THE BIG IDEA

Everything pulls on everything else.

Gravity was not discovered by Isaac Newton. What Newton discovered, prompted by a falling apple, was that gravity is a universal force—that it is not unique to Earth, as others of his time assumed.

13.1 The Falling Apple

Newton reasoned that the moon is falling toward Earth for the same reason an apple falls from a tree—they are both pulled by Earth's gravity.

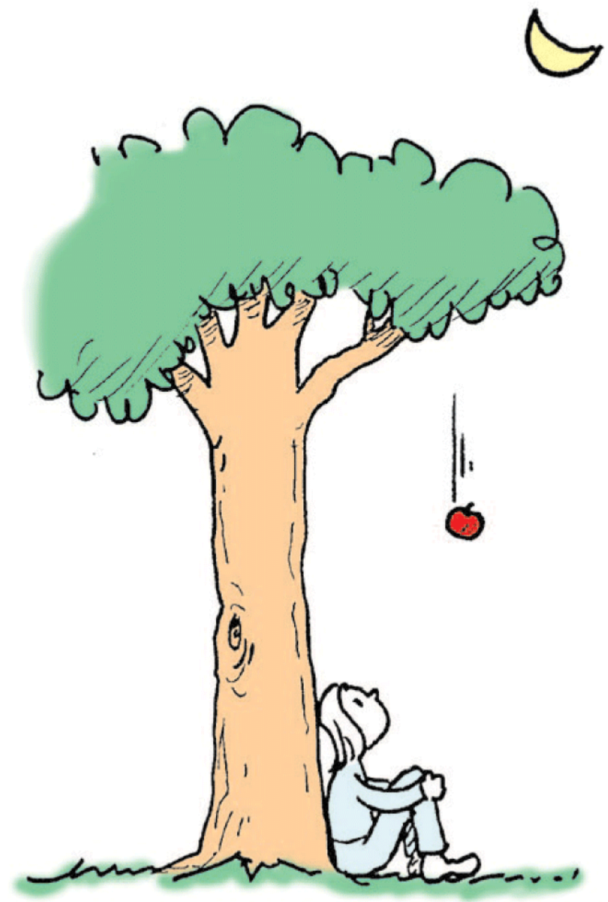
13.1 The Falling Apple

Newton understood the concept of inertia developed earlier by Galileo.

- He knew that without an outside force, moving objects continue to move at constant speed in a straight line.
- He knew that if an object undergoes a change in speed or direction, then a force is responsible.

13.1 The Falling Apple

According to legend, Newton discovered gravity while sitting under an apple tree.



13.1 The Falling Apple

Newton saw the apple fall, or maybe even felt it fall on his head. Perhaps he looked up through the apple tree branches and noticed the moon.

- He may have been puzzled by the fact that the moon does not follow a straight-line path, but instead circles about Earth.
- He knew that circular motion is accelerated motion, which requires a force.
- Newton had the insight to see that the moon is falling toward Earth, just as the apple is.

13.1 The Falling Apple

CONCEPT CHECK

What was Newton's reasoning about the apple falling from the tree?

13.2 The Falling Moon

The moon is actually falling toward Earth but has great enough tangential velocity to avoid hitting Earth.

13.2 The Falling Moon

Newton realized that if the moon did not fall, it would move off in a straight line and leave its orbit.

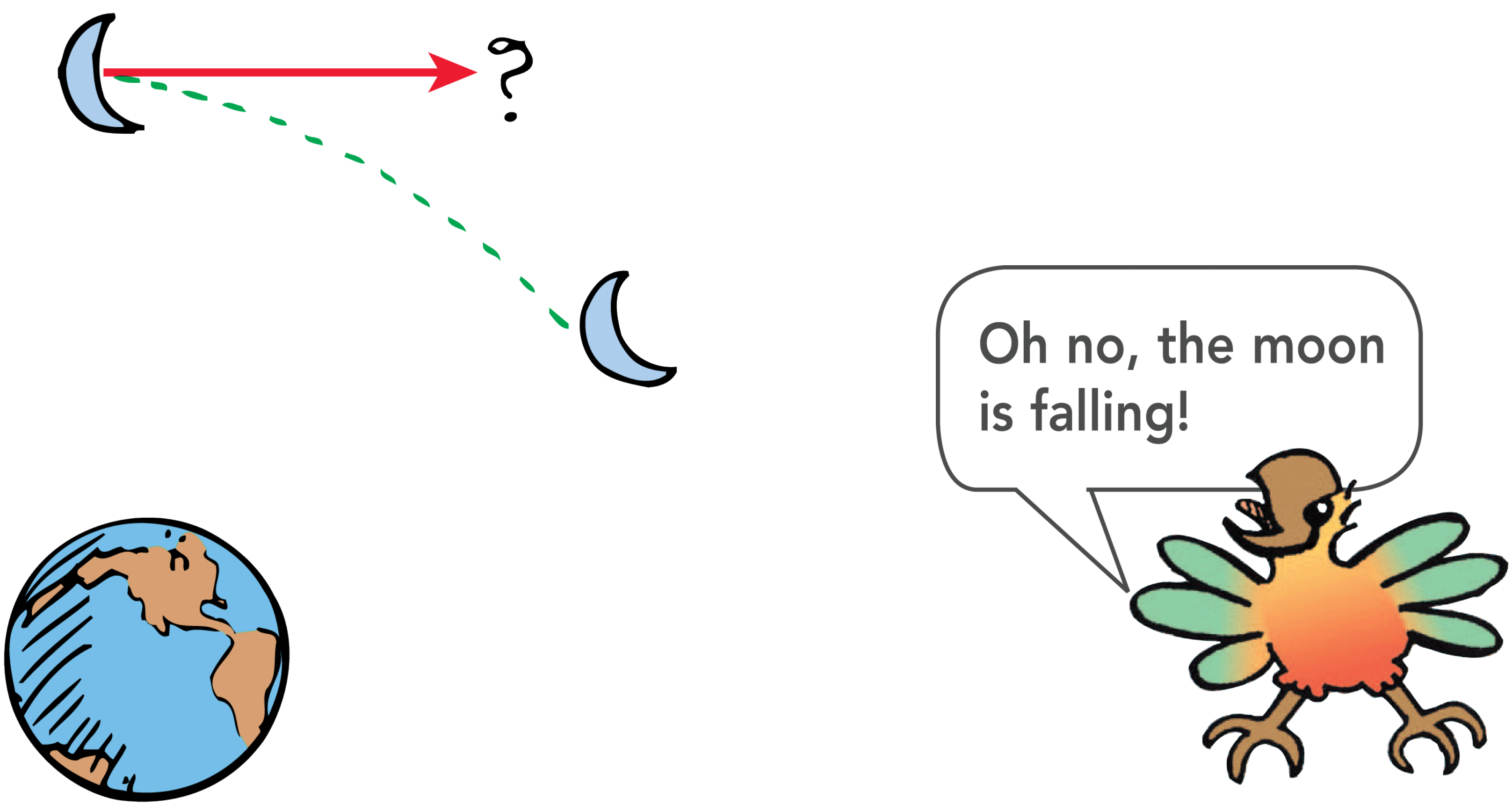
His idea was that the moon must be falling *around* Earth.

Thus the moon falls in the sense that it *falls beneath the straight line it would follow if no force acted on it.*

He hypothesized that the moon was simply a projectile circling Earth under the attraction of gravity.

13.2 The Falling Moon

If the moon did not fall, it would follow a straight-line path.



13.2 The Falling Moon

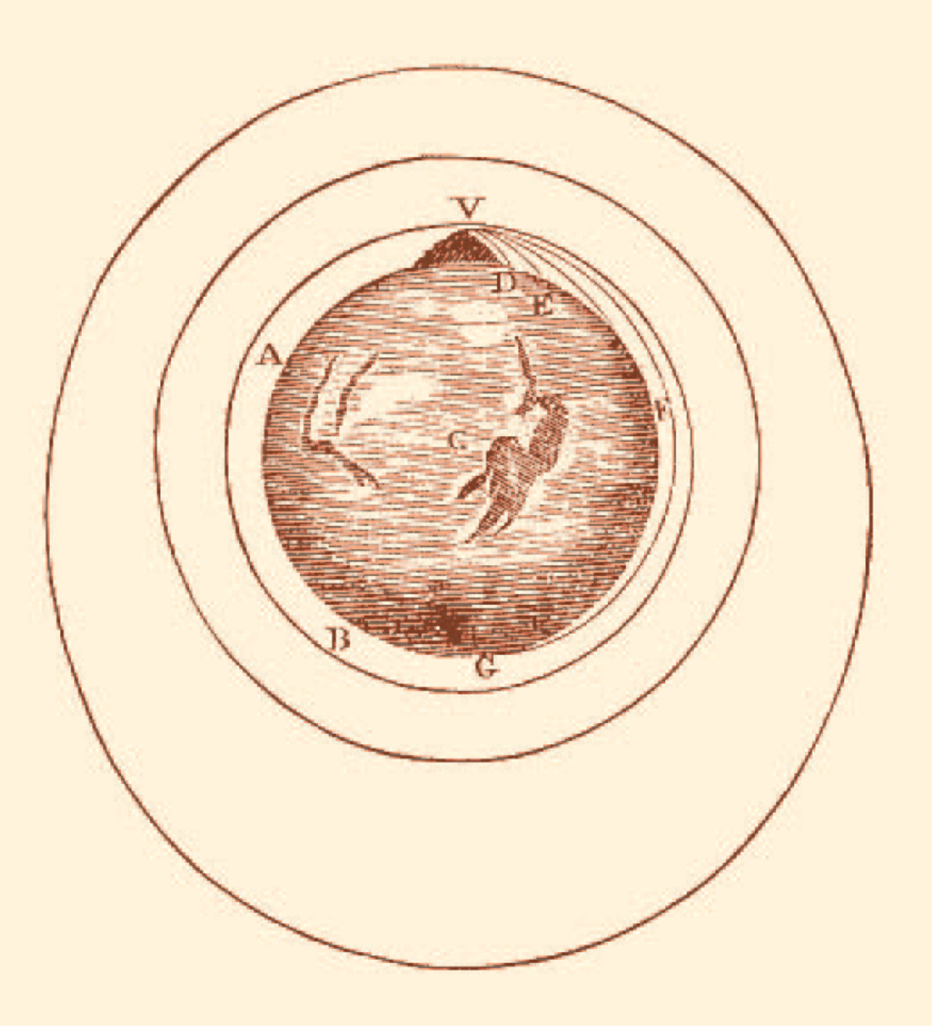
Newton's Hypothesis

Newton compared motion of the moon to a cannonball fired from the top of a high mountain.

- If a cannonball were fired with a small horizontal speed, it would follow a parabolic path and soon hit Earth below.
- Fired faster, its path would be less curved and it would hit Earth farther away.
- If the cannonball were fired fast enough, its path would become a circle and the cannonball would circle indefinitely.

13.2 The Falling Moon

This original drawing by Isaac Newton shows how a projectile fired fast enough would fall around Earth and become an Earth satellite.



13.2 The Falling Moon

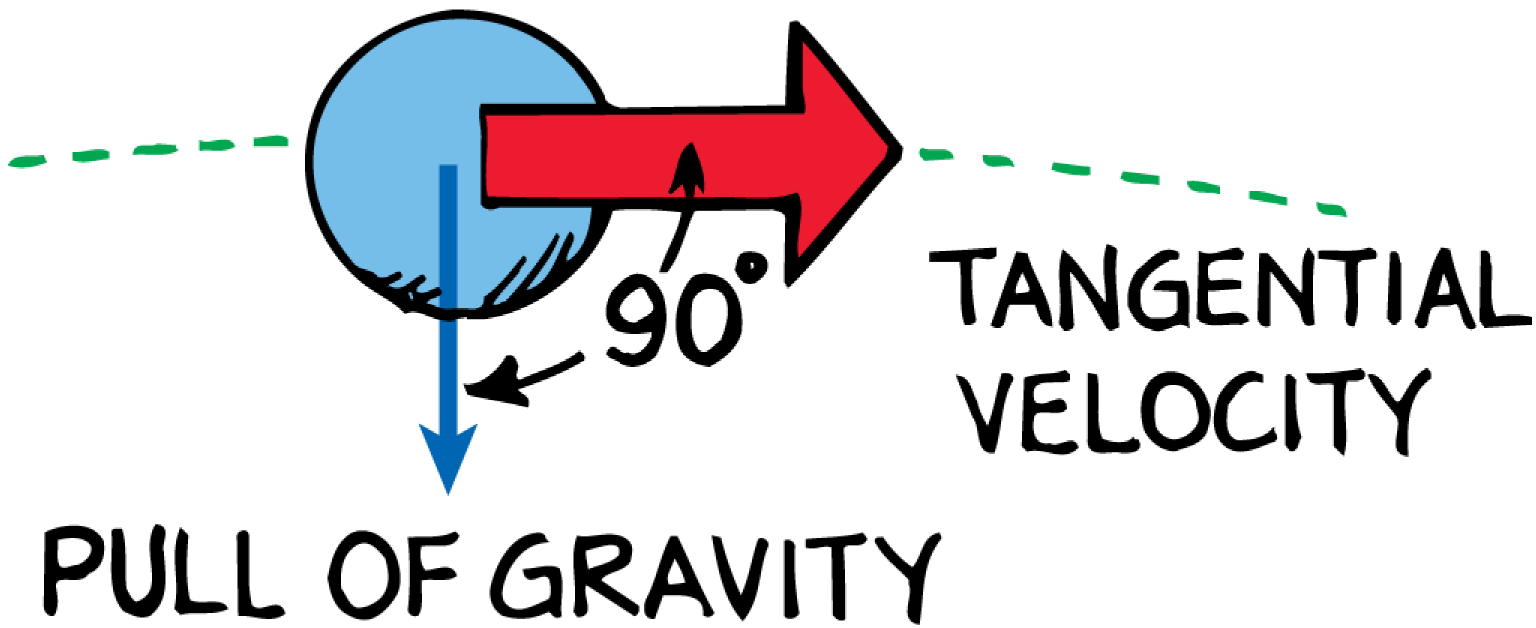
Both the orbiting cannonball and the moon have a component of velocity parallel to Earth's surface.

This sideways or *tangential velocity* is sufficient to ensure nearly circular motion *around* Earth rather than *into* it.

