

Phys 100: The Physical World

Chapters 9 & 10

Aaron Wirthwein

Department of Physics and Astronomy
University of Southern California



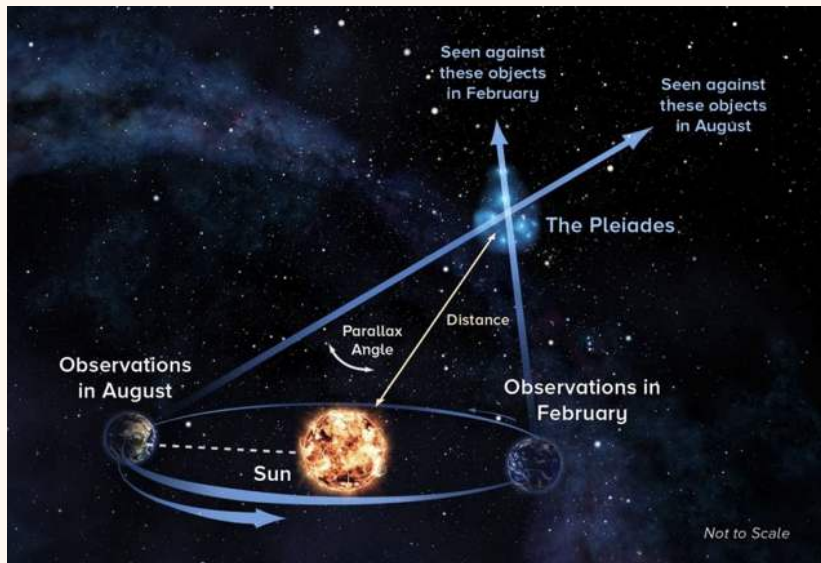
Geocentrism

Aristotle used the following arguments to conclude that the Earth must be the center of the universe:

1. Earth could not be moving as birds, clouds, etc. would be left behind.
2. The heavens were perfect and unchanging, so planetary orbits must be circular.
3. **Stellar parallax** had not been observed, so the Earth could not orbit the Sun.

Additionally, he believed the laws of nature were fundamentally different on Earth than they were in the Heavens, the Earth is “special” in the sense that what happens here cannot happen anywhere else, and the universe must be finite in size.

Stellar Parallax

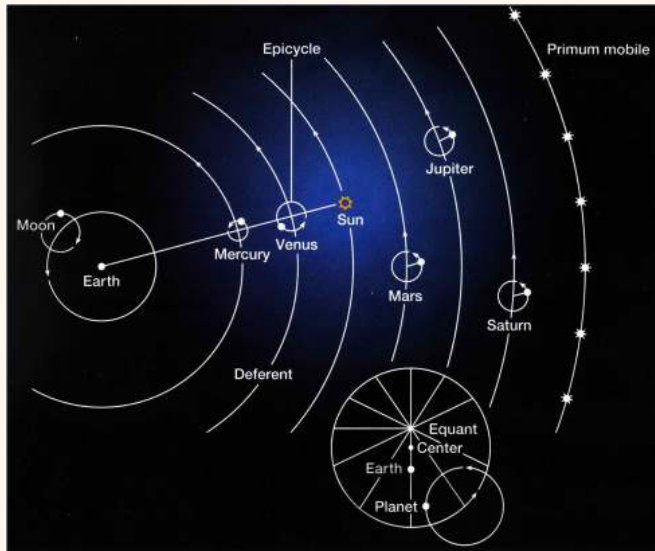


Ancient Greek Astronomy



[Click here to watch video.](#) (15:47)

The Ptolemaic System



Conceptual Question 1

How many years did it take us to overcome the incorrect teachings of Aristotle?

- (a) about 100 years
- (b) about 300 years, 1 AD
- (c) about 2000 years
- (d) in the late 1960's

Heliocentrism

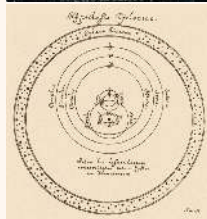
Aristarchus of Samos (310 BCE-230 BCE) was the first to propose a heliocentric model with the planets orbiting the Sun. He explained the lack of stellar parallax by proposing the stars must be extremely far away.

