, very small masses have very, very small inertia, therefore they move. In contrast, the Earth relatively does zero movement because it is astronomically more massive and has trillions of times the inertia. Things fall to the Earth's surface; the Earth does not move up to meet the things even through the gravity attraction force between them is equal and opposite. Additionally, the gravity field around a planet accelerates objects downward toward the planet's surface on all sides of the planet at the same time.

Illustrative Example 5

Regardless of the side of the Earth or hemisphere or topography, all small objects are accelerated down towards the Earth's surface. Once on the ground, objects are bound by gravitational attraction to the Earth's surface—the objects do not float away. Gravity is still accelerating objects downward, but the Earth's surface stops them from moving in the downward direction.

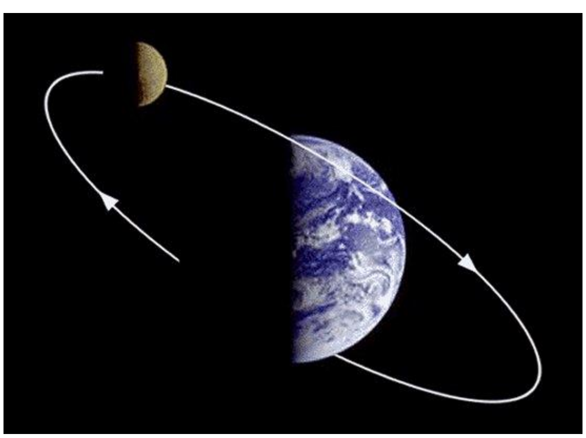


Illustrative Example 6

Falling is caused by the vast difference in inertia between the falling object and the astronomically large Earth. Falling objects and the Earth are pulling on each other with a force that is equal and opposite, but only the objects move. The ball, the skydivers, and the meteor will accelerate to the Earth's surface (fall down). The Earth will not accelerate upward towards the objects.

Illustrative Example 7

Planets orbit stars, stars do not orbit planets. The mass of each planet in our solar system is miniscule compared to the overwhelmingly large mass of the Sun. Planets must do the moving in their orbits because they have miniscule inertia by comparison. The Sun effectively is anchored as a stationary body in the center of the solar system.



Satellites and moons orbit planets, planets do not orbit satellites and moons. The mass of moons is 1/100 to 1/1,00,000 times less than the planets they orbit. Their inertia is very, very small by comparison. The planet effectively is anchored in the center of the orbit.

Calculating Gravitational Attraction Force

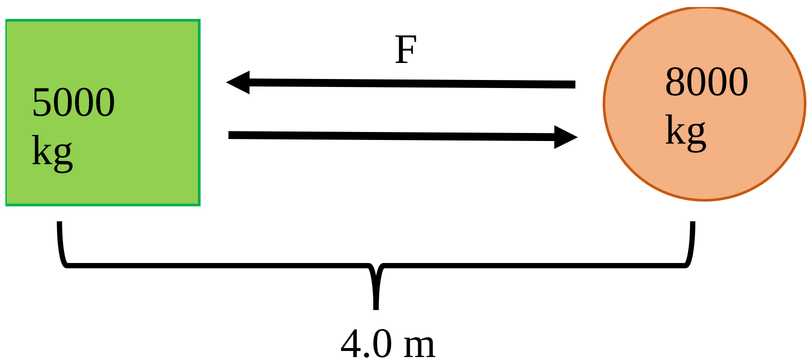
$$F_g = G \cdot \frac{m_1 \cdot m_2}{d^2}$$

$$G = 6.67 \times 10^{-11} N \frac{m^2}{kg^2}$$

Equation for Newton's Law of Universal Gravitation (attraction force strength)

F_g = attractive force due to gravity (N)
m_1 = mass of object 1 (kg)
m_2 = mass of object 2 (kg)
d = distance between centers of mass (m)
G = universal gravitational constant (a number)

Calculation Example 1



Two objects attract each other by gravity. The green block has a mass of 5000 kg. The orange sphere has a mass of 8000 kg. The distance between the two objects is 4.0 m.