With no resistance to reduce its speed, the moon will continue "falling" around and around Earth indefinitely.

13.2 The Falling Moon

Tangential velocity is the “sideways” velocity—the component of velocity perpendicular to the pull of gravity.



13.2 The Falling Moon

Newton's Apple-Moon Test

For Newton's idea to advance from hypothesis to scientific theory, it would have to be tested.

- He reasoned that the mass of the moon should not affect how it falls, just as mass has no effect on the acceleration of freely falling objects on Earth.
- How far the moon, or an apple at Earth's surface, falls should relate only to its respective *distance* from Earth's center.

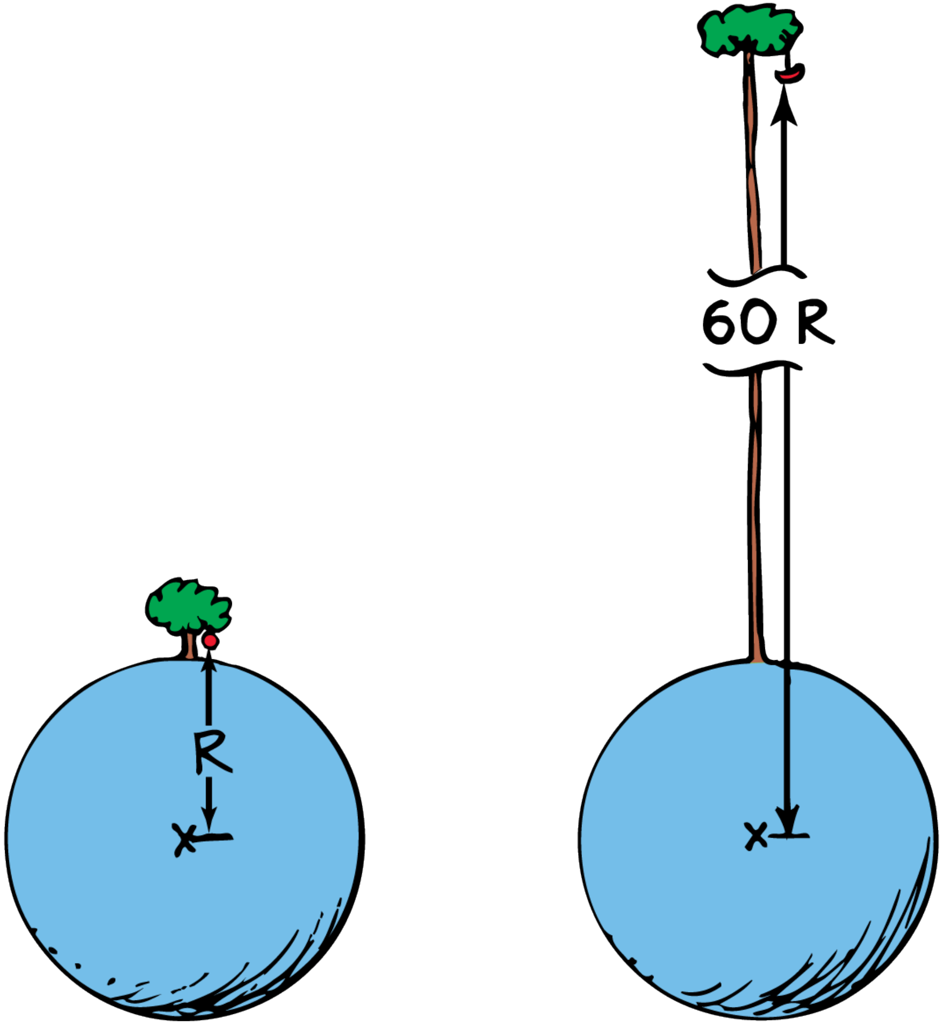
13.2 The Falling Moon

The moon was already known to be 60 times farther from the center of Earth than an apple at Earth's surface.

- The apple will fall 5 m in its first second of fall.
- Newton reasoned that gravitational attraction to Earth must be "diluted" by distance.
- The influence of gravity should be diluted to 1/60 of 1/60.
- In one second the moon should fall $1/(60)^2$ of 5 m, which is 1.4 millimeters.

13.2 The Falling Moon

An apple falls 5 m during its first second of fall when it is near Earth's surface. Newton asked how far the moon would fall in the same time if it were 60 times farther from the center of Earth.



13.2 The Falling Moon

Newton's Calculation

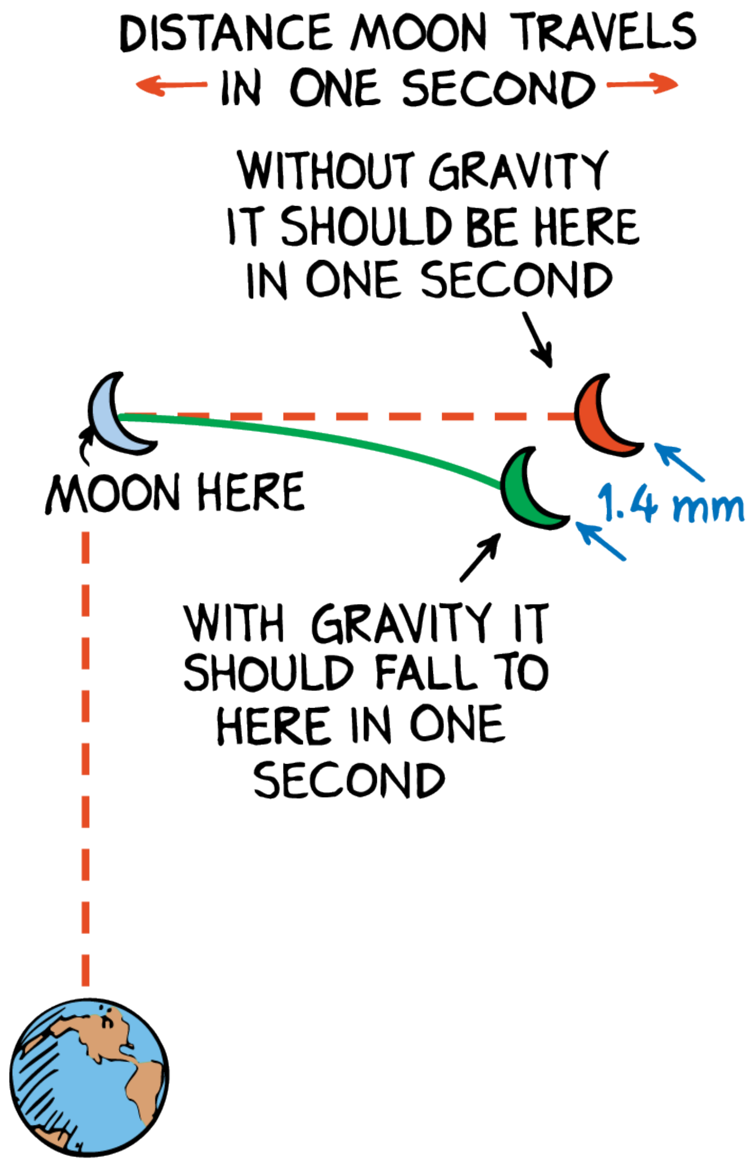
Newton calculated how far the circle of the moon's orbit lies below the straight-line distance the moon would otherwise travel in one second.

His value turned out to be about the 1.4-mm distance accepted today.

He was unsure of the exact Earth-moon distance and whether the correct distance to use was the distance between their centers.

13.2 The Falling Moon

If the force that pulls apples off trees also pulls the moon into orbit, the circle of the moon's orbit should fall 1.4 mm below a point along the straight line where the moon would otherwise be one second later.



13.2 The Falling Moon

It wasn't until after Newton invented a new branch of mathematics, calculus, to prove his center-of-gravity hypothesis, that he published the law of universal gravitation.

Newton generalized his moon finding to all objects, and stated that all objects in the universe attract each other.

13.2 The Falling Moon

CONCEPT CHECK

Why doesn't the moon hit Earth?

13.3 The Falling Earth

Newton's theory of gravity confirmed the Copernican theory of the solar system.

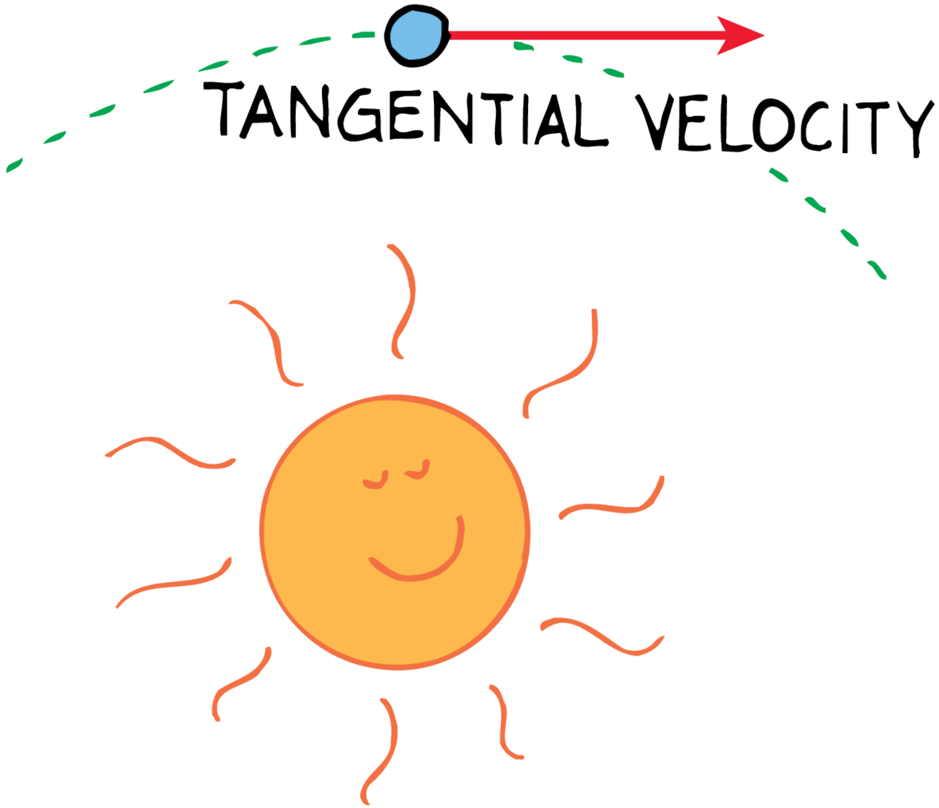
13.3 The Falling Earth

No longer was Earth considered to be the center of the universe.

- It became clear that the planets orbit the sun in the same way that the moon orbits Earth.
- The planets continually "fall" around the sun in closed paths.

13.3 The Falling Earth

The tangential velocity of Earth about the sun allows it to fall around the sun rather than directly into it.



13.3 The Falling Earth

What would happen if the tangential velocities of the planets were reduced to zero?

Their motion would be straight toward the sun and they would indeed crash into it.

Any objects in the solar system with insufficient tangential velocities have long ago crashed into the sun.

13.3 The Falling Earth

CONCEPT CHECK

What theory of the solar system did Newton's theory of gravity confirm?

13.4 Newton's Law of Universal Gravitation

Newton discovered that gravity is universal. Everything pulls on everything else in a way that involves only mass and distance.

13.4 Newton's Law of Universal Gravitation

Newton's **law of universal gravitation** states that every object attracts every other object with a force that for any two objects is directly proportional to the mass of each object.

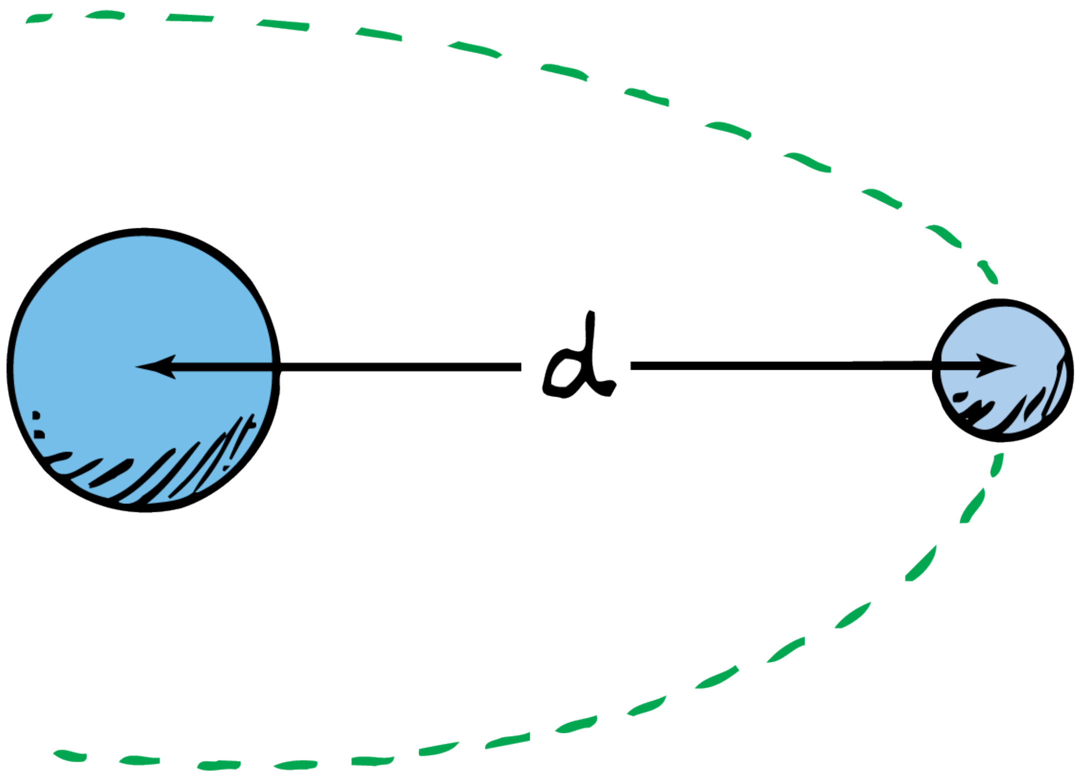
Newton deduced that the force decreases as the square of the distance between the centers of mass of the objects increases.

$$\text{Force} \sim \frac{\text{mass}_1 \times \text{mass}_2}{\text{distance}^2}$$

