Name: ______________________________________ Date: ________________________

Guided Learning: History of Gravity

Learning goals
After completing this activity, you will be able to …

- Describe the contributions of Aristotle, Copernicus, Kepler, Galileo, Newton, Einstein, and others in the developing our understanding of gravitational force.
- Apply Newton's law of universal gravitation.
- Differentiate Newtonian gravity from general relativity.

Vocabulary: ellipse, general relativity, geocentric, gravitational constant, gravity, heliocentric, law of universal gravitation

Warm-up questions

1. Why does a feather take a lot longer to fall to the ground than a rock? _________________

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2. Suppose you drop a small rock and a large rock from a balcony. Do you think one would hit the ground a long time before the other, or that they would hit the ground at approximately the same time? Explain why you think so.

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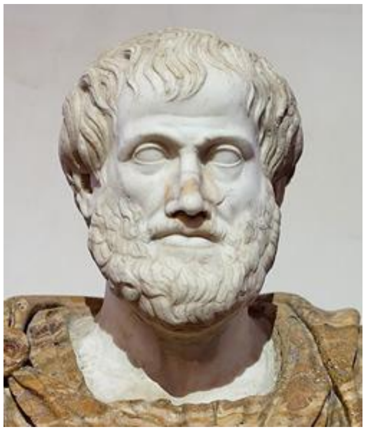
Early concepts of gravity
Although people have observed objects falling to Earth's surface as long as they have existed, the first explanation of **gravity** is attributed to the Greek philosopher Aristotle (384–322 BCE). Aristotle believed in five elements, earth, water, air, fire, and aether, a crystalline substance that made up celestial objects. Each element occupied a sphere, with Earth in the center, followed by water, air, fire, and aether. Objects would move naturally to take their proper positions. Objects made of earth, such as rocks, tended to move toward their natural position at the center of the universe (towards Earth's center, in other words.) Aristotle also believed that heavier objects would naturally fall more quickly than lighter objects and that a continuous force was required to maintain the motion of an object.



Bust of Aristotle

Aristotle's ideas about physics, all of which would eventually be proven wrong, were nevertheless tremendously influential for nearly 2,000 years, even becoming incorporated into the doctrine of the Catholic Church. Although several thinkers had questioned some of Aristotle's claims through the centuries, the gradual dismantling of Aristotle's physics did not begin in earnest until the 16th century.

1. A feather will fall much more slowly than a rock, but a small pebble with the same mass as the feather will fall just as quickly as the rock. Why do you think the small pebble falls so much faster than the feather?

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2. The idea that heavier things fall faster than light things can be disproven by dropping a rock and a pebble. Why do you think nobody questioned this theory for nearly 2,000 years?

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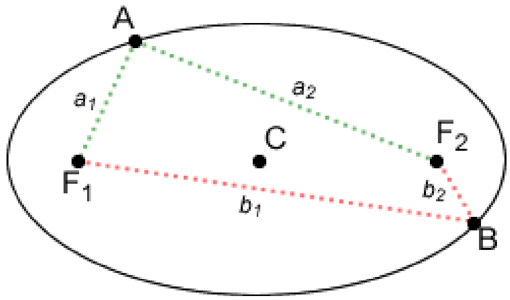
Challenging Aristotle: Copernicus, Kepler, and Galileo

A major challenge to Aristotle's **geocentric** (Earth-centered) universe came from a Polish cleric named Nicholas Copernicus (1473–1543). Copernicus was interested in mathematics, medicine, art, and even politics, but his greatest passion was astronomy. In particular, Copernicus was dissatisfied with the geocentric model.

Nicholas Copernicus, Johannes Kepler, and Galileo Galilei

Copernicus proposed a **heliocentric**, or Sun-centered system. Copernicus died shortly after publishing his book, *De Revolutionibus Orbium Coelestium*, in 1543. Although most scholars at the time dismissed the idea that Earth was in motion, the idea captured the imagination of two astronomers: Johannes Kepler and Galileo Galiei.