Nicholas Copernicus (1473 – 1543) was influenced by the work of Aristarchus and his own observations to propose a heliocentric model where the planets move with uniform speed in circular orbits with the Sun at the center. His model was able to explain **apparent retrograde motion**, but was unable to explain non-uniform motion without using epicycles. In other words, there was no clear advantage over the Ptolemaic system even though it offered a vastly different picture of the physical world—and one that contradicted prevailing religious doctrine at the time.

Tycho Brahe (1546– 1601)

Danish nobleman with a passion for astronomy. He had the most detailed and accurate observations of planetary motion. Proposed the “Tychonic model,” which had the planets orbiting the Sun, and the Sun orbiting the Earth. Observed supernova of 1573 and, by making parallax measurements, refuted Aristotle’s claim of unchanging “Heavens.”

Tycho famously lost part of his nose during a sword duel over who was the superior mathematician... For the rest of his life, he wore a prosthetic likely made of brass.



Johannes Kepler (1571 – 1630)

Hired by Tycho Brahe to “make sense” of his observational data and prove the Tychonic model was correct. Tycho was notoriously protective of his data and only fed Kepler what he thought was necessary to confirm his theory. It wasn't until after Tycho's death that Kepler was granted unfettered access to Tycho's precise data. Eventually, Kepler came to realize that not only was the Tychonic model wrong, but **planetary orbits were in fact elliptical and not circular**. This explained the non-uniform motion of the planets around the Sun.



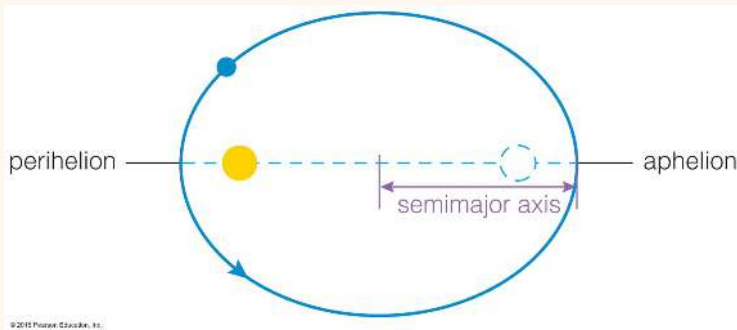
Kepler's Laws of Planetary Motion



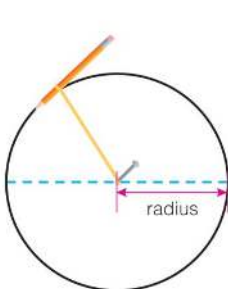
[Click here to watch video.](#) (4:10)

Kepler's First Law

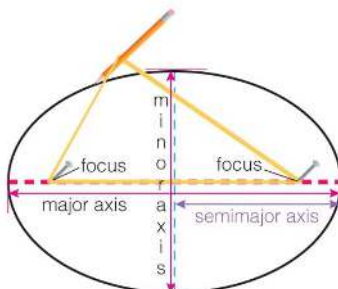
First Law: The orbit of each planet about the Sun is an ellipse with the Sun at one focus.



Drawing a Circle vs. an Ellipse



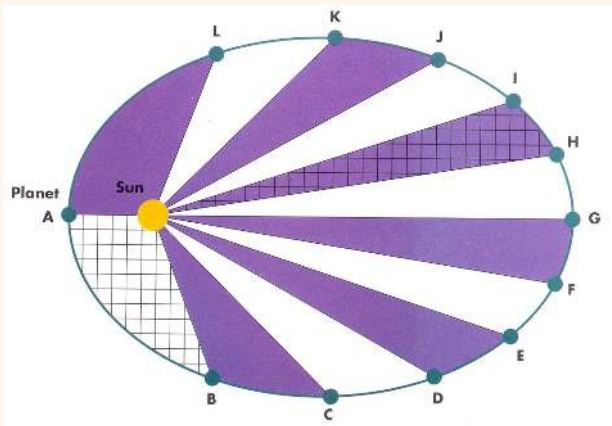
a Drawing a circle with a string of fixed length.



b Drawing an ellipse with a string of fixed length.