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

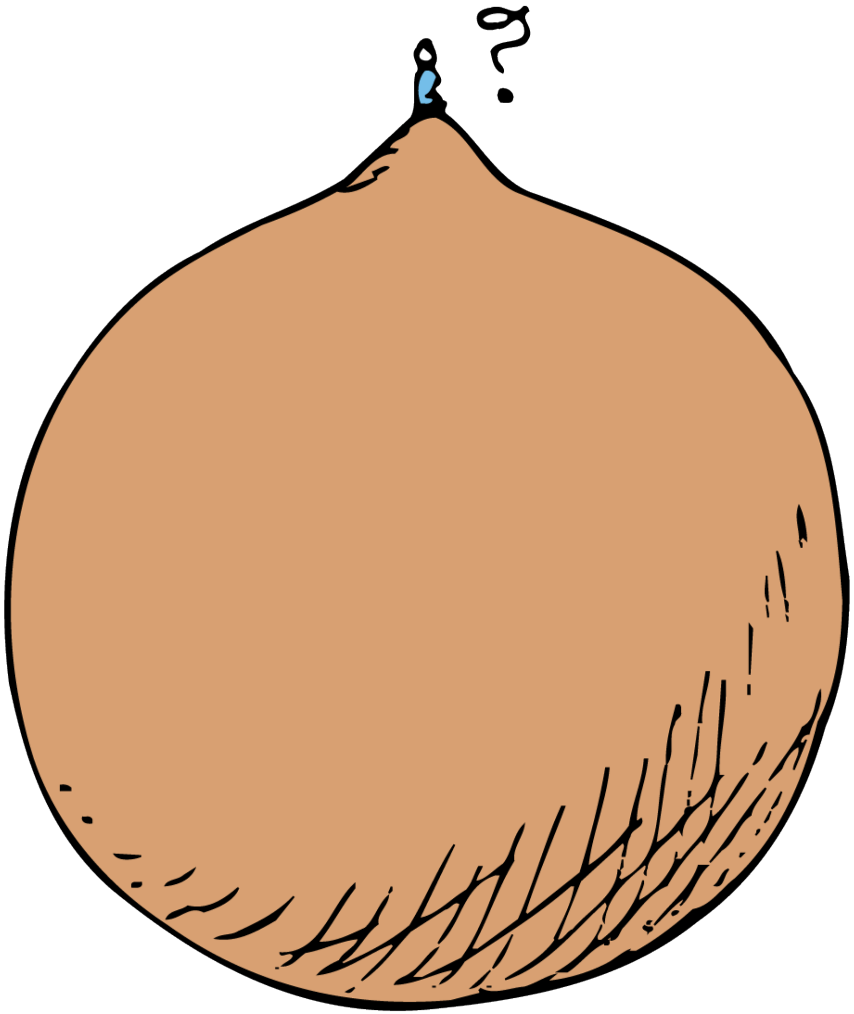
13.4 Newton's Law of Universal Gravitation

The force of gravity between objects depends on the distance between their centers of mass.



13.4 Newton’s Law of Universal Gravitation

Your weight is less at the top of a mountain because you are farther from the center of Earth.



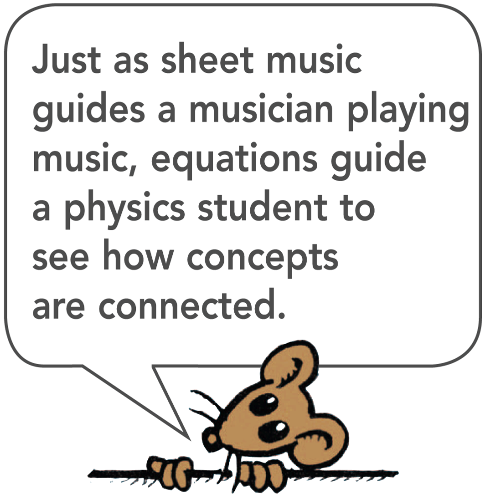
13.4 Newton's Law of Universal Gravitation

The Universal Gravitational Constant, *G*

The law of universal gravitation can be expressed as an exact equation when a proportionality constant is introduced.

The **universal gravitational constant,** *G,* in the equation for universal gravitation describes the strength of gravity.

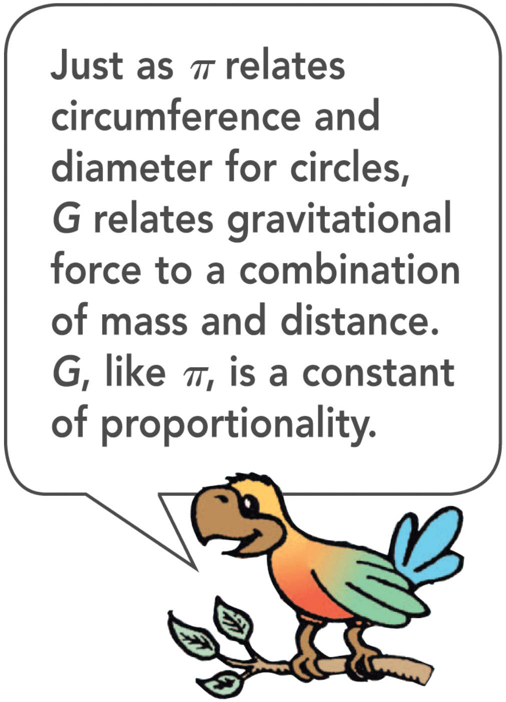
$$F = G\frac{m_1 m_2}{d^2}$$



13.4 Newton's Law of Universal Gravitation

The force of gravity between two objects is found by multiplying their masses, dividing by the square of the distance between their centers, and then multiplying this result by *G*.

- The magnitude of *G* is given by the magnitude of the force between two masses of 1 kilogram each, 1 meter apart: 0.0000000000667 newton. (In scientific notation: $G = 6.67 \times 10^{-11}$ $N{\cdot}m^2/kg^2$)
- The units of *G* are such as to make the force of gravity come out in newtons.



13.4 Newton's Law of Universal Gravitation

Measuring *G*

G was first measured 150 years after Newton's discovery of universal gravitation by an English physicist, Henry Cavendish.

Cavendish accomplished this by measuring the tiny force between lead masses with an extremely sensitive torsion balance.

13.4 Newton's Law of Universal Gravitation

A simpler method was developed by Philipp von Jolly.

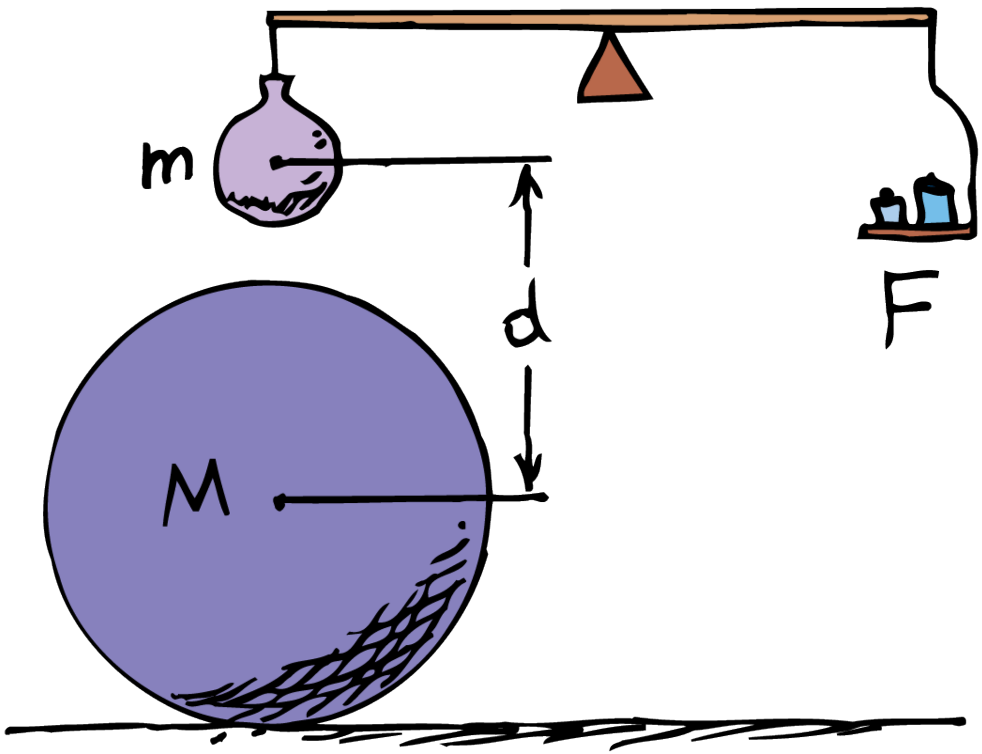
- He attached a spherical flask of mercury to one arm of a sensitive balance.
- A 6-ton lead sphere was rolled beneath the mercury flask.
- The flask was pulled slightly downward.
- The gravitational force *F*, between the lead mass and the mercury, was equal to the weight that had to be placed on the opposite end of the balance to restore equilibrium.

F, m_1, m_2, and *d* were all known, so the ratio *G* was calculated:

$$G = \frac{F}{m_1 m_2 / d^2} = \frac{\mathrm{N}}{\mathrm{kg}^2/\mathrm{m}^2} = 6.67 \times 10^{-11}\ \mathrm{N \cdot m^2/kg^2}$$

13.4 Newton's Law of Universal Gravitation

Philipp von Jolly developed a method of measuring the attraction between two masses.



13.4 Newton's Law of Universal Gravitation

The value of *G* tells us that gravity is a very weak force.

It is the weakest of the presently known four fundamental forces.

We sense gravitation only when masses like that of Earth are involved.

13.4 Newton's Law of Universal Gravitation

Cavendish's first measure of G was called the "Weighing the Earth" experiment.

- Once the value of G was known, the mass of Earth was easily calculated.
- The force that Earth exerts on a mass of 1 kilogram at its surface is 10 newtons.
- The distance between the 1-kilogram mass and the center of mass of Earth is Earth's radius, 6.4×10^6 meters.

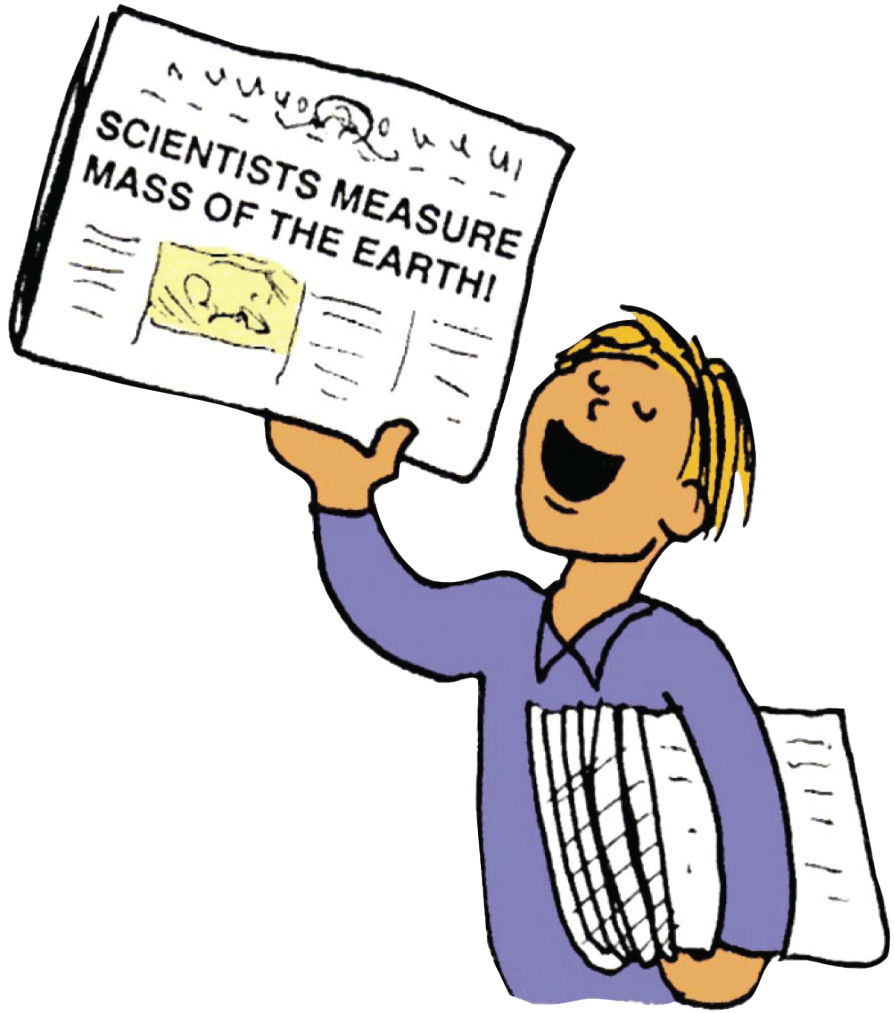
$$10\ \text{N} = 6.67 \times 10^{-11}\ \text{N}\cdot\text{m}^2/\text{kg}^2 \times \frac{1\ \text{kg} \times m_1}{(6.4 \times 10^6\ \text{m})^2}$$

$$m_1 = \frac{10\ \text{N} \times (6.4 \times 10^6\ \text{m})^2}{1\ \text{kg} \times (6.67 \times 10^{-11}\ \text{N}\cdot\text{m}^2/\text{kg}^2)}$$

from which the mass of Earth $m_1 = 6 \times 10^{24}$ kilograms.

13.4 Newton's Law of Universal Gravitation

When *G* was first measured in the 1700s, newspapers everywhere announced the discovery as one that measured the mass of Earth.



13.4 Newton's Law of Universal Gravitation

CONCEPT CHECK What did Newton discover about gravity?

13.5 Gravity and Distance: The Inverse-Square Law

Gravity decreases according to the inverse-square law. The force of gravity weakens as the square of distance.