Johannes Kepler (1571–1630) was a German mathematician whose interest in astronomy sprung from a lifelong fascination with astrology. Unlike his mentor, Tycho Brahe, Kepler supported heliocentrism and dedicated his astronomical career to determining the laws that govern planetary motion. After several years of analyzing Tycho's observations of Mars, Kepler eventually determined that the orbit of Mars was an **ellipse**, a slightly flattened circle.



An ellipse has two foci (F_1 and F_2). For any point on the ellipse, the sum of the distances to the focal points is constant: $a_1 + a_2 = b_1 + b_2$

Kepler went on to formulate three laws of planetary motion:

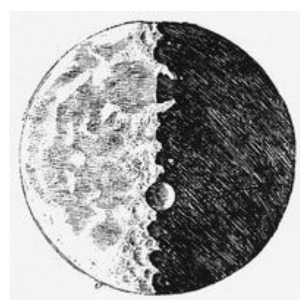
- *The orbits of planets are elliptical with the Sun at one focus of the ellipse.*
- *If you drew a line from the planet to the Sun, it would mark out equal areas in equal times.*
- *The square of the period of a planet's orbit is proportional to the cube of its average distance from the Sun.*

While Kepler's laws do an excellent job of describing planetary motion, Kepler was puzzled by what force held the planets in orbit. Kepler imagined lines of magnetic force that radiated from the Sun like the spokes of a wheel, pushing the planets along their paths. While this theory proved to be wrong, Kepler was one of the first astronomers to hypothesize that the attractive force of the Moon caused the tides, a conjecture that has proven to be true. Kepler's laws were essential in allowing Newton to develop his gravitational theory a century later.

Galileo Galilei (1564–1642) was an Italian mathematician and astronomer with a knack for showmanship and a nose for controversy. Galileo's studies of free fall and acceleration set the stage for Newton's laws of motion, while his astronomical discoveries provided crucial evidence for heliocentrism.

Although not all scholars agree that Galileo actually dropped cannonballs of varying mass from the Tower of Pisa, Galileo effectively argued that objects of different mass should fall at the same rate barring the effects of air resistance. In addition, Galileo determined the relationship between distance (d) and time (t) for a body with acceleration a: $d = at^2 / 2$. Finally, Galileo was one of the first to argue that force was not required to maintain constant motion. This insight later became the basis of Newton's first law of motion.

In 1609, Galileo began to observe the night skies with a telescope of his own design. He quickly made a variety of observations that helped to discredit the theories of Aristotle and the Catholic Church. These included observing craters and plains on the Moon (Aristotle believed all celestial spheres to be perfectly smooth), discovering Jupiter's moons (proving that not all celestial objects orbited Earth), and tracking sunspots to measure the rotation of the Sun. One of Galileo's Moon sketches is shown at right.



Most significantly, Galileo observed Venus passing through a full range of phases, from crescent to full. These observations demonstrated conclusively that Venus orbited the Sun and suggested that Earth orbited the Sun as well. While Galileo was never able to conclusively prove that Earth orbited the Sun, his work helped to popularize heliocentric theory, especially among some of the leading scientists of Europe.

1. Using your own words, summarize the contributions of each scholar in one short sentence.

   Nicholas Copernicus: ____

   Johannes Kepler: ____

   Galileo Galilei: ____

2. Why do you think the acceptance of the heliocentric theory by scientists, was a key step in the development of the theory of gravity? ____

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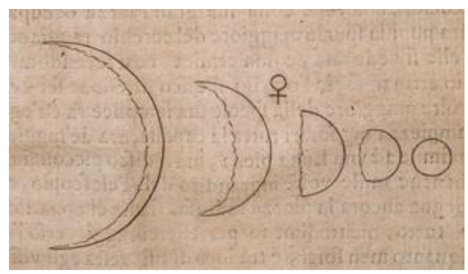
3. **Geometry challenge:** Galileo's sketches of the phases of Venus are shown at right. Notice that the sketches show the apparent size of Venus as well as its phase. On a separate sheet of paper, explain how this proves that Venus orbits the Sun. Draw diagrams to support your argument. (Hint: Draw two sketches, one showing Venus orbiting the Sun and one showing Venus orbiting Earth.)

