SECTION 7.2

Newton's Law of Universal Gravitation

Gravitational Force

You are attracted toward Earth. So are the atmosphere around you, falling rain, falling meteors, and all other matter near Earth. The **gravitational force** is a mutual force of attraction between all particles of matter. It depends on an object's mass. There is a gravitational attraction between a rock and a raindrop. But because the planet below them is so much larger, the effect of this comparatively tiny gravitational force is harder to observe.

KEY TERM

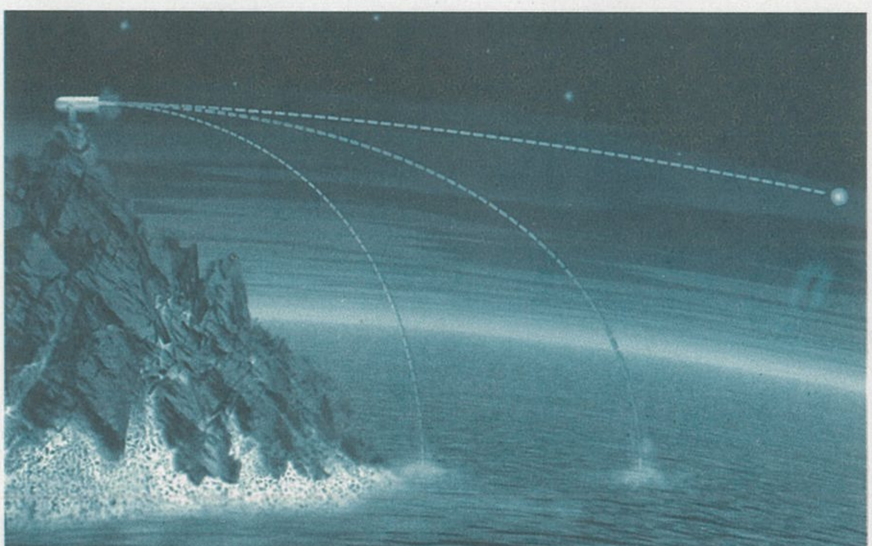
gravitational force

READING CHECK

1. Why do you notice the attraction between you and Earth more than the attraction between you and this book?

Orbiting objects are in free fall.

Consider a cannon sitting on a cliff. The cannonballs would continue on horizontally without gravity. Their paths curve downward when gravity is present. A cannonball at a high velocity will curve toward Earth in the same way that Earth curves out from under it.



The cannonball will fall toward Earth as fast as Earth curves away from it. The ball is in orbit around Earth.

This thought experiment was developed by Isaac Newton. He realized that the force that pulls an apple toward Earth as it falls from a tree and the force that pulls the moon toward Earth as it orbits are the same.

Gravitational force depends on the masses and the distances.

Newton developed an equation to describe the attraction between two masses.

$$\text{gravitational force} = \text{constant} \times \frac{(\text{mass 1})(\text{mass 2})}{(\text{distance between them})^2}$$

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

G is called the *constant of universal gravitation.* It was unknown when Newton was alive. Later experiments determined it to be 6.673×10^{-11} N•m²/kg².