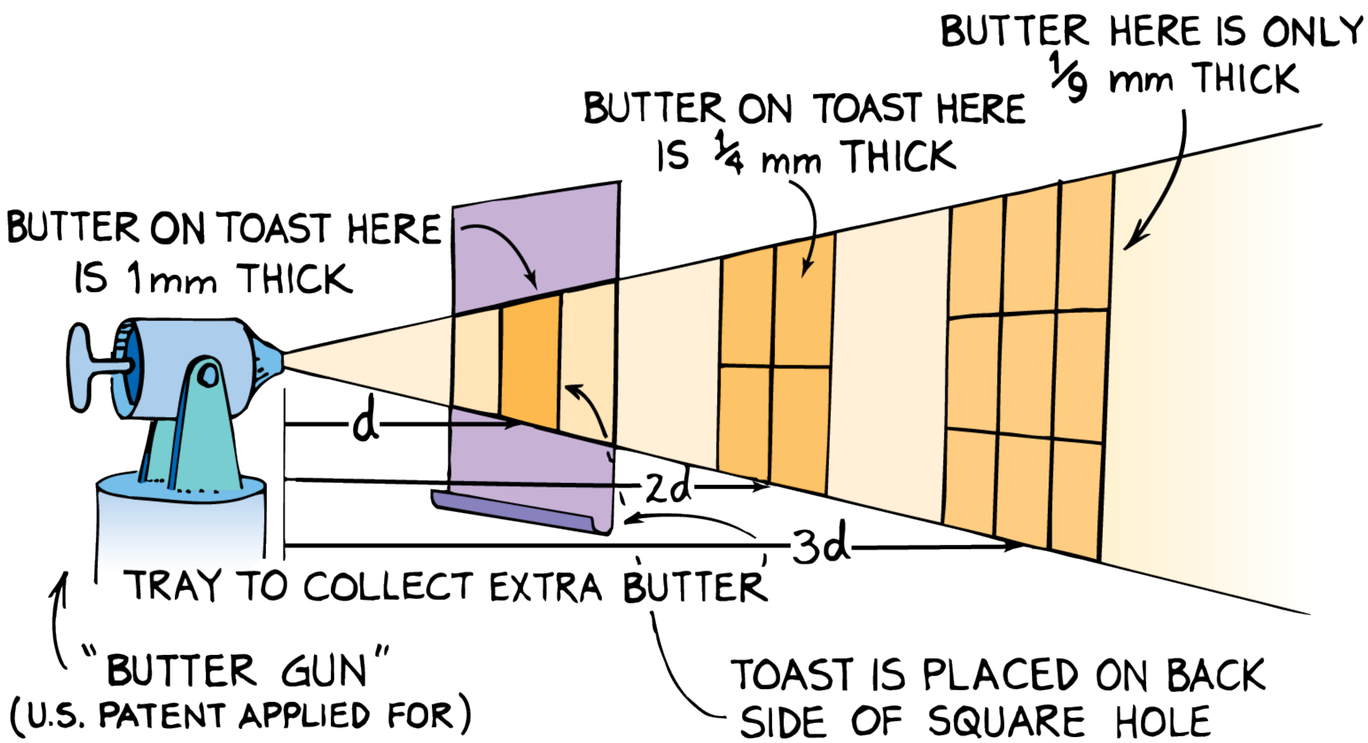
13.5 Gravity and Distance: The Inverse-Square Law

Consider an imaginary “butter gun” for buttering toast.

- Melted butter is sprayed through a square opening exactly the size of one piece of square toast
- The gun deposits a layer of butter 1 mm thick.
- Twice as far from the butter gun, butter would cover twice as much toast vertically and twice as much toast horizontally.
- Since the butter has been diluted to cover four times as much area, its thickness will be one quarter as much, or 0.25 mm.

13.5 Gravity and Distance: The Inverse-Square Law

Butter spray travels outward from the nozzle in straight lines. Like gravity, the "strength" of the spray obeys an inverse-square law.



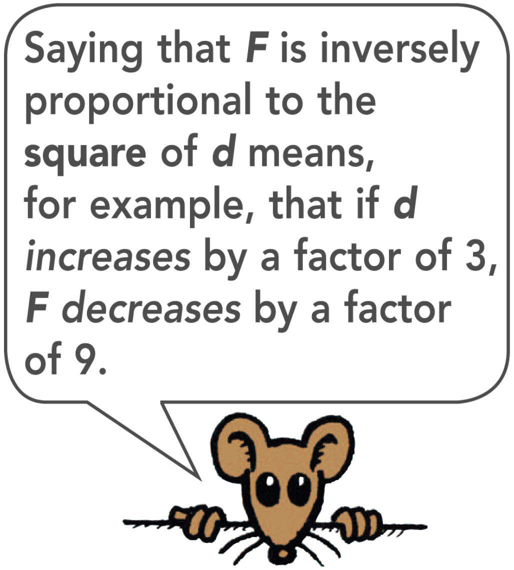
13.5 Gravity and Distance: The Inverse-Square Law

Twice as far from the gun, the butter is only 1/4 as thick.

Three times as far, it will be 1/9 as thick.

1/9 is the inverse *square* of 3.

When a quantity varies as the inverse square of its distance from its source, it follows an **inverse-square law.**



13.5 Gravity and Distance: The Inverse-Square Law

This law applies to the weakening of gravity with distance.

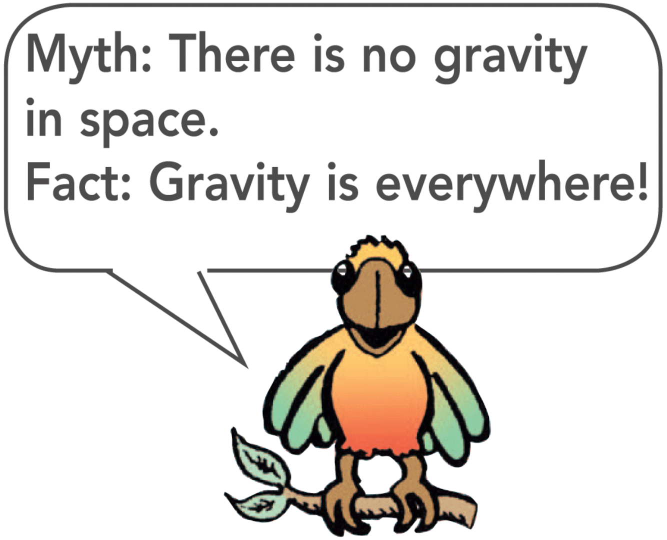
It also applies to all cases where the effect from a localized source spreads evenly throughout the surrounding space.

Examples are light, radiation, and sound.

13.5 Gravity and Distance: The Inverse-Square Law

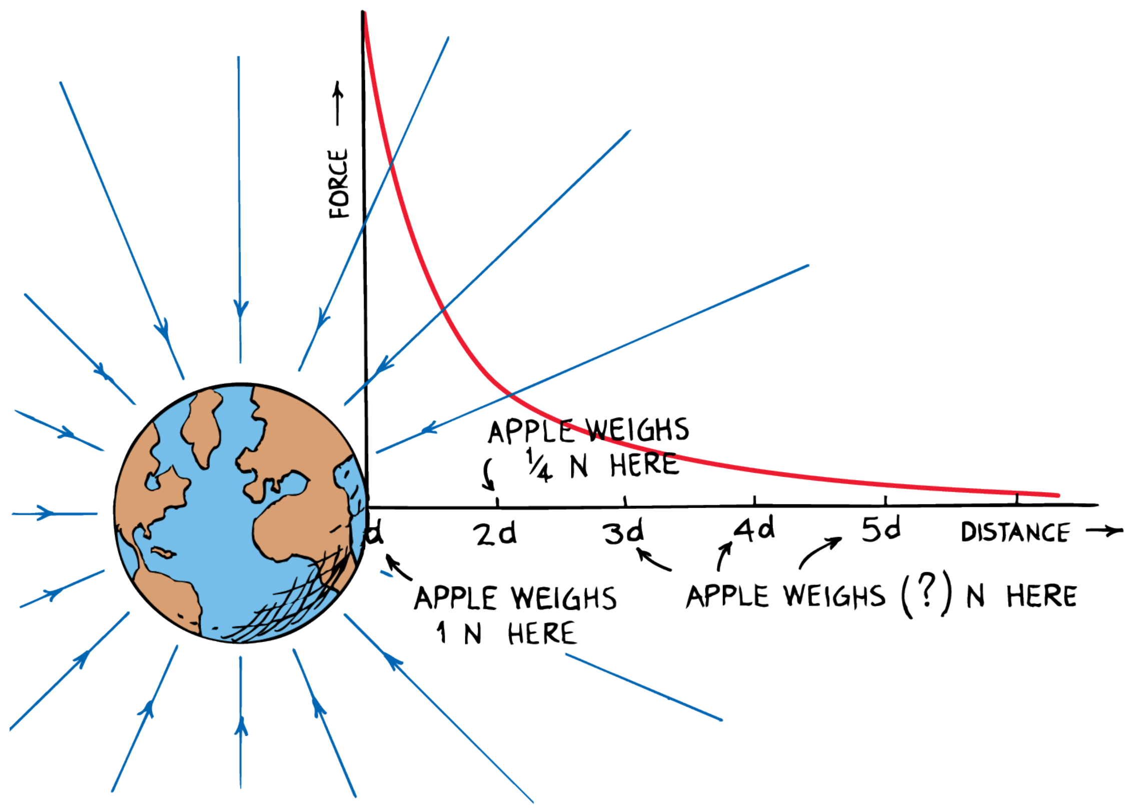
The greater the distance from Earth's center, the less an object will weigh.

- An apple that weighs 1 N at Earth's surface weighs only 0.25 N when located twice as far from Earth's center.
- When it is 3 times as far, it weighs only 1/9 as much.
- But no matter how great the distance, Earth's gravity does not drop to zero.
- The gravitational influence of every object, however small or far, is exerted through all space.



13.5 Gravity and Distance: The Inverse-Square Law

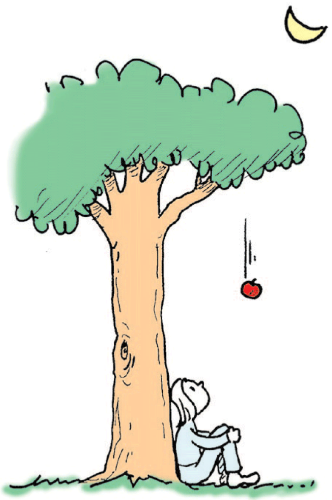
Gravitational force is plotted versus distance from Earth's center.



13.5 Gravity and Distance: The Inverse-Square Law

think!

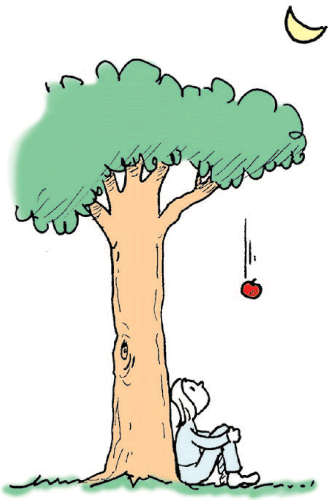
Suppose that an apple at the top of a tree is pulled by Earth's gravity with a force of 1 N. If the tree were twice as tall, would the force of gravity on the apple be only 1/4 as strong? Explain your answer.



13.5 Gravity and Distance: The Inverse-Square Law

think!

Suppose that an apple at the top of a tree is pulled by Earth's gravity with a force of 1 N. If the tree were twice as tall, would the force of gravity on the apple be only 1/4 as strong? Explain your answer.



Answer:

No, the twice-as-tall apple tree is not twice as far from Earth's center. The taller tree would have to have a height equal to the radius of Earth (6370 km) before the weight of the apple would reduce to 1/4 N.

13.5 Gravity and Distance: The Inverse-Square Law

CONCEPT CHECK

How does the force of gravity change with distance?

13.6 Gravitational Field

Earth can be thought of as being surrounded by a gravitational field that interacts with objects and causes them to experience gravitational forces.

13.6 Gravitational Field

We can regard the moon as in contact with the gravitational field of Earth.

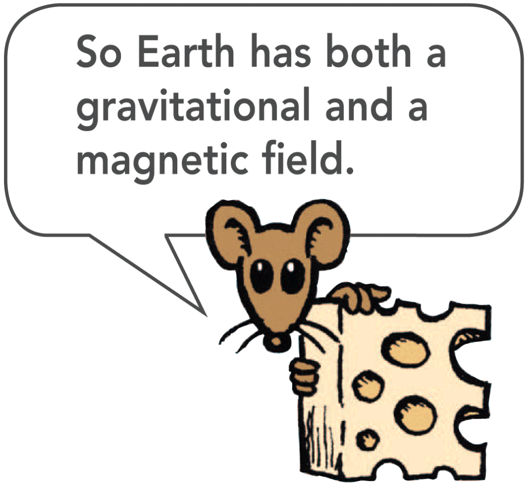
A **gravitational field** occupies the space surrounding a massive body.

A gravitational field is an example of a *force field,* for any mass in the field space experiences a force.

13.6 Gravitational Field

A more familiar force field is the magnetic field of a magnet.

- Iron filings sprinkled over a sheet of paper on top of a magnet reveal the shape of the magnet's magnetic field.
- Where the filings are close together, the field is strong.
- The direction of the filings shows the direction of the field at each point.
- Planet Earth is a giant magnet, and like all magnets, is surrounded in a magnetic field.