Kepler's Second Law

Second Law: As a planet moves around the Sun in its orbit, it sweeps out equal areas in equal times.



Kepler's Third Law

Third Law: more distant planets orbit the sun at slower average speeds, obeying a precise mathematical relationship.

$$(\text{period of orbit})^2 \propto (\text{avg distance})^3$$

TABLE 2-3 A Demonstration of Kepler's Third Law

	Sidereal period P (yr)	Semimajor axis a (AU)	P^2	=	a^3
Mercury	0.24	0.39	0.06		0.06
Venus	0.61	0.72	0.37		0.37
Earth	1.00	1.00	1.00		1.00
Mars	1.88	1.52	3.53		3.51
Jupiter	11.86	5.20	140.7		140.6
Saturn	29.46	9.54	867.9		868.3
Uranus	84.01	19.19	7,058		7,067
Neptune	164.79	30.06	27,160		27,160
Pluto	248.54	39.53	61,770		61,770

In-Class Poll

A planet is closest to the Sun when it is at

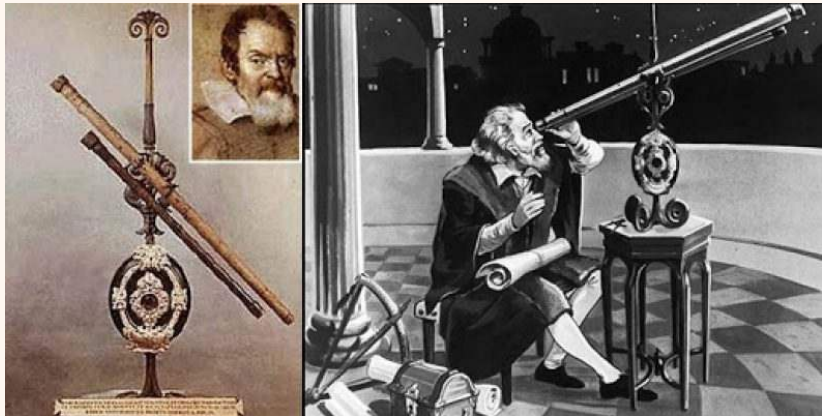
- (a) perigee
- (b) apogee
- (c) perihelion
- (d) aphelion

Galileo vs. Aristotle & Geocentrism

Galileo's mission in life was to prove Aristotle wrong. Not only did Galileo convincingly disprove that heavier objects fall faster, he also introduced the law of inertia, which nullifies Aristotle's argument against a moving Earth. The birds and clouds in the sky are moving right along with the Earth, and they require no force in order to do so!

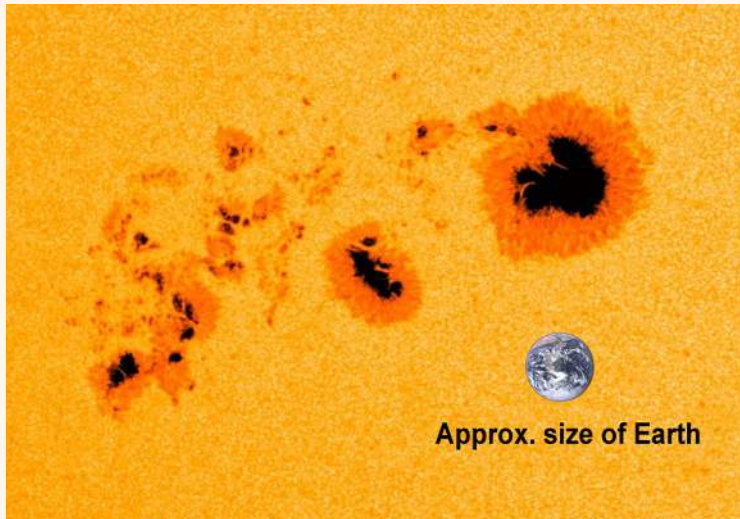
Using a telescope no more powerful than one you can pick up for \$20 on Amazon, he observed **Sun spots**, **stellar parallax**, **moons orbiting Jupiter**, and even observed Venus to go through phases just like our Moon—alternating between bright and dark. The last of these directly contradicted the Ptolemaic model. Rather than being celebrated for his discoveries, he was tried by the Roman Inquisition in 1633 for heresy. He was forced to recant and spent the rest of his life under house arrest.