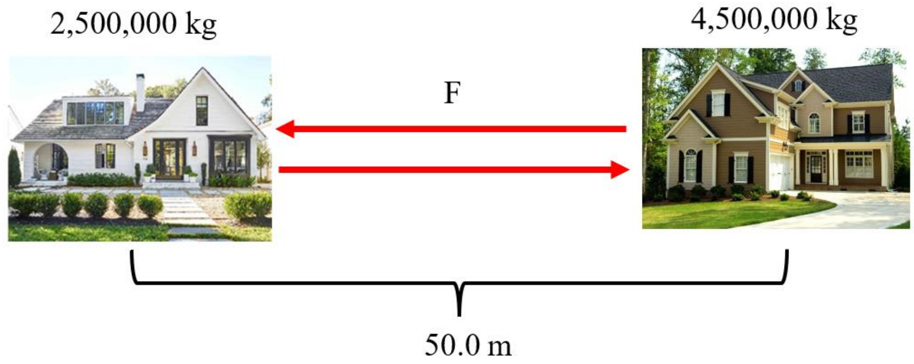
$$F_g = G \cdot \frac{m_1 \cdot m_2}{d^2} = \left(6.67 \times 10^{-11} N \frac{m^2}{kg^2}\right) \cdot \frac{5000\ kg \cdot 8000\ kg}{(4.0\ m)^2}$$

$$F_g = G \cdot \frac{m_1 \cdot m_2}{d^2} = \left(6.67 \times 10^{-11} N \frac{m^2}{kg^2}\right) \cdot \frac{40{,}000{,}000}{16.0}$$

$$F_g = 1.667 \times 10^{-4} N = 0.0001667\ N$$

Note that the attraction force between the green block and the orange sphere is very, very weak. It is so weak that there is no effect of gravity on them. Friction holding them in place is stronger.

Calculation Example 2



Two house sit 50.0 m apart on opposite street corners. House #1 has a mass of 2,500,000 kg. House #2 has a mass of 4,500,000 kg.

$$F_g = G \cdot \frac{m_1 \cdot m_2}{d^2} = \left(6.67 \times 10^{-11} N \frac{m^2}{kg^2}\right) \cdot \frac{2{,}500{,}000 \text{ kg} \cdot 4{,}500{,}000 \text{ kg}}{(50.0 \text{ m})^2}$$

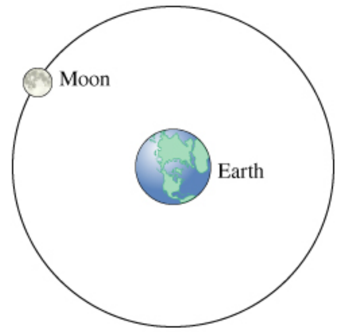
$$F_g = G \cdot \frac{m_1 \cdot m_2}{d^2} = \left(6.67 \times 10^{-11} N \frac{m^2}{kg^2}\right) \cdot \frac{1.125 \times 10^{13}}{2500}$$

$$F_g = 750 \text{ N}$$

Note that the attraction force between the two houses is 750 N. That is very, very weak. The force of friction holding them in place is thousands of times stronger.

Calculation Example 3

The average distance between the Earth and Earth's moon is ~385,000 km = 385,000,000 m. The Earth has a radius of 6,380 km and a mass of 5.98×10^{24} kg. The Earth's moon has a radius of 1737 km and a mass of 7.35×10^{22} kg. Calculate the gravitational attraction force between the Earth and Earth's moon.



The distance between the Earth's center of mass and the Moon's center of mass is the sum of the radii and the distance between them. Distance must be in meters.

d = 385,000,000 m + 6,380,000 m + 1,737,000 m = 393,117,000 m

$$F_g = G \cdot \frac{m_1 \cdot m_2}{d^2} = \left(6.67 \times 10^{-11} N \frac{m^2}{kg^2}\right) \cdot \frac{5.98 \times 10^{24} kg \cdot 7.35 \times 10^{22} kg}{(3.931 \times 10^8 \mathrm{m})^2}$$