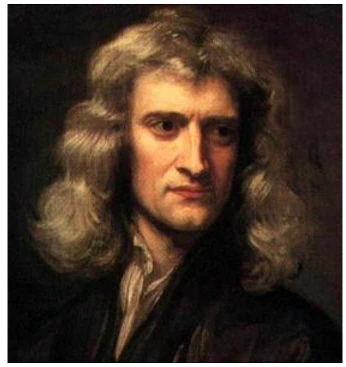


René Descartes

Universal gravitation
As heliocentric theory quietly grew in popularity among scientists and philosophers (while still banned by the church), some scientists turned to the problem of why objects fell to Earth and what caused Earth and the other planets to orbit the Sun. One of the first connect these two phenomena was the French philosopher René Descartes (1596–1650). Descartes theory had two main tenants: 1) The universe is filled with particles, and 2) objects have a tendency to move *away* from the center of rotation. Objects fall to Earth's surface because the particles surrounding Earth had a greater tendency to move outward than objects, so the objects were displaced downward..

Descartes imagined the solar system divided into a series of rotating bands, or vortices, that were filled with particles. Planets would move outward until their tendency to move outward was balanced by the same tendency in the particles of that vortex. Once equilibrium was reached, the planets would orbit the Sun within their vortex. Although further evidence of these vortices was never found, Descartes' ideas about gravity remained influential for over a century.

When Isaac Newton (1643–1727) became a student at Cambridge University in 1661, he was immediately attracted to the heliocentric ideas of Copernicus, Kepler, and Galileo. In 1665, while the university was closed during an outbreak of the plague, Newton returned home for the two most productive years of his life.



Isaac Newton in 1689

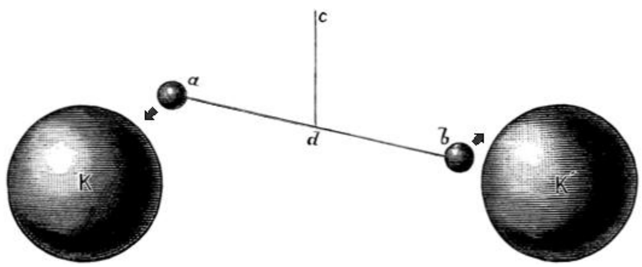
After he may or may not have been beaned by an apple, Newton began to think about the force that caused planets to orbit the Sun and the force that caused objects to fall to the ground. Newton sought a mathematical proof that a force of attraction was sufficient to produce circular and elliptical orbits of planets.

Newton eventually fleshed out the mathematics of this idea and published it in 1687. Newton's **law of universal gravitation** states that the force of gravity between two objects is proportional to the product of their masses and inversely proportional to the square of the distance between them. Written as an equation, we have:

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

In this equation, $F_{gravity}$ is the force of gravity between two objects of mass m_1 and m_2, separated by a distance r. The constant G is the **gravitational constant**. If mass is measured in kilograms and distance in meters, the value of the gravitational constant is 6.67259×10^{-11} $m^3/kg \cdot s^2$.

Although Newton is generally given sole credit for the law of universal gravitation, there is some controversy about his claim as Newton's contemporary Robert Hooke was working on similar ideas at the time. In 1666, Hooke discussed the gravitational attraction of the Sun on the planets in a lecture, and he proposed that the force of gravity is proportional to the inverse square of the distance in a letter to Newton in 1679. Whomever came up with the idea first, there is no doubt that Newton was the first to mathematically prove that this force results in elliptical orbits.