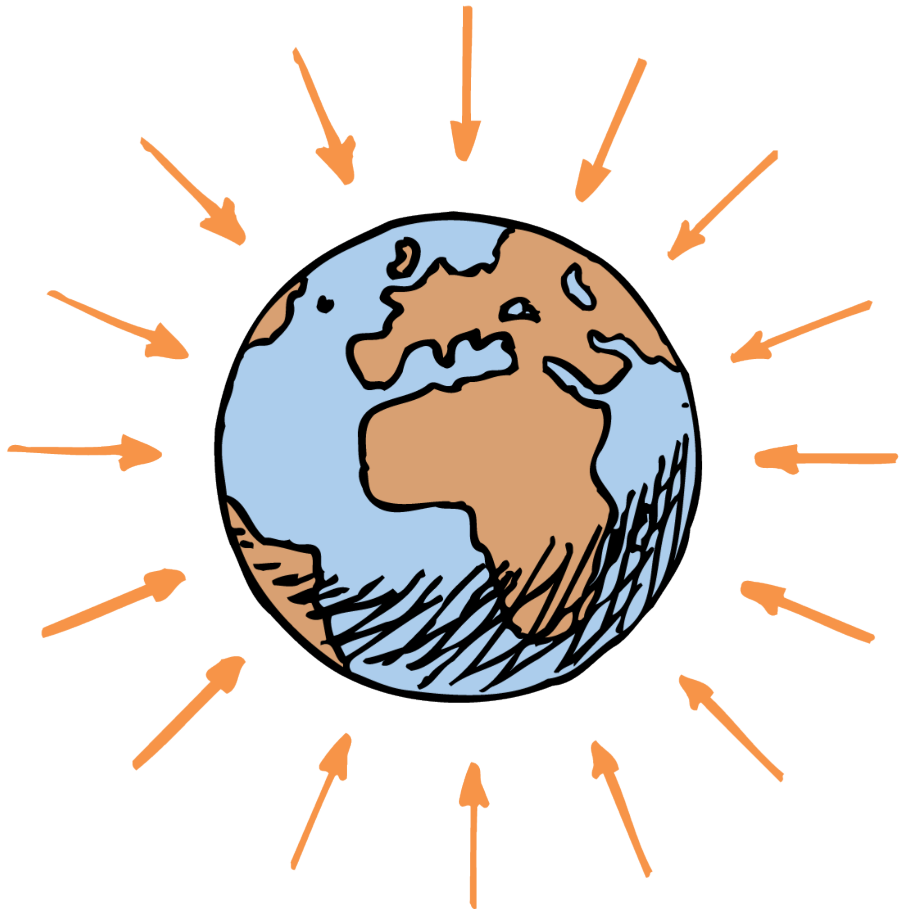
13.6 Gravitational Field

Field lines can also represent the pattern of Earth's gravitational field.

- The field lines are closer together where the gravitational field is stronger.
- Any mass in the vicinity of Earth will be accelerated in the direction of the field lines at that location.
- Earth's gravitational field follows the inverse-square law.
- Earth's gravitational field is strongest near Earth's surface and weaker at greater distances from Earth.

13.6 Gravitational Field

Field lines represent the gravitational field about Earth.



13.6 Gravitational Field

CONCEPT CHECK

What kind of field surrounds Earth and causes objects to experience gravitational forces?

13.7 Gravitational Field Inside a Planet

The gravitational field of Earth at its center is zero!

13.7 Gravitational Field Inside a Planet

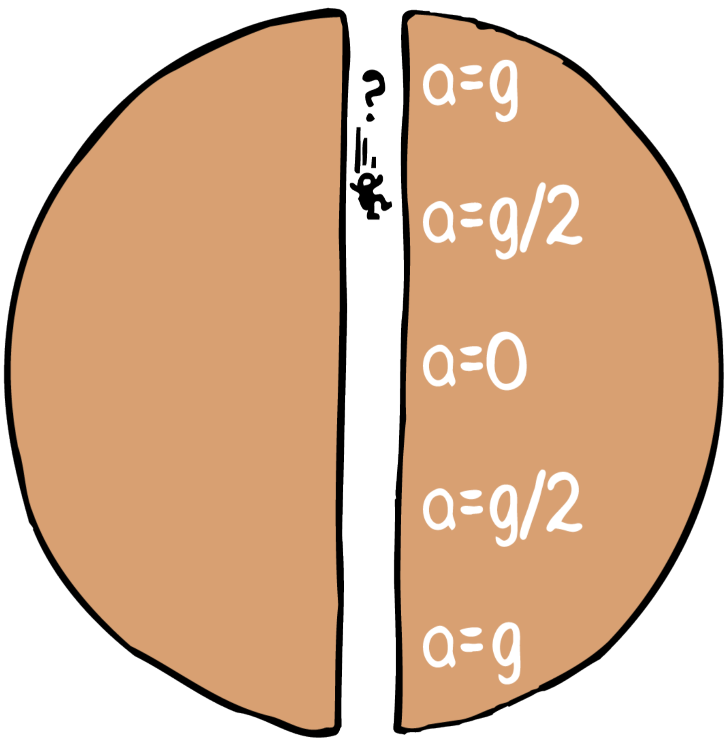
The gravitational field of Earth exists inside Earth as well as outside.

Imagine a hole drilled completely through Earth.

Consider the kind of motion you would undergo if you fell into such a hole.

13.7 Gravitational Field Inside a Planet

As you fall into a hole bored through Earth, your acceleration diminishes. The pull of the mass above you partly cancels the pull below.



13.7 Gravitational Field Inside a Planet

Starting at the North Pole end, you'd fall and gain speed all the way down to the center, and then overshoot and lose speed all the way to the South Pole.

You'd gain speed moving toward the center, and lose speed moving away from the center.

Without air drag, the trip would take nearly 45 minutes.

13.7 Gravitational Field Inside a Planet

At the beginning of the fall, your acceleration would be *g*, but it would decrease as you continue toward the center of Earth.

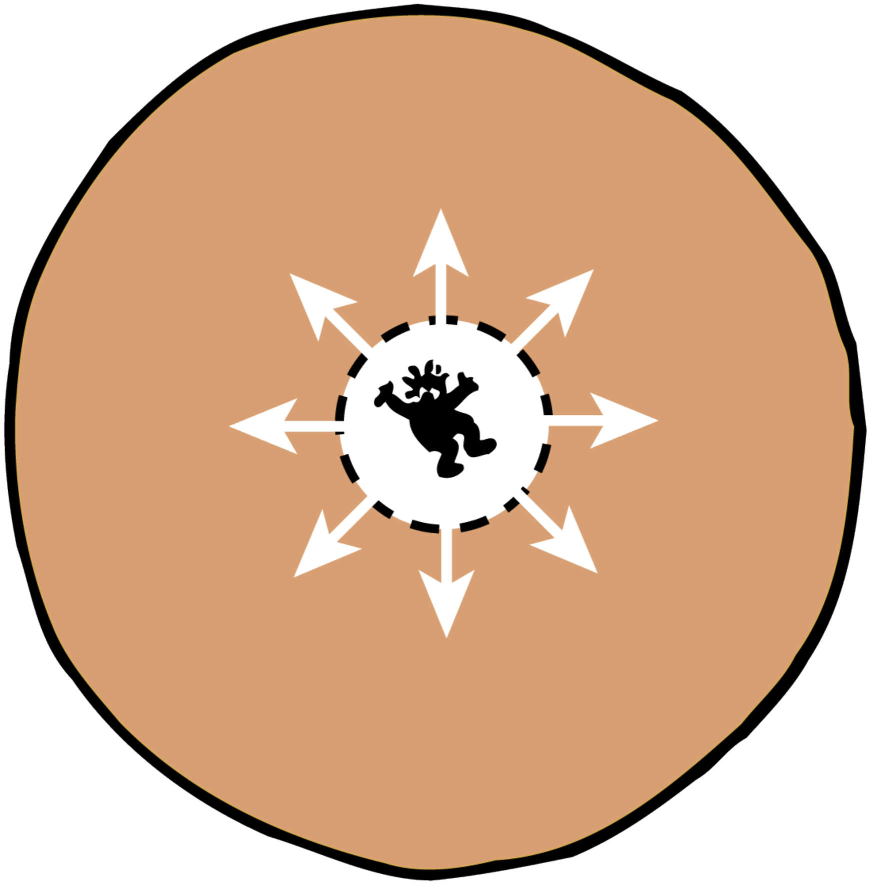
As you are pulled “downward” toward Earth’s center, you are also being pulled “upward” by the part of Earth that is “above” you.

When you get to the center of Earth, the net force on you is zero.

There is no acceleration as you whiz with maximum speed past the center of Earth.

13.7 Gravitational Field Inside a Planet

In a cavity at the center of Earth, your weight would be zero, because you would be pulled equally by gravity in all directions.



13.7 Gravitational Field Inside a Planet

think!

If you stepped into a hole bored completely through Earth and made no attempt to grab the edges at either end, what kind of motion would you experience?

13.7 Gravitational Field Inside a Planet

think!

If you stepped into a hole bored completely through Earth and made no attempt to grab the edges at either end, what kind of motion would you experience?

Answer:

You would oscillate back and forth, approximating *simple harmonic motion*. Each round trip would take nearly 90 minutes. Interestingly enough, we will see in the next chapter that an Earth satellite in close orbit about Earth also takes the same 90 minutes to make a complete round trip.

13.7 Gravitational Field Inside a Planet

CONCEPT CHECK

Describe the gravitational field of Earth at its center.

13.8 Weight and Weightlessness

Pressure against Earth is the sensation we interpret as weight.

13.8 Weight and Weightlessness

The force of gravity, like any force, causes acceleration.

Objects under the influence of gravity are pulled toward each other and accelerate.

We are almost always in contact with Earth, so we think of gravity as something that presses us against Earth rather than as something that accelerates us.

13.8 Weight and Weightlessness

Stand on a bathroom scale that is supported on a stationary floor. The gravitational force between you and Earth pulls you against the supporting floor and scale.

By Newton's third law, the floor and scale in turn push upward on you.

Between you and the supporting floor is a spring-like gauge inside the bathroom scale.

This pair of forces compresses the gauge. The weight reading on the scale is linked to the amount of compression.

13.8 Weight and Weightlessness

Repeat this weighing procedure in a moving elevator and you would find your weight reading would vary during accelerated motion.

When the elevator accelerates upward, the bathroom scale and floor push harder against your feet.

The scale would show an increase in your weight.

13.8 Weight and Weightlessness

When the elevator accelerates downward, the support force of the floor is less.

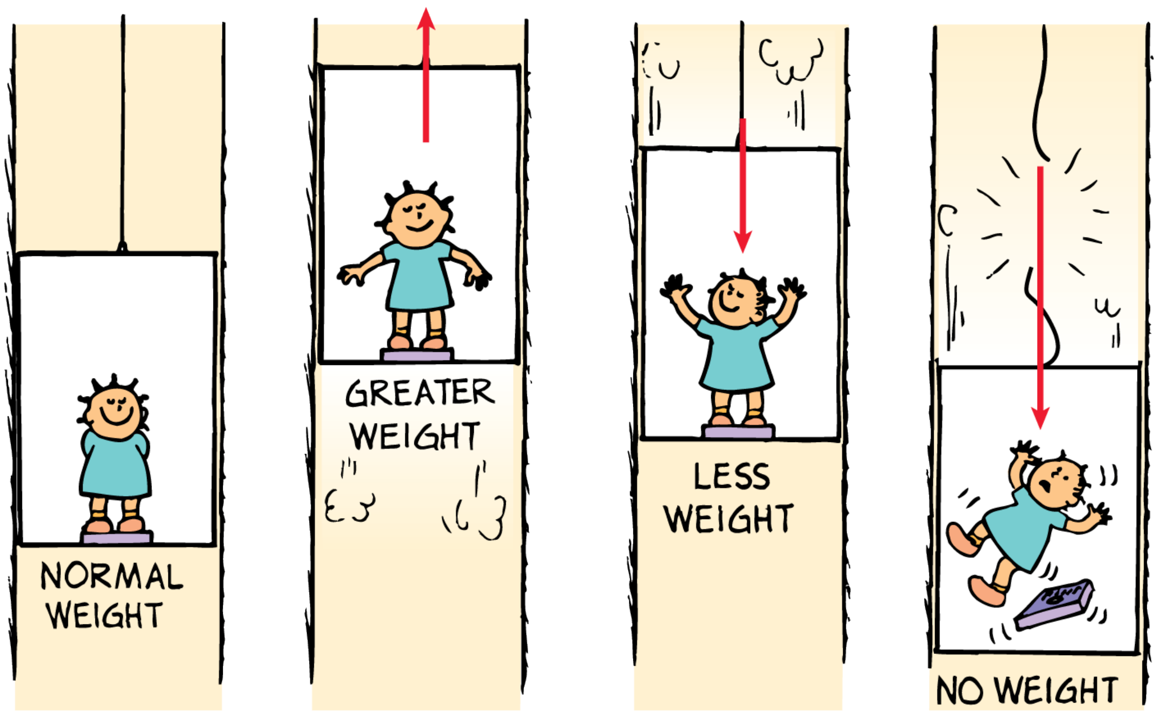
The scale would show a decrease in your weight.

If the elevator fell freely, the scale reading would register zero. According to the scale, you would be weightless.

You would feel weightless, for your insides would no longer be supported by your legs and pelvic region.

13.8 Weight and Weightlessness

The sensation of weight is equal to the force that you exert against the supporting floor.



13.8 Weight and Weightlessness

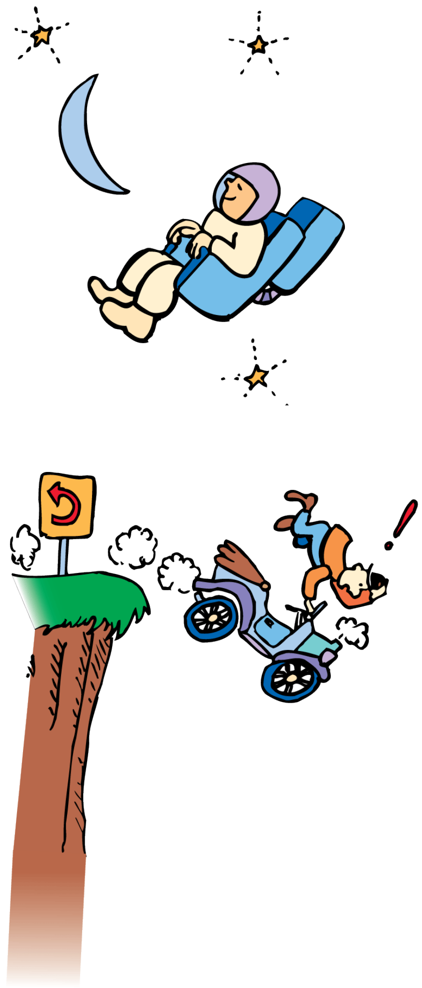
Rather than define your weight as the force of gravity that acts on you, it is more practical to define weight as the force you exert against a supporting floor.

According to this definition, you are as heavy as you feel.

The condition of **weightlessness** is not the absence of gravity, but the absence of a support force.

13.8 Weight and Weightlessness

Both people are without a support force and therefore experience weightlessness.



13.8 Weight and Weightlessness

CONCEPT CHECK

What sensation do we interpret as weight?