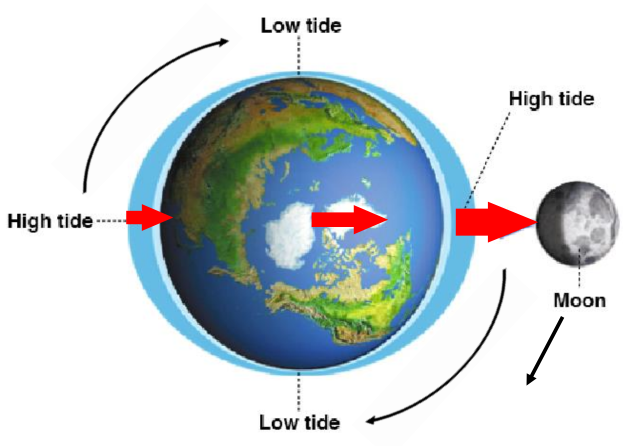
$$F_g = G \cdot \frac{m_1 \cdot m_2}{d^2} = \left(6.67 \times 10^{-11} N \frac{m^2}{kg^2}\right) \cdot \frac{4.396 \times 10^{47}}{1.545 \times 10^{17}}$$

$$F_g = 1.898 \times 10^{20} N$$

Note that the attraction force between the Earth and Earth's moon is very, very strong. Their masses are astronomically large. Very large product of masses will generally make a very strong gravitational attraction force.

Earth’s Tides

The Earth’s rotation is every 24 hours (1 day). The moon’s orbit period is much longer at 1 revolution every 28 days. In other words, the Earth spins 28 times under the moon as the moon makes one orbit around the Earth. The moon is held in orbit around the Earth by the gravitational attraction, Earth pulls on the moon and the moon pulls on the Earth. 71% of the Earth’s surface is covered by liquid water, and liquids can flow under the influences of forces like gravity and the spinning motion of the Earth (called Coriolis).

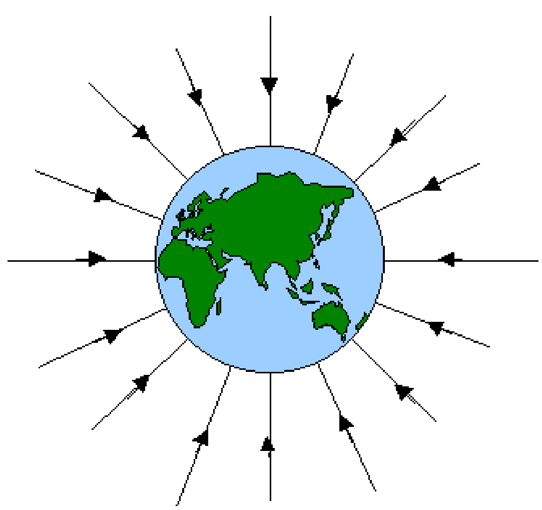


Tides are the result of gravitational attraction between the moon and Earth’s oceans. There are **two high tides and two low tides** on Earth at the same time. High tides follow the moon and also at exactly opposite side of the Earth facing away from the moon. Low tides are at 90° to the moon.

The moon’s gravitational pull on the Earth’s oceans creates the high tide facing the moon. The liquid water surface bulges upward towards the moon forming the high tide. And the bulging is further enhanced by the spinning Earth crowding water at the bulge. In addition to the moon pulling on the ocean water under it, the moon also pulls the Earth slightly. The Earth’s slight shift toward the moon makes the high tide on the side of the Earth facing away from the moon.

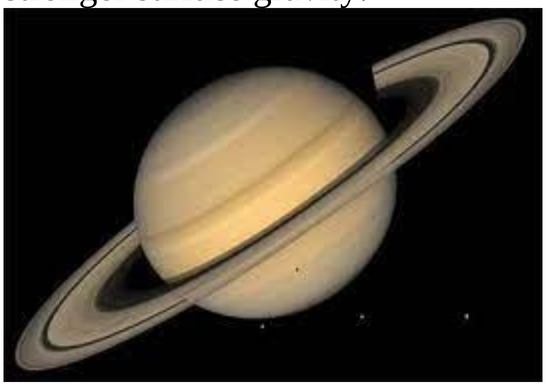
Gravity Fields

A **gravity field** is the physical space around an object in which gravitational attraction force between that object and other objects is strong enough to cause the objects to accelerate or move together. Gravity is the weakest fundamental force, however, gravity can become very strong if the masses of objects are very large. The gravity field surrounding a small object—such as a human or a pebble or an atom—is very weak. The gravity field surrounding a larger, more massive object—such as a planet, star, or moon—is very strong.