Torsion balance: Gravitational attraction between the small weights (*a* and *b*) and the large weights (*K*) cause the string (*cd*) to twist.

Although unknown when the law of universal gravitation was first published, the value of *G* was determined thanks to an ingenious experiment by Henry Cavendish in 1797. Cavendish used a delicate instrument called a torsion balance (left) to measure the minute force between two lead balls. Because the force of gravity is so small, it can only be felt when at least one of the objects involved is very massive, such as Earth.

Newton's law of universal gravitation was enormously powerful. It allowed Newton to prove Kepler's three laws of planetary motion and explained Galileo's observation that objects with different mass accelerate at the same rate. One of the greatest triumphs for Newton's law occurred in 1846. Based on irregularities in the orbit of Uranus, astronomers used Newton's laws to infer the position of an eighth planet beyond Uranus. This planet, now called Neptune, was discovered less than a degree from its predicted position in the sky. Similar methods were used to discover the dwarf planet Pluto in 1930.

While Newton's theory of gravity is universally acknowledged to be a triumph of the scientific revolution, it had one major flaw. Like others who had gone before him, Newton struggled to explain *why* gravity occurred. Newton's gravitational force, which could reach across vast distances of empty space, was in some ways more mysterious now than ever before.

1. Lots of people had seen apples fall before Isaac Newton walked into the orchard. What was so significant about Newton's insight into the nature of gravity?

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2. Based on the law of universal gravitation, what will happen to the force of gravity between two objects if the mass of each object was doubled? _________________________

3. Based on the law of universal gravitation, what will happen to the force of gravity between two objects if the distance between the objects was doubled? _________________________

4. Why is it so hard to detect the gravitational attraction between two heavy objects, such as two heavy rocks? (Hint: Look at the value of *G*.)

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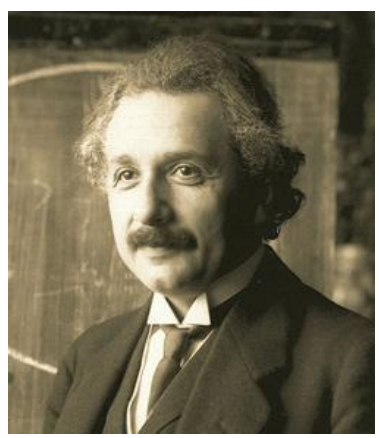
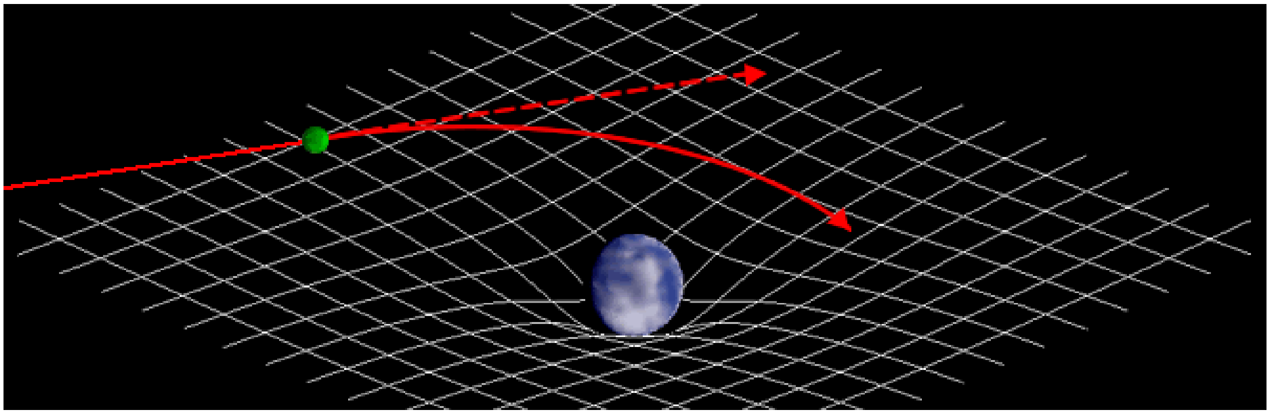
General relativity

While Newton's theory proved very successful, during the 19th century astronomers discovered small discrepancies in the orbit of Mercury that could not be explained by Newton's theory. The problem was solved by Albert Einstein (1879–1955), one of the most original thinkers in the history of science.