13.9 Ocean Tides

Newton showed that the ocean tides are caused by *differences* in the gravitational pull of the moon on opposite sides of Earth.

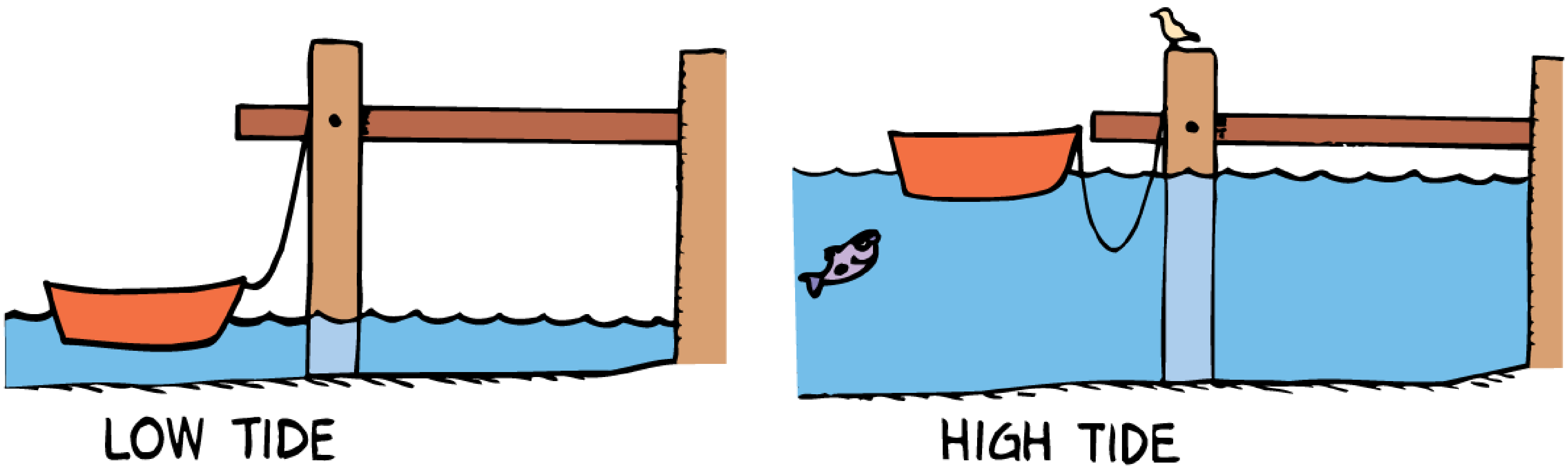
13.9 Ocean Tides

The moon’s attraction is stronger on Earth’s oceans closer to the moon, and weaker on the oceans farther from the moon.

This is simply because the gravitational force is weaker with increased distance.

13.9 Ocean Tides

The ocean tides are caused by differences in the gravitational pull of the moon on opposite sides of Earth.



13.9 Ocean Tides

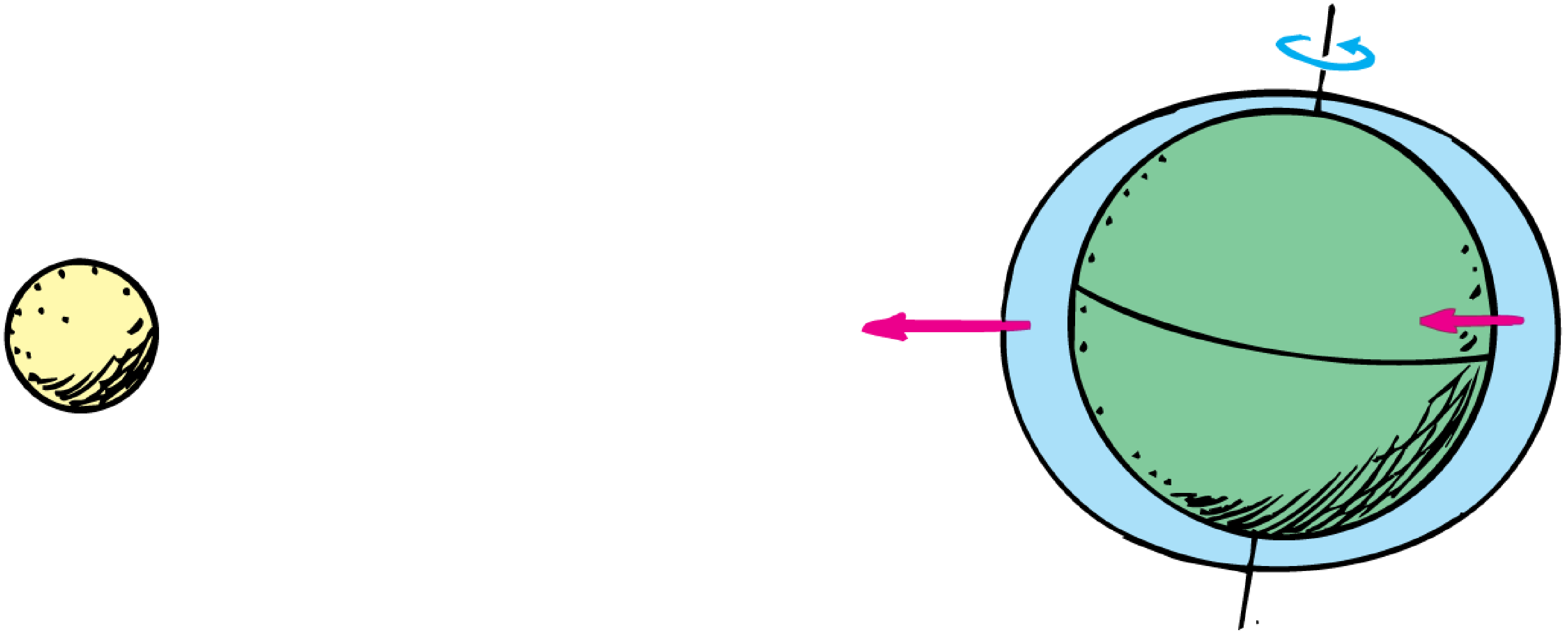
This difference in pulls across Earth slightly elongates it.

The oceans bulge out about 1 meter on average, on opposite sides of Earth.

Because Earth spins once per day, a fixed point on Earth passes beneath both of these bulges each day, producing two sets of ocean tides per day—two high tides and two low tides.

13.9 Ocean Tides

The two tidal bulges remain relatively fixed with respect to the moon while Earth spins daily beneath them.



13.9 Ocean Tides

Factors Affecting Ocean Tides

The sun also contributes to ocean tides, about half as much as the moon.

Its pull on Earth is 180 times greater than the moon’s pull on Earth, so why aren’t solar tides 180 times greater than lunar tides?

The *difference* in gravitational pulls by the sun on opposite sides of Earth is very small.

13.9 Ocean Tides

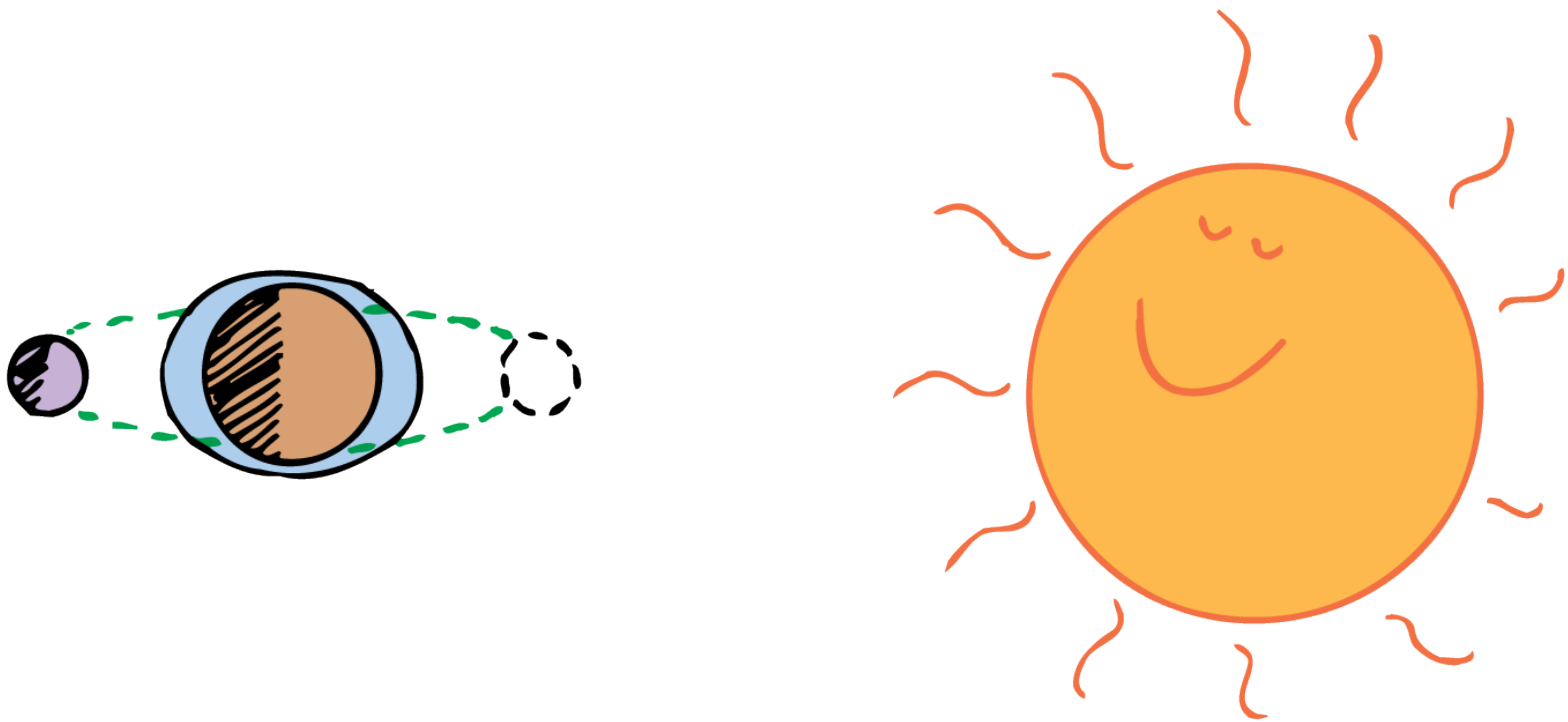
A **spring tide** is a high or low tide that occurs when the sun, Earth, and moon are all lined up.

The tides due to the sun and the moon coincide, making the high tides higher than average and the low tides lower than average.

Spring tides occur at the times of a new or full moon.

13.9 Ocean Tides

When the sun, the moon, and Earth are aligned, spring tides occur.



13.9 Ocean Tides

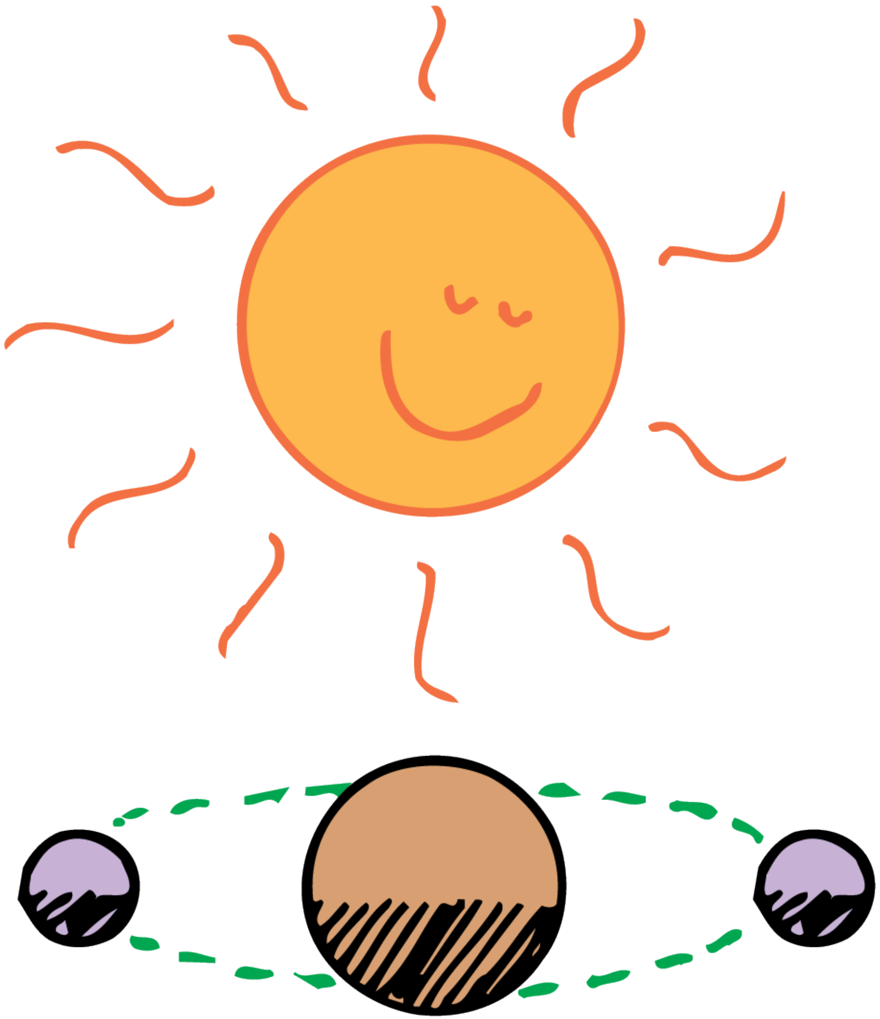
A **neap tide** occurs when the moon is halfway between a new moon and a full moon, in either direction.

The pulls of the moon and sun are perpendicular to each other.

The solar and lunar tides do not overlap, so the high tides are not as high and low tides are not as low.

13.9 Ocean Tides

When the attractions of the sun and the moon are at right angles to each other (at the time of a half moon), neap tides occur.