Illustrative Example 7

Planets and moons are very massive will have strong gravity fields. Planets and moons are very, very massive. More mass will cause a stronger surface gravity.



Objects on Earth's surface have gravity fields, also. The gravity fields are very, very tiny because their masses are very, very tiny. The pull by small objects is so weak that it has zero effect on the motion of other objects around them.

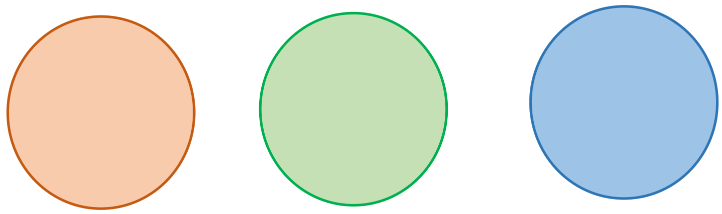
The very, very large mass of planets will create a strong gravitational pull to objects nearby. They cause moons to orbit them. They pull asteroids and meteors into their atomspheres. They hold objects onto their surfaces. By comparison, objects ranging in size from atoms to mountains have so much less mass that they have zero ability to pull on objects through gravity or anchor them to their surfaces. Regardless, they still have gravity.

There are two variables that affect the strength of a planet or moon's gravity field: (1) the mass of the planet or moon, and (2) the spherical radius of the planet or moon.

Gravity field strength is **proportional to mass**. The greater the mass of the planet or moon, the stronger the downward pull of its gravity at its surface. The smaller the mass of the planet or moon, the weaker the downward pull of gravity at its surface. Earth has a much greater mass than Earth's moon. The downward pull of Earth's gravity field is 6-times stronger than on Earth's moon. Astronauts feel very heavy on Earth, but feel very light on the moon due to the gravity field difference.

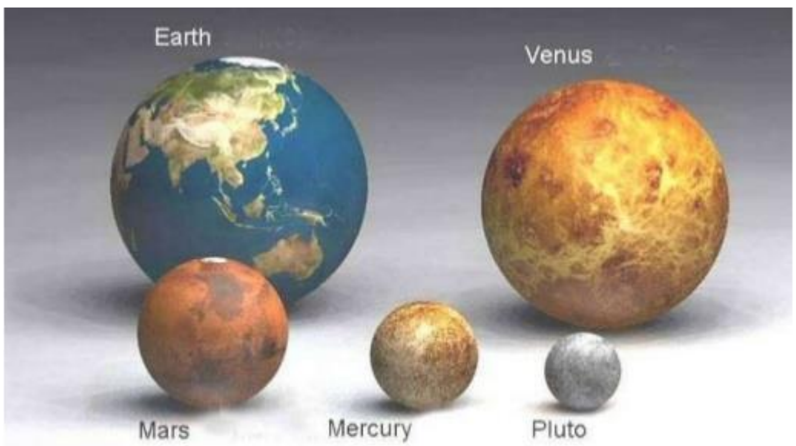
Illustrative Example 8

Orion A | Aries B | Taurus C



$2.00x10^{22}$ kg | $4.00x10^{22}$ kg | $6.00x10^{22}$ kg

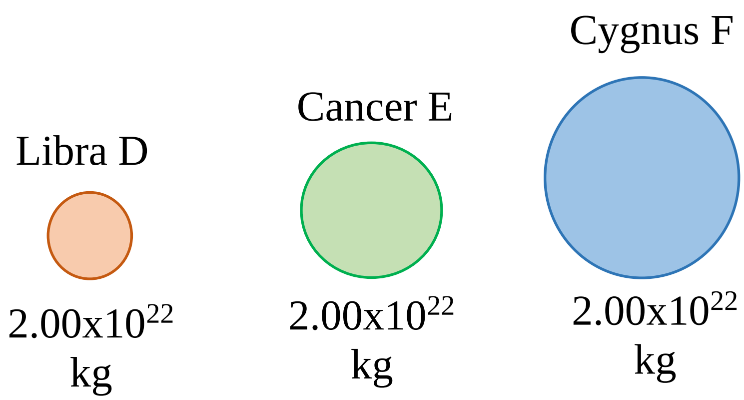
Three planets have the same radius (size) but different masses. Gravity field strength is proportional to the mass of the planet. Taurus C has the greatest mass, thus it will have the strongest gravity field. Orion A has the lowest mass, thus it will have the weakest gravity field.