Albert Einstein in 1921

Einstein's theory of **general relativity**, first proposed in 1915, posits that all objects with mass caused a bending, or warping, of both space and time. To picture this in two dimensions, imagine a heavy bowling ball resting on a thin, elastic sheet, causing it to bend downward. If a smaller ball is then rolled across the sheet, its path will be bent as it enters the depression caused by the first ball. This is shown on the diagram on the next page.



The path of a small celestial body (green) is bent by the gravitation of a massive planet or star

One advantage of general relativity over Newton's theory of gravity is that relativity actually provides a mechanism for gravity to work. If space itself is bent by gravity, the curved paths of objects in orbit are equivalent to straight paths in curved space. In other words, gravity is not a "force" that acts over a distance, but a warping of the fabric of space that causes objects to appear as if they are influenced by a force.

An interesting aspect of Einstein's theory of general relativity is that, because space itself becomes curved, the path of light is bent by gravity. Thus light from distant stars located behind the Sun would be bent by the gravitation of the Sun. The solar eclipse of 1919 provided a way to test the predictions of general relativity and universal gravitation by allowing scientists to observe starlight from stars behind the Sun. Precise measurements made by Sir Arthur Eddington during the eclipse agreed with the predictions of general relativity and made Einstein an international sensation. Since then, numerous observations have confirmed general relativity and cemented its status as one of the seminal advances of 20th century physics.

Although the law of universal gravitation has been replaced by general relativity, universal gravitation still has practical value. In the vast majority of applications, Newton's law is both accurate and much easier to use than the equations of general relativity. Thus Newton's law is still used by scientists when calculating the trajectories of planets, moons, or spacecraft.

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1. How does general relativity explain the origin of gravity? ______________________________

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2. What was the significance of the 1919 solar eclipse? ________________________________

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3. Even though universal gravitation has been replaced by general relativity, why do astronomers and engineers still use Newton's law of universal gravitation today?

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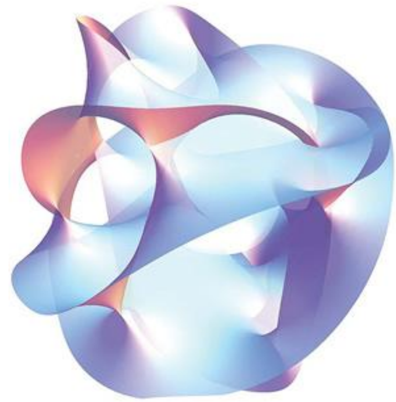
Gravity today

Despite the centuries of progress made by countless scientists, gravity remains one of the most mysterious phenomena in nature. One major problem is the seeming incompatibility of general relativity and *quantum mechanics*, the other great physics theory of the 20th century. Many scientists believe that the unification of gravity and quantum mechanics can be done using *string theory*, an idea that all fundamental particles are actually vibrating lines, or "strings."



Some versions of string theory propose a universe with 11 dimensions.

Another mystery of gravity is the observed acceleration of the expansion of the universe. After the Big Bang, astronomers believed that the gravity of all of the matter in the universe would cause the expansion of the universe to slow down. Instead, astronomers have discovered that the expansion of the universe is actually speeding up! Explanations for this acceleration have centered on such exotic concepts as "dark energy" and "dark matter." Some scientists believe that these observations will cause future changes to our theories of gravity.

Wrap-up question: Why is it important that scientists consider new evidence, even if it contradicts an established theory? Give examples from the history of gravitational theory.

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