13.9 Ocean Tides

Other Types of Tides

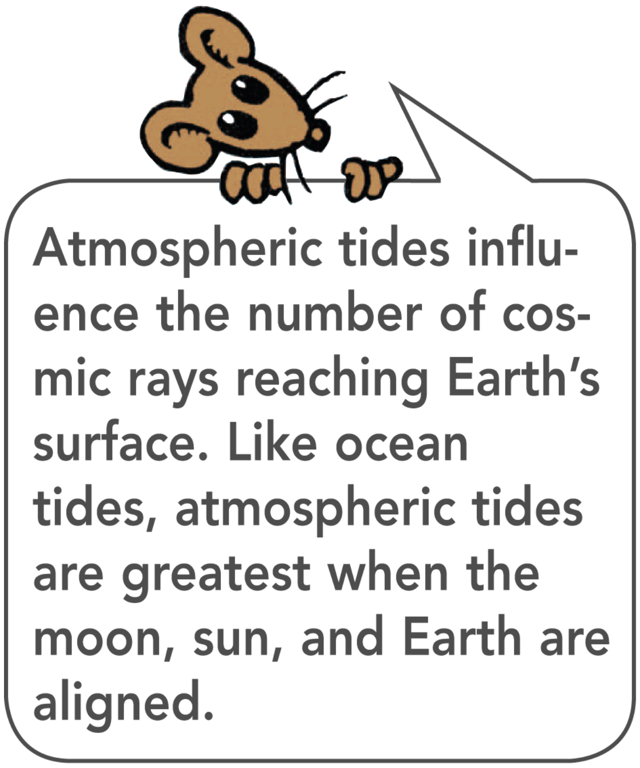
Because much of the Earth's interior is deformable, we have Earth tides, though they are less pronounced than ocean tides.

Twice each day the solid surface of Earth rises and falls as much as one-quarter meter.

13.9 Ocean Tides

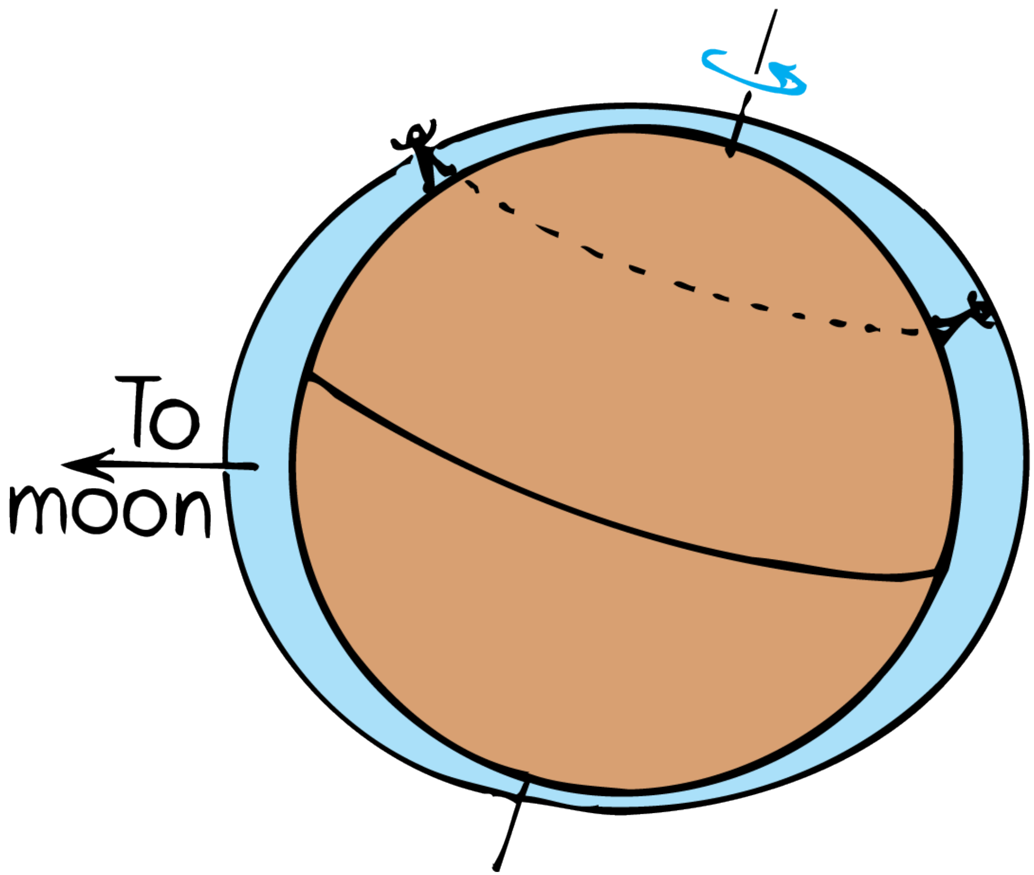
There are also atmospheric tides, which affect the intensity of cosmic rays that reach Earth’s surface.

The tilt of Earth’s axis, interfering landmasses, friction with the ocean bottom, and other factors complicate tidal motions.



13.9 Ocean Tides

Earth's tilt causes the two daily high tides to be unequal.



13.9 Ocean Tides

The moon produces scarcely any tides in a lake.

No part of the lake is significantly closer to the moon than any other part—this means there is no significant *difference* in the moon’s pull on different parts of the lake.

13.9 Ocean Tides

CONCEPT CHECK

What causes ocean tides?

13.10 Black Holes

When a massive star collapses into a black hole, there is no change in the gravitational field at any point beyond the original radius of the star.

13.10 Black Holes

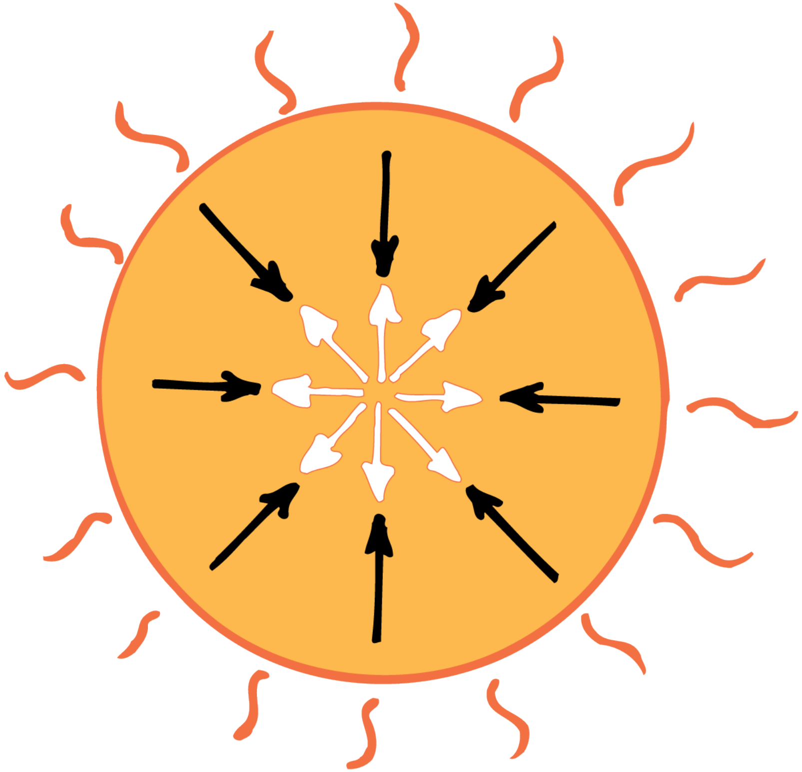
Two main processes go on continuously in stars like our sun.

- Gravitation tends to crush all solar material toward the center.
- Thermonuclear fusion, consisting of reactions similar to those in a hydrogen bomb, tends to blow solar material outward.

When the processes of gravitation and thermonuclear fusion balance each other, the result is the sun of a given size.

13.10 Black Holes

The size of the sun is the result of a “tug of war” between two opposing processes: nuclear fusion and gravitational contraction.



13.10 Black Holes

Formation of Black Holes

If the fusion rate increases, the sun will get hotter and bigger.

If the fusion rate decreases, the sun will get cooler and smaller.

When the sun runs out of fusion fuel (hydrogen), gravitation will dominate and the sun will start to collapse.

13.10 Black Holes

For our sun, this collapse will ignite the nuclear ashes of fusion (helium) and fuse them into carbon.

During this fusion process, the sun will expand to become the type of star known as a *red giant.*

When the helium is all “burned,” the red giant will collapse.

It will no longer give off heat and light. It will then be the type of star called a *black dwarf*—a cool cinder among billions of others.

13.10 Black Holes

For a star that is at least two to three times more massive than our sun, once the flame of thermonuclear fusion is extinguished, gravitational collapse takes over—and it doesn't stop!

The star caves in on itself and the atoms that compose the star cave in on themselves until there are no empty spaces.

The density becomes infinite near these **black holes.** Even light cannot escape a black hole.

13.10 Black Holes

Gravitational Field Near Black Holes

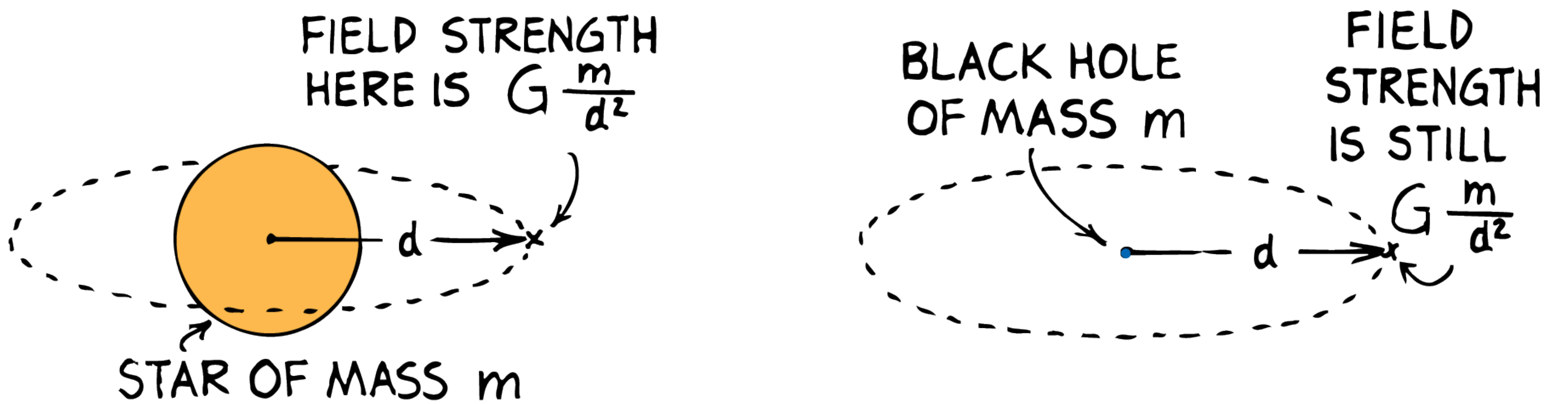
A black hole is no more massive than the star from which it collapsed.

The gravitational field near the black hole may be enormous but the field beyond the original radius of the star is no different after collapse than before.

The amount of mass has not changed, so there is no change in the field at any point beyond this distance.

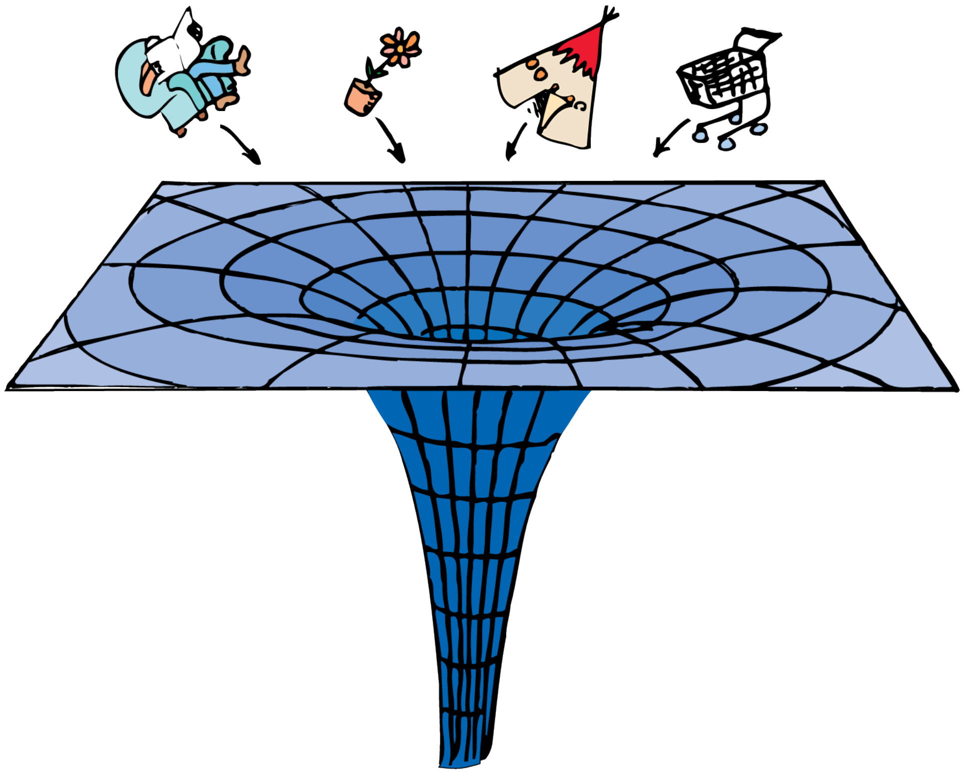
13.10 Black Holes

The gravitational field strength near a giant star that collapses to become a black hole is the same before collapse (left) and after collapse (right).



13.10 Black Holes

The gravitational field around a black hole is usually represented as a warped two-dimensional surface.



13.10 Black Holes

Astronauts could enter the fringes of this warp and, with a powerful spaceship, still escape.

After a certain distance, however, they could not escape, and they would disappear from the observable universe.

Contrary to stories about black holes, they're non-aggressive and don't reach out to swallow innocents at a distance. Their gravitational fields are no stronger than the original fields about the stars before their collapse—except at distances smaller than the radius of the original star. Black holes shouldn't worry future astronauts, unless they get too close.

13.10 Black Holes

Effects of Black Holes

Although black holes can’t be seen, their effects can be.

Many stars in the sky occur as binaries—pairs that orbit around each other. Sometimes only one star of a binary pair is seen.

Matter streams from this visible star toward its invisible companion, emitting X-rays as it accelerates toward the black hole.

13.10 Black Holes

Near the centers of most galaxies are immensely massive yet very small centers of force that cause stars near them to speed around in tight orbits.