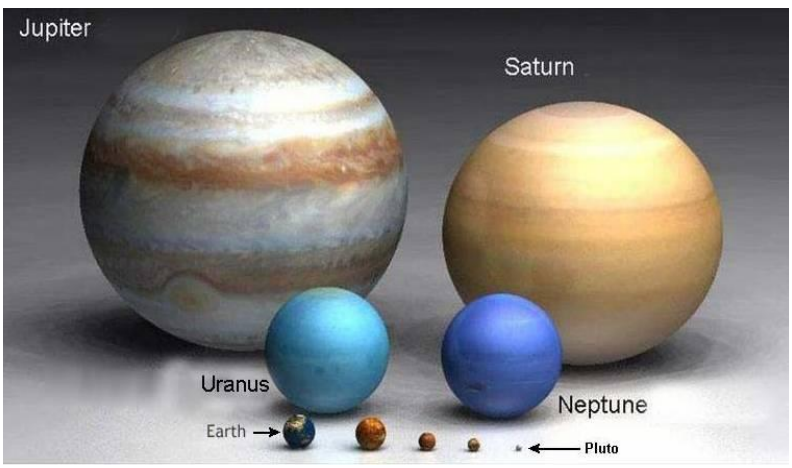
Earth has the strongest gravity field of the terrestrial planets. It has the greatest mass relative to its size. The gravity fields on Venus, Mars, and Mercury are weaker because they are less massive bodies.

Gravity field strength is **inversely proportional to the radius of the planet or moon**. The greater the radius of the planet or moon, the weaker the gravity field will be at its surface. The smaller the radius of the planet or moon, the stronger the downward pull of gravity at its surface. Gravity is maximized by massive, yet dense, planets and moons. If the body is compact and dense, gravity will be very strong. If the body has a relatively low density and its volume is very large, gravity is much weaker due to the expansive size.

Illustrative Example 9



Three planets have the same mass but different radii (sizes). Gravity field is inversely proportional to the radius of the planet. Libra D has the smallest radius, thus it is the densest body and will have the strongest gravity field at its surface. Cygnus F has the largest radius, thus it is less dense and it will have the weakest gravity field at its surface.



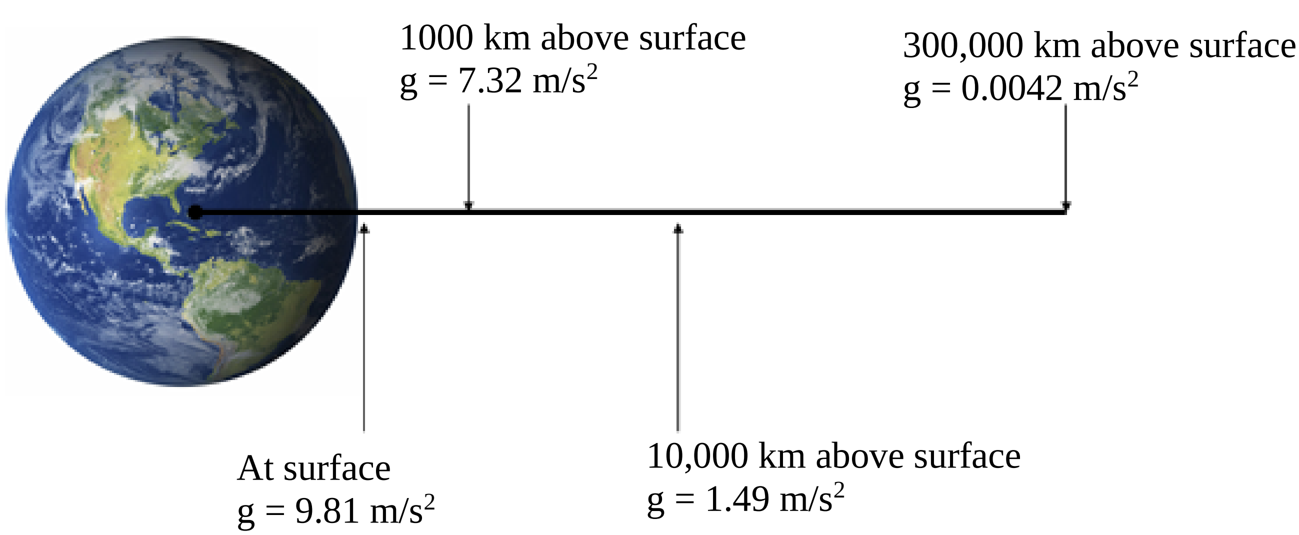
Jupiter’s mass is 317-times greater than Earth’s mass. Saturn’s mass is 95-times greater than Earth’s mass. It would be expected that their surface gravities would also be that much greater. They are not. Jupiter’s surface gravity is only 2.5-times stronger than Earth’s. Saturn’s surface gravity is only 1.1-times stronger than Earth’s. Why?