Galileo's Contributions to Astronomy

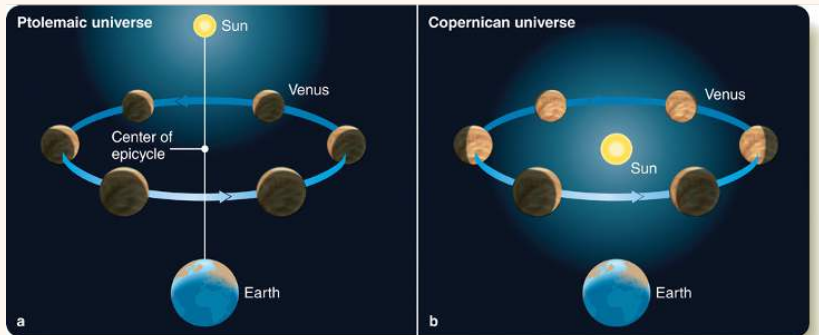


[Click here to watch video.](#) (3:30)

Sunspots



Phases of Venus



© 2016 Cengage Learning®

Newton's Contributions to Astronomy

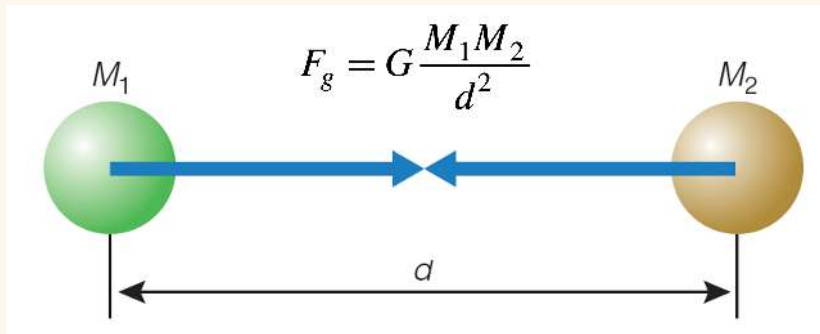
Kepler and Galileo based their assertions on more precise observations than the Greeks, but they never quite uncovered a well-reasoned explanation based on fundamental principles.

In the apocryphal tale, Newton realizes while sitting under an apple tree that the same gravitational force that makes an apple fall from a tree is responsible for keeping the Moon in its orbit. The gravitational force turns out to have a precise mathematical description that works incredibly well for *any two objects*.

Newton transformed astronomy from a largely observational science into one governed by universal physical laws. His three laws of motion and universal law of gravity supported the heliocentric model and explained the empirical observations of planetary motion, tides, and the orbits of comets and moons.

Newton's Universal Law of Gravity

Every massive particle in the universe attracts every other massive particle with a force along a line joining them that is **directly proportional to the product of their masses** and **inversely proportional to the square of the distance between them**.



Conceptual Question 2

If the masses of two planets are each somehow doubled, the force of gravity between them

- (a) doubles
- (b) quadruples
- (c) stays the same
- (d) reduces by half
- (e) reduces by one-quarter

If the mass of only one planet doubles and the two planets are separated by twice the distance, the force of gravity between them

- (a) doubles
- (b) quadruples
- (c) stays the same
- (d) reduces by half
- (e) reduces by one-quarter

Gravitational Constant

The constant big G , not to be confused with the acceleration due to gravity little g , is incredibly small in SI units:

$$G = 6.67340 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2$$

Gravity is the weakest of the four known fundamental forces. Think about it; given the enormous mass and overall size of the Earth, we can still walk around freely and even jump several feet from the surface!