These black holes, if that's what they are, are more massive than a million suns.

13.10 Black Holes

CONCEPT CHECK

What happens to the gravitational field of a star that has collapsed into a black hole?

13.11 Universal Gravitation

The formulation of the law of universal gravitation is one of the major reasons for the success in science that followed, for it provided hope that other phenomena of the world might also be described by equally simple and universal laws.

13.11 Universal Gravitation

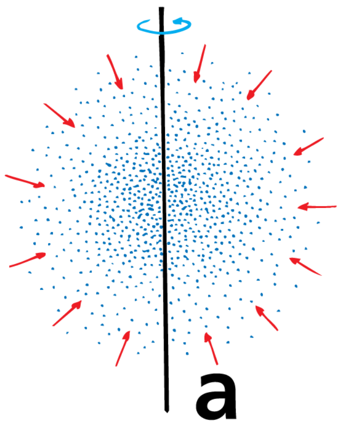
The Earth is round because of gravitation.

- Since everything attracts everything else, Earth had attracted itself together before it became solid.
- The sun, the moon, and Earth are all fairly spherical because they have to be.

13.11 Universal Gravitation

Gravity played a role in the formation of the solar system.

a. A slightly rotating ball of interstellar gas contracted due to mutual gravitation.

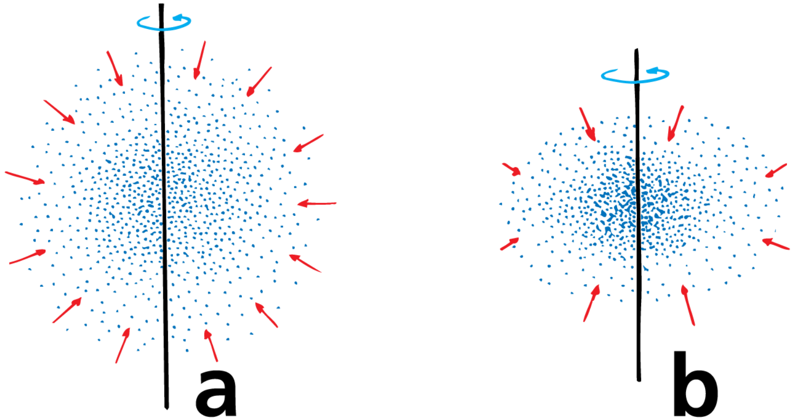


13.11 Universal Gravitation

Gravity played a role in the formation of the solar system.

a. A slightly rotating ball of interstellar gas contracted due to mutual gravitation.

b. To conserve angular momentum, the rotational speed of the ball of gas increased.



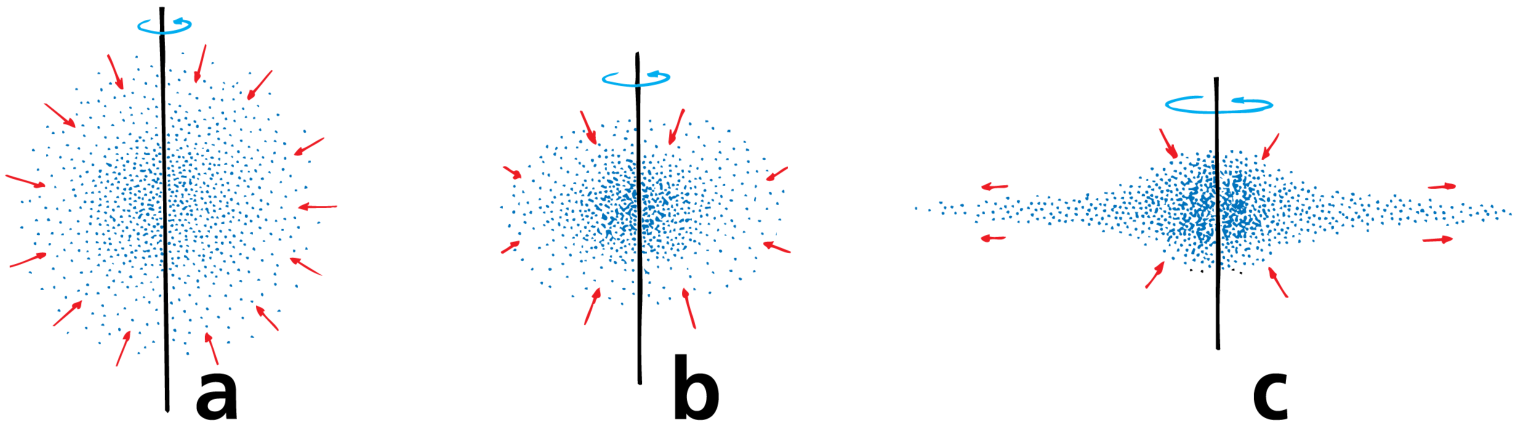
13.11 Universal Gravitation

Gravity played a role in the formation of the solar system.

a. A slightly rotating ball of interstellar gas contracted due to mutual gravitation.

b. To conserve angular momentum, the rotational speed of the ball of gas increased.

c. The increased momentum of the individual particles and clusters of particles caused them to sweep in wider paths about the rotational axis, producing an overall disk shape. The greater surface area of the disk promoted cooling and clusters of swirling matter—the birthplace of planets.



13.11 Universal Gravitation

Perturbations in the Solar System

If everything pulls on everything else, then the planets must pull on each other. The net force that controls Jupiter, for example, is not just from the sun, but from the planets also.

Their effect is small compared with the pull of the more massive sun, but it still shows.

The deviation of an orbiting object from its path caused by the action of an additional center of force is called a **perturbation.**

13.11 Universal Gravitation

Until the middle of the last century astronomers were puzzled by unexplained perturbations of the planet Uranus.

The source of Uranus's perturbation was uncovered in 1845 and 1846 by two astronomers, John Adams in England and Urbain Leverrier in France.

Applying Newton's law of gravitation, both astronomers concluded that there was a body beyond the orbit of Uranus.

The planet Neptune was discovered.

13.11 Universal Gravitation

The Expanding Universe

The shapes of distant galaxies provide further evidence that the law of gravity applies to larger distances.

According to current scientific understanding, the universe originated and grew from the explosion of a primordial fireball some 13.7 billion years ago.

This is the "Big Bang" theory of the origin of the universe.

13.11 Universal Gravitation

Recent evidence suggests the universe is not only expanding, but *accelerating* outward.

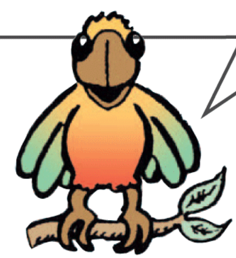
It is pushed by an anti-gravity *dark energy* that makes up an estimated 73 percent of the universe.

Twenty-three percent of the universe is composed of the yet-to-be discovered particles of exotic *dark matter*.

The concepts of dark matter and dark energy will continue to inspire exciting research throughout this century.

13.11 Universal Gravitation

Scientists' usage of the term theory differs from common usage. The theory of gravity, for example, is universally accepted by scientists, based on the preponderance of evidence and the success of the model. The term *theory* does not imply fundamental doubts about a phenomenon's existence.

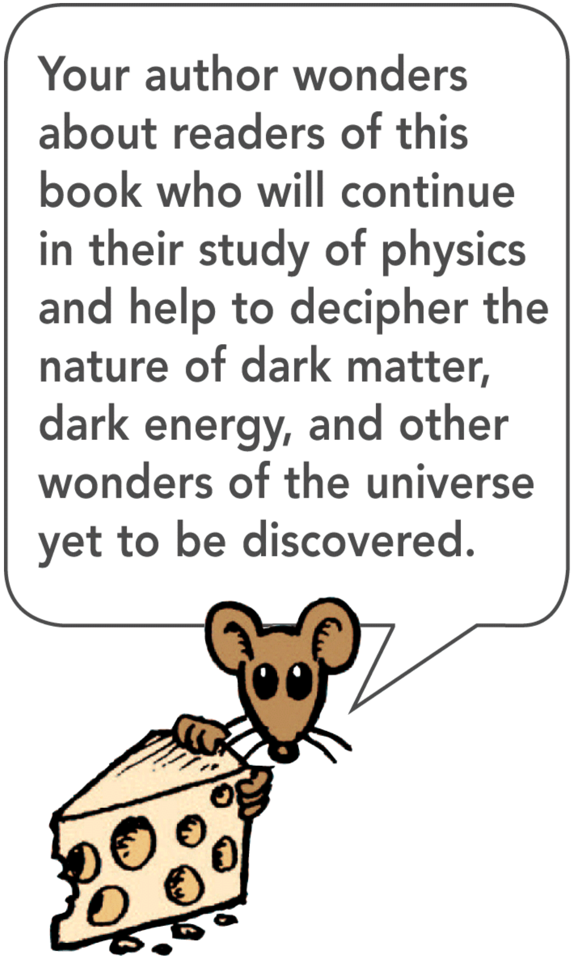


13.11 Universal Gravitation

Newton's Impact on Science

Few theories have affected science and civilization as much as Newton's theory of gravity.

Newton demonstrated that by observation and reason, people could uncover the workings of the physical universe.



13.11 Universal Gravitation

CONCEPT CHECK

How did the formulation of the law of universal gravitation affect science?

Assessment Questions

1. Newton determined that the pull of Earth’s gravity caused both apples and
   a. the moon to fall toward Earth.
   b. the moon to move away from Earth.
   c. the sun to move away from Earth.
   d. stars to fall toward Earth.

Assessment Questions

1. Newton determined that the pull of Earth's gravity caused both apples and
   a. the moon to fall toward Earth.
   b. the moon to move away from Earth.
   c. the sun to move away from Earth.
   d. stars to fall toward Earth.

Answer: A

Assessment Questions

2. The moon falls toward Earth in the sense that it falls
   a. with an acceleration of 10 m/s^2, as apples fall on Earth.
   b. with an acceleration greater than 10 m/s^2.
   c. beneath the straight-line path it would take without gravity.
   d. above the straight-line path it would take without gravity.

Assessment Questions

2. The moon falls toward Earth in the sense that it falls
   a. with an acceleration of 10 m/s^2, as apples fall on Earth.
   b. with an acceleration greater than 10 m/s^2.
   c. beneath the straight-line path it would take without gravity.
   d. above the straight-line path it would take without gravity.

Answer: C

Assessment Questions

3. Planets remain in orbit while falling around the sun due to their
   a. tangential velocities.
   b. zero tangential velocities.
   c. accelerations of about 10 m/s^2.
   d. centrifugal forces that keep them up.

Assessment Questions

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   a. tangential velocities.
   b. zero tangential velocities.
   c. accelerations of about 10 m/s^2.
   d. centrifugal forces that keep them up.

Answer: A

Assessment Questions

4. Newton did not discover gravity, for early humans discovered it whenever they fell. What Newton did discover is that gravity
   a. tells us about why the universe expands.
   b. tells us how to discover new planets.
   c. accounts for the existence of black holes.
   d. extends throughout the universe.

Assessment Questions

4. Newton did not discover gravity, for early humans discovered it whenever they fell. What Newton did discover is that gravity
   a. tells us about why the universe expands.
   b. tells us how to discover new planets.
   c. accounts for the existence of black holes.
   d. extends throughout the universe.

Answer: D

Assessment Questions

5. Consider a space probe three times as far from Earth's center. Compared at Earth's surface, its gravitational attraction to Earth at this distance is about
   a. one third as much.
   b. one half as much.
   c. one ninth as much.
   d. zero.

Assessment Questions

5. Consider a space probe three times as far from Earth's center. Compared at Earth's surface, its gravitational attraction to Earth at this distance is about
   a. one third as much.
   b. one half as much.
   c. one ninth as much.
   d. zero.

Answer: C

Assessment Questions

6. Compared to the gravitational field of Earth at its surface, Earth's gravitational field at a distance three times as far from Earth's center is about
   a. one third as much.
   b. one half as much.
   c. one ninth as much.
   d. zero.

Assessment Questions

6. Compared to the gravitational field of Earth at its surface, Earth's gravitational field at a distance three times as far from Earth's center is about
   a. one third as much.
   b. one half as much.
   c. one ninth as much.
   d. zero.

Answer: C

Assessment Questions

7. Compared to the gravitational field of Earth at its surface, Earth's gravitational field at Earth's center is
   a. zero.
   b. half as much.
   c. twice as much.
   d. three times as much.

Assessment Questions

7. Compared to the gravitational field of Earth at its surface, Earth's gravitational field at Earth's center is
   a. zero.
   b. half as much.
   c. twice as much.
   d. three times as much.

Answer: A

Assessment Questions

8. When an astronaut in orbit is weightless, he or she is
   a. beyond the pull of Earth's gravity.
   b. still in the pull of Earth's gravity.
   c. in the pull of interstellar gravity.
   d. beyond the pull of the sun's gravity.

Assessment Questions

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   a. beyond the pull of Earth's gravity.
   b. still in the pull of Earth's gravity.
   c. in the pull of interstellar gravity.
   d. beyond the pull of the sun's gravity.

Answer: B

Assessment Questions

9. The highest ocean tides occur when the Earth and moon are
   a. lined up with the sun.
   b. at right angles to the sun.
   c. at any angle to the sun.
   d. lined up during spring.

Assessment Questions

9. The highest ocean tides occur when the Earth and moon are
   a. lined up with the sun.
   b. at right angles to the sun.
   c. at any angle to the sun.
   d. lined up during spring.

Answer: A

Assessment Questions

10. A black hole is
    a. simply a collapsed star.
    b. a two-dimensional surface in space.
    c. barely visible with high-powered telescopes.
    d. a new form of gravity.

Assessment Questions

10. A black hole is
    a. simply a collapsed star.
    b. a two-dimensional surface in space.
    c. barely visible with high-powered telescopes.
    d. a new form of gravity.

Answer: A

Assessment Questions

11. Newton's law of universal gravitation had a great impact on society as many scientists, artists, writers, and philosophers hoped that
    a. more complex and universal laws would explain other phenomena of the world.
    b. greater observations would require fewer experimentations.
    c. no further explanation of other phenomena of the world would be required.
    d. studying other phenomena of the world would lead to just as simple and universal laws.

Assessment Questions

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    d. studying other phenomena of the world would lead to just as simple and universal laws.

Answer: D