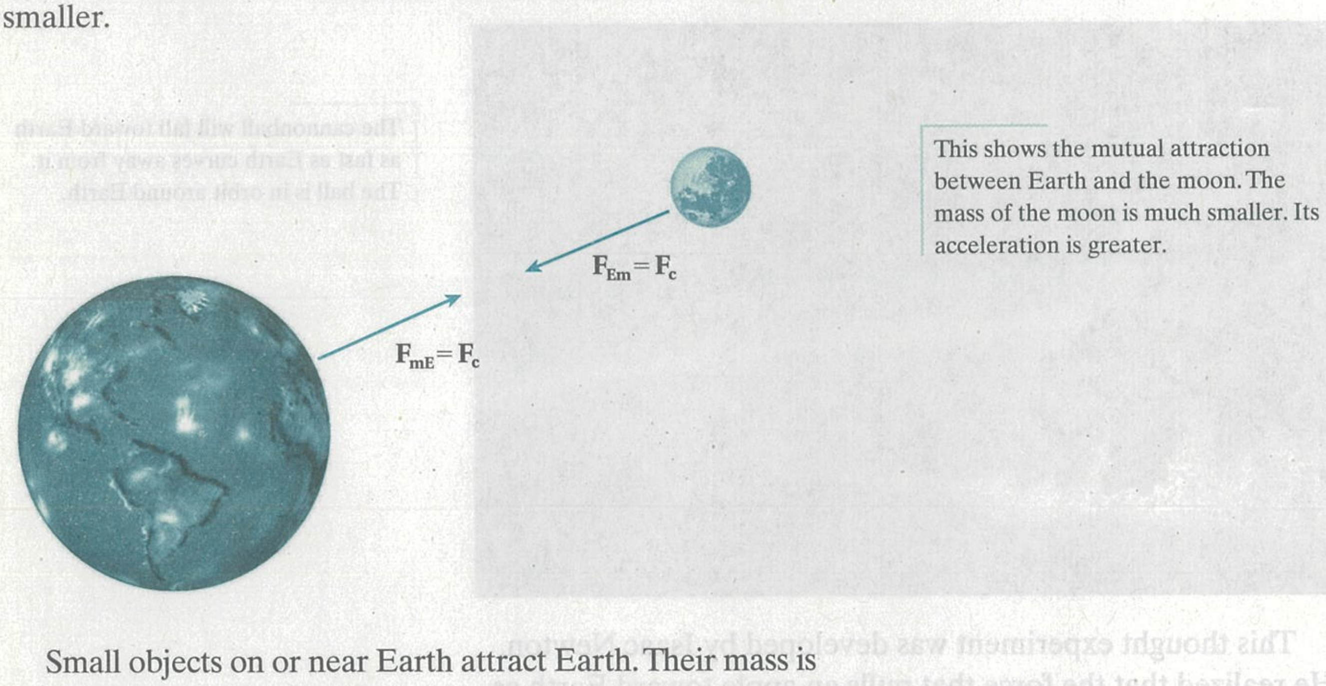
Newton also demonstrated that the gravitational force exerted by a sphere like Earth on any point outside the sphere would be the same if the entire mass of each was concentrated at a point in the center. Suppose you want to calculate the force between Earth and an apple or Earth and the sun. Use the distance between their centers.

Critical Thinking

2. Predict What happens to the gravitational attraction between two objects as they move apart?

Gravitational force acts between all masses.

The gravitational force of Earth on the sun and the sun on Earth are equal and opposite. The mass of the sun is much larger and so the acceleration given to it by this force is much smaller.



This shows the mutual attraction between Earth and the moon. The mass of the moon is much smaller. Its acceleration is greater.

Small objects on or near Earth attract Earth. Their mass is much smaller and so their effect on Earth's motion is very small.

SAMPLE PROBLEM

The sun has a mass of 2.0×10^{30} kg. Its radius is 7.0×10^{8} m. The gravitational force between the sun and a section of the sun's surface is 470 N. What is the mass of this section?

SOLUTION

1 ANALYZE *Determine what information is given and unknown.*

Given: $m_1 = 2.0 \times 10^{30}$ kg $\quad r = 7.0 \times 10^{8}$ m

$F_g = 470$ N

$G = 6.673 \times 10^{11}$ N•m²/kg²

Unknown: $m_2 = ?$

2 SOLVE *Use Newton's law of gravitation. Rearrange to solve for m_2.*

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

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

$$m_2 = \frac{F_g r^2}{G m_1} = \frac{(470\ \text{N})(7.0 \times 10^{8}\ \text{m})^2}{(6.673 \times 10^{-11}\ \frac{\text{N}\cdot\text{m}^2}{\text{kg}^2})(2.0 \times 10^{30}\ \text{kg})} = \boxed{1.7\ \text{kg}}$$

PRACTICE

A. The gravitational force between two 0.800 kg balls is 8.92×10^{-11} N. How far apart are they?

B. A 66.5 kg astronaut stands on the surface of Pluto. Pluto's mass is 1.25×10^{22} kg. Its radius is 1.20×10^{6} m. Find the gravitational force exerted by Pluto on the astronaut.

Applying the Law of Gravitation

The water level along many coastal areas slowly rises and falls over the course of the day. This cycle of high and low tides repeats about every 12 hours. People had known for a long time that the tidal cycle is related to the position of the moon. But how it was related was not understood until Newton.

Newton's law of gravitation accounts for ocean tides.

The tides result from the *difference* of the gravitational force of the moon at different distances. As the distance from the moon increases, the gravitational force of the moon on any mass at that point decreases. So the attraction to the moon is strongest on the side of Earth facing the moon. The attraction is less in the middle. It is smallest on the side away from the moon.