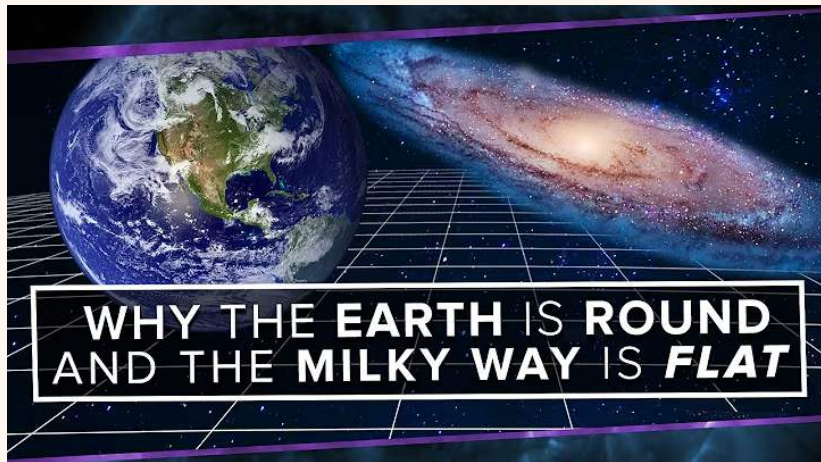
The earliest experiment to find the value of G was conducted by Henry Cavendish using something called a torsion balance. The experiment measured the faint gravitational attraction between lead balls, which deflected the torsion balance rod by a small but detectable amount.

Mass of the Earth

From the acceleration due to gravity near the Earth's surface g , the universal gravitational constant G , and the radius of the Earth, we can estimate the mass of the Earth to be around 6×10^{24} kg. If we divide the mass by the volume, we calculate the mass density and find that it's much larger than the density of most rocks found in the Earth's crust.

We conclude that the Earth cannot be uniform; **the interior must be much more dense than its surface**. According to geophysical models, the maximum density of the Earth at its center is around 13 g/cm^3 . For reference, lead has a density of about 11 g/cm^3 at room temperature.

Why does the universe make spheres and disks?



[Click here to watch.](#) (14:17)

Inverse-Square Law

The gravitational force between two massive particles (particles that have mass; they don't necessarily have to be heavy) is an inverse-square law, meaning the force is proportional to one divided by the distance squared. The force law also works for spherical bodies, as long as we compute the distance between their geometric centers.

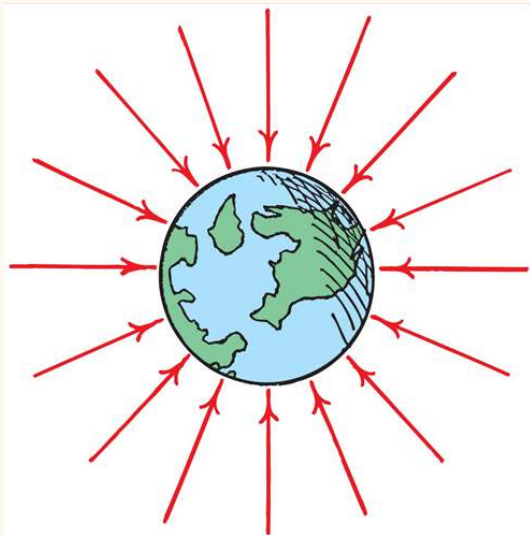
One way to understand this is to imagine the gravitational influence around a spherical body is spread evenly over the surface of spheres. As the distance from the center increases, so too does the radius of the sphere over which the gravitational influence is spread. Since the area of a sphere with radius R is $4\pi R^2$, the influence is spread thinner and thinner as the distance grows.