Jupiter and Saturn are gas giant planets. Their spherical radii and volumes relative to their masses are very, very large. The much greater radius counteracts their large masses and weakens their surface gravity. Their expanded volumes create a greater distance from their centers of mass. The same is true for Uranus and Neptune. Uranus is 14-times and Neptune is 17-times more massive than Earth. Despite being more massive, their large volumes counteracts their larger masses to weaken their surface gravity.

List of gravity fields on bodies in our solar system. Lowercase letter **g** is gravity field strength. It is reported in units of m/s^2, exactly the same as acceleration.

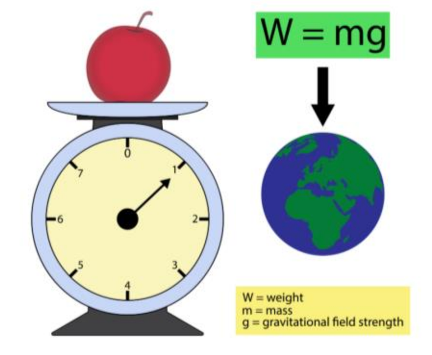
Body	**Gravity Field g (m/s^2)**
Mercury	3.70
Venus	8.87
Earth	9.81
Mars	3.71
Jupiter	24.9
Saturn	10.4
Uranus	8.87
Neptune	11.15
Pluto	0.62
Earth's moon	1.62

The gravitational pull of a planet or moon decreases with increasing distance away from its center of mass. At the Earth's surface, Earth's gravity field strength is at its maximum of 9.81 m/s2. If a rocket were to leave Earth's surface and travel into space, the gravitational pull between the Earth and rocket will get weaker and weaker. At 1000 km above the Earth's surface, gravity field decreased to 7.32 m/s^2. At 10,000 km above the Earth's surface, gravity field decreased to 1.49 m/s^2. Eventually, the pull of Earth's gravity on the rocket would be so weak, it would have zero effect on the rocket.



Weight

Mass is the quantity of matter contained in an object. **Mass is always conserved**. Mass is independent of all forces and motions affecting it, and mass never changes based on location or motion. Conversely, weight will change based on its location because weight is dependent on the planet's gravity field strength.



Weight is the measure of heaviness of an object in a planet's or moon's gravity field. **Weight is the downward force upon an object that results from a planet's or moon's gravity field accelerating the object in the downward direction.** Weight is calculated as the product of the object's mass and the downward acceleration in the planet's gravity field.

Weight is a force, and like all forces, weight is reported in units of Newtons. Weight is calculated as the product of the mass multiplied by the gravity field acceleration (g) for the planet or moon. Weight is reported as a positive number despite the acceleration due to gravity in the down direction.

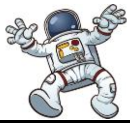
$$F_{grav} = w = m \cdot g$$

w = weight (N) [Gravity force]
g = acceleration due to the gravity field (m/s^2)
m = mass of the object (kg)

Illustrative Example 10

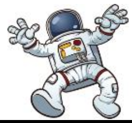
If the same astronaut traveled from Earth to different bodies in our solar system, his weight would differ on the different bodies, but his mass would remain constant. Mass is a conserved property. It is the same astronaut, just in different locations. Weight is dependent on the strength of the gravity field of the body. The same astronaut would weight 2.5-times more on Jupiter (actually in its upper atmosphere) than on Earth. The same astronaut would weight 1/6 of his Earth's weight on Earth's moon.