The ocean on the side facing the moon bulges slightly outward. The moon's force on it is slightly larger than its force on Earth's center because the distance is smaller. The ocean would also bulge outward on the far side because the ocean at that point is farther away from the moon. These two locations experience high tides. The points between the two high tides are at low tide.

The sun also has an effect on Earth's tides. But the effect is smaller because the sun is much farther away.

Did YOU Know?

Sometimes the sun and moon are in line. This produces a greater difference between high and low tide on Earth. This is called a spring tide. Sometimes the sun and moon are at right angles. This results in a smaller difference between high and low tide. This is called a neap tide. Each of these tides happens twice during one orbit of the moon around Earth.

Cavendish finds the value of *G* and Earth's mass.

Henry Cavendish conducted an experiment in 1798. Two small spheres were fixed to the end of a light rod that could rotate. Two larger spheres were moved close to the small spheres. One was placed on either side of the rod. The rod rotated by a tiny amount as each small sphere was attracted to the nearby large sphere. Cavendish knew m_1, m_2, and r, and measured F_g. He could then solve the equation for universal gravitation for G. Once he knew the value of G, he replaced m_2 with m_{Earth} and solved to find m_{Earth}.

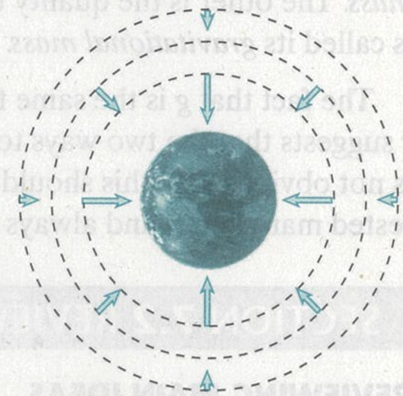
Gravity is a field force.

A mass creates a gravitational field in the space around it. The fields of massive objects add together. Gravitational force is the interaction between a mass and the gravitational field created by other masses.

The gravitational potential energy of a falling object is converted to kinetic energy. Its gravitational potential energy is stored in the gravitational field.

Earth's gravitational field can be described by the gravitational field strength g at any point. The value of g is the acceleration the gravitational field would give a unit mass at that point.

The gravitational field is strongest close to Earth. The strength of the field decreases as the distance from Earth's center increases.



Gravitational field strength equals free-fall acceleration.

The value of g is equal to the acceleration due to gravity at that point. The two values are equal. But they do not describe the same thing. The strength of Earth's gravitational field on a pencil resting on the desk is g. But the acceleration of the pencil is zero.

Weight changes with location.

Weight is the magnitude of the force on an object due to gravity. This is g at Earth's surface. It can be found using the equation for the force of gravity on a mass m_1.

$$F_g = G\frac{m_1 m_{Earth}}{r^2} \text{ or } F_g = m_1 \frac{Gm_{Earth}}{r^2} = m_1 g$$

So $g = \frac{Gm_{Earth}}{r^2}$. If m_{planet} or r changes, then the value of g will change. r is larger at a high elevation than at sea level. So g is smaller and your weight is also lower on top of a mountain than at sea level. Your weight is also lower in a flying plane. g will also have a different value on the surface of another planet.

Conceptual Challenge

Gravity on the Moon The magnitude of g on the surface of the moon is about 1/6 its value on Earth. Does it follow that the mass of the moon must be 1/6 the mass of Earth? Why or why not? Hint: Does g depend only on mass?

Selling Gold A scam artist hopes to buy gold where its weight is lower and sell where its weight is higher. At what altitude should the scam artist buy and sell? Explain.

READING CHECK

3. What factors determine the value of g?

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Gravitational mass equals inertial mass.

You know that free-fall acceleration does not depend on a falling object's mass. Recall the equation $F = ma$. The mass m of the object can be thought of in two ways. One is an object's resistance to a change in its motion. This is called its *inertial mass.* The other is the quality that attracts any other mass. This is called its *gravitational mass.*

The fact that g is the same for all objects at a given distance r suggests that the two ways to think of mass are equivalent. It is not obvious why this should be the case. But it has been tested many times and always held up.

SECTION 7.2 REVIEW

REVIEWING MAIN IDEAS

1. Explain how the force due to gravity keeps a satellite in orbit.

2. What is the magnitude of g at a height above Earth's surface where free-fall acceleration equals 6.5 m/s^2?

Critical Thinking

3. The radius of Earth is about 6.38×10^6 m. Use $g = 9.81\ m/s^2$ and $G = 6.673 \times 10^{-11}\ N \bullet m^2/kg^2$ to calculate Earth's mass.