Gravitational Field

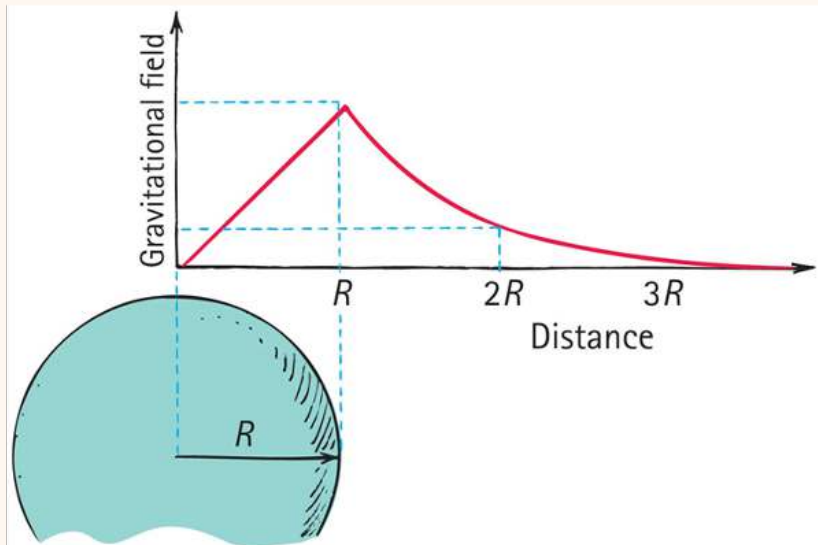
One hallmark of good science is the ability to criticize your own work. Newton was famously troubled by his law of gravity, despite its success. “That one body may act upon another at a distance through a vacuum without the mediation of anything else... is to me so great an absurdity.”

In everyday life, we typically observe objects responding to their immediate surroundings (we call this locality). The concept of a **gravitational field** was introduced to restore some notion of locality to gravitational interactions. For instance, we say that Earth creates a gravitational field in the space surrounding it, and other objects like you, me, and the Moon, are all interacting with the gravitational field in our immediate surroundings. All massive objects both create and respond to gravitational fields!

Gravitational Field

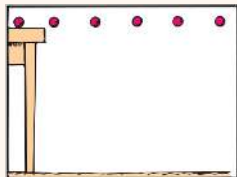


Gravitational Field

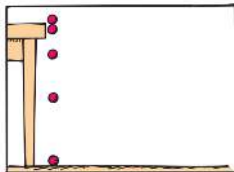


Projectile Motion

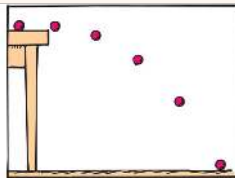
A projectile launched horizontally feels only a downward pull of gravity. Hence, the horizontal component of velocity does not change and the vertical component behaves as if it were falling vertically. The overall motion is a curved path through space.



Horizontal motion
with no gravity



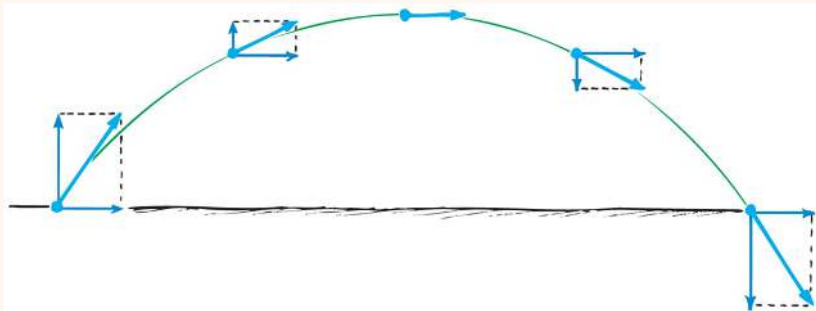
Vertical motion only
with gravity



Combined horizontal
and vertical motion

Parabolic Trajectory

A projectile launched at any angle relative to the horizontal will follow a parabolic trajectory (shaped like a parabola).