Earth
m = 100 kg
w = 981 N



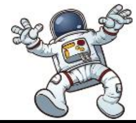
Earth
g = 9.81

Mars
m = 100 kg
w = 371 N



Mars
g = 3.71

Jupiter
m = 100 kg
w = 2490 N



Jupiter
g = 24.9

Earth's moon
m = 100 kg
w = 162 N

Earth's moon
g = 1.62

Example Calculation 4

Calculate the weight of the car on Earth. The car's mass is 1200 kg.

$$w = m \cdot g$$
$$w = 1200\text{kg} \cdot 9.81\,{}^{\text{m}}/_{\text{s}^2} = 11{,}772\text{N}$$

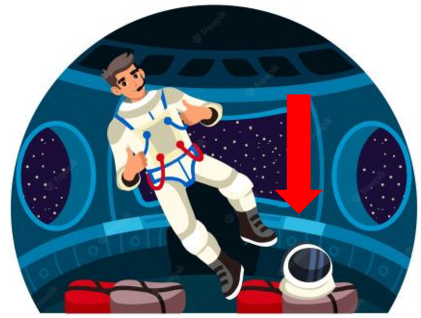
Example Calculation 5

A spaceship landed on Mars. The mass of the spaceship on Earth is 30,000 kg. Calculate the weight of the spaceship on Mars.

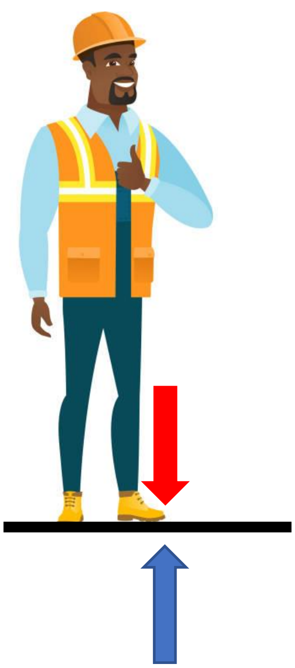
$$w = m \cdot g$$
$$w = 30{,}000\text{kg} \cdot 3.71\,{}^{\text{m}}/_{\text{s}^2} = 111{,}300\text{N}$$

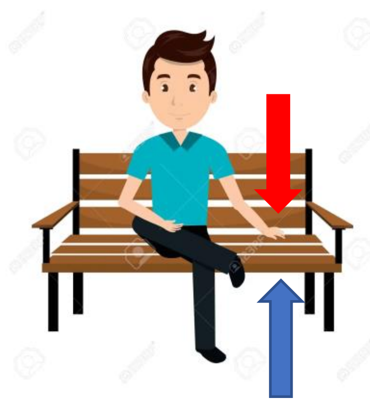
Weight or gravity force is the heaviness of an object being accelerated downward by the gravity of a planet or moon. Weight or heaviness can only be felt if the object is supported underneath by a surface such as the solid surface of a planet or a building's floor. The surface must push back with a force opposite that of gravity force. Remember, the pushback force by the surface onto the object is called the **normal force**. The normal force must be present for weight to be felt. If the object is unsupported, then the object has the **sensation of being weightless** because there is no surface pushing up or pushing back. The object still has weight because the object has mass (m) is acted upon by the gravity field in the downward direction (g). There is no such thing as true weightlessness, only the sensation of weightlessness.

Illustrative Example 11



The **sense of weightlessness** happens when an object lacks a normal force pushing back on him or her in the direction opposite of gravity. The skydiver, the girl bouncing in the air on the trampoline, and the floating astronaut experience the sense of weightlessness because the Earth's surface (first two) and the floor of the spaceship is not pushing back on their bodies. They still have weight because all three are within the gravity field of Earth, so there is still an gravitational attraction between the Earth and the people. In the case of the astronaut in the spaceship, the spaceship is farther distance away in space where the pull of Earth's gravity is much weaker. Addtionally, the spaceship is moving very fast as it orbits, that the sides of the spaceship facing "down toward earth" is always changing.





In contrast to the above scenarios, both men have weight and feels the magnitude of their weight. The force of gravity pulling them down onto the Earth's surface is equal and opposite to the force of the ground pushing back or the bench seat pushing back (normal force). The normal force pushing back makes the "heaviness" associated with weight.