Conceptual Question 3

The velocity of a projectile has horizontal and vertical components. Assuming negligible air resistance, the horizontal velocity component of a projectile

- (a) increases with time.
- (b) decreases with time.
- (c) remains the same.
- (d) Not enough information.

Which hits the ground first?

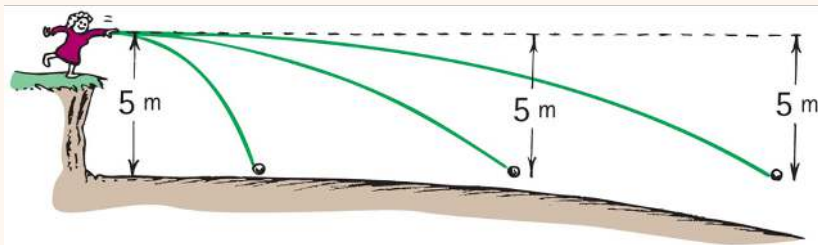


[Click here to watch video.](#) (2:23)

Conceptual Question 4

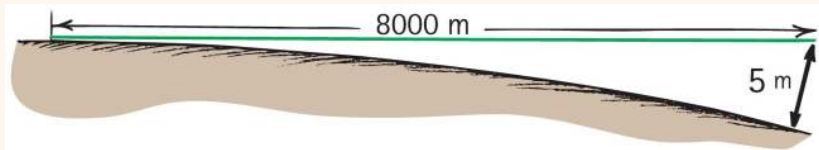
A girl throws a rock horizontally from a cliff. One second after she releases the rock it will have fallen vertically by

- (a) 1 meter
- (b) 5 meters
- (c) 10 meters
- (d) none of the above



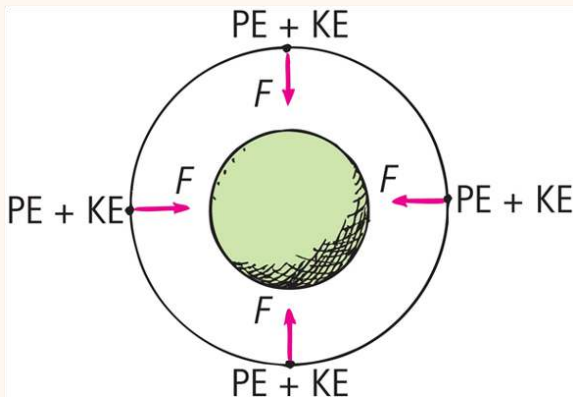
Satellites are High-Speed Projectiles

The Earth's surface drops a vertical distance of 5 meters for every 8000 meters tangent to the surface. A satellite is simply a projectile that's been launched so fast that it falls around the Earth rather than onto it. It is theoretically possible for you to "levitate" above the Earth's surface; the catch is you'll have to get yourself moving at 18,000 mph (god speed).

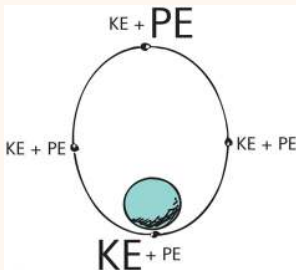


Circular Orbits

In a circular orbit, the potential energy of the satellite-Earth system never changes, so the kinetic energy cannot change. Hence, the speed is constant for a circular orbit.

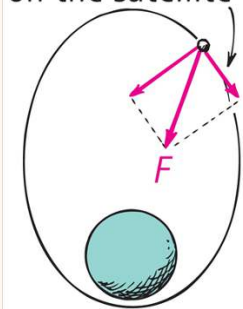


Elliptical Orbit



A satellite's speed varies throughout an elliptical orbit. PE is greatest when the satellite is farthest away (apogee). PE is least when the satellite is closest (perigee). KE is least when PE is the most and vice versa.

This component of force does work on the satellite

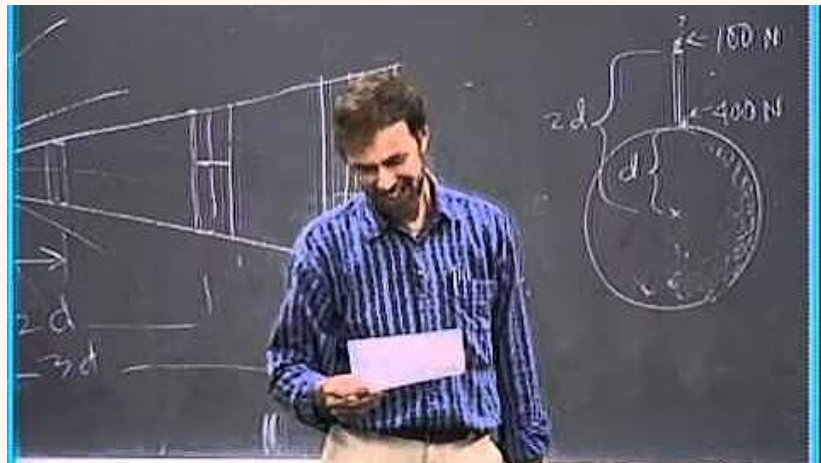


Conceptual Question 5

The speed of a satellite in an elliptical orbit

- (a) is greatest when farthest from Earth.
- (b) is least when farthest from Earth.
- (c) remains constant for all elliptical orbits
- (d) is greatest if the orbit is circular

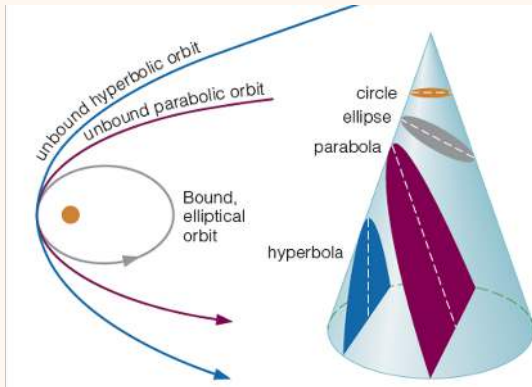
Discovery of Neptune



[Click here to watch video.](#) (2:37)

Kepler vs. Newton

Newton discovered that ellipses are not the only kinds of orbits. Kepler's first and third laws only work for *bounded orbits*. Newton showed that orbits are cross sections of a cone made by slicing at various angles—these are called conic sections.



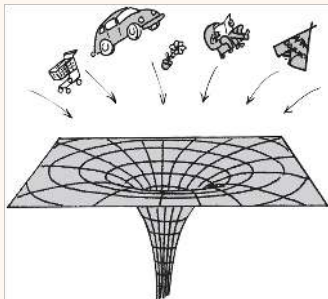
Escape Speed

The escape speed is the minimum speed needed for an object to escape from contact with or orbit of a primary body (like a planet or star). From the surface of the Earth, $v_{\text{esc}} = 11.2 \text{ km/s}$, and from the solar system at Earth's orbit $v_{\text{esc}} = 42.1 \text{ km/s}$.

Currently, we don't have rockets capable of traveling fast enough to escape the Sun, so we must use a “gravitational slingshot method” involving nearby encounters with massive planets like Jupiter and Saturn, as we did with the Voyager 1 mission, which is currently the most distant human-made object from Earth (162.7 AU as of June 2024).

Black Holes

When a star exhausts nuclear fuel, it shrinks, so that its mass becomes concentrated within a smaller radius, and the gravitational field on the surface increases. When a very massive star collapses, it can become so small that its gravitational field exceeds the threshold for allowing anything, even light, to escape, and a black hole is formed, trapping (almost) everything inside.



Conceptual Question 6

What would happen to Earth if the Sun became a black hole?

- (a) It would break away from the attraction of the Sun.
- (b) It would be pulled into the Sun.
- (c) It would become a black hole too.
- (d) None of the above.



[Click here to watch video.](#) (5:56)