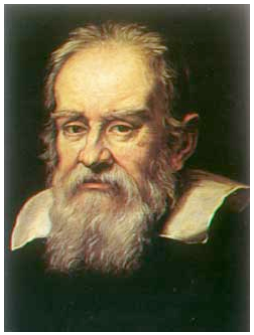
Part 1: The Sky; History of Astronomy; How Science Works

- Tuesday, January 17 Reading: Chapters 1 & 2.1, Appendix A
  - Introduction, syllabus, class rules; units, scales,
  - rotation of the Earth, time zones, constellations; tour – where we go in the course
- Thursday, January 19 Reading: Chapters 2, 3 HW 1 assigned
  - The sky: Rotation of Earth, seasons, phases, eclipses
- Tuesday, January 24 Reading: Chapter 4-1, 4-2, 4-3
  - History of Astronomy: Greeks, Copernicus, Tycho, Kepler
- Thursday, January 26 Reading: Chapter 4-4, 4-5
  - History of Astronomy: Galileo, Newton
- Tuesday, January 31 Reading: "Windows on science" sections or
  - How science works "How do we know?" sections in Chapters 1, 2, 3, 4
- Thursday, February 2 Reading: Chapter 5 HW 1 due
  - The nature of light, telescopes, spectra
- Monday, February 6 Help session from 4 — 6 PM in RLM 4.102
- Tuesday, February 7 Exam 1

Galileo Galilei

1564-1642



"Pure logical thinking cannot yield us any knowledge of the empirical world; all knowledge of reality starts from experience and ends in it. … Because Galileo saw this and because he drummed it into the scientific world, he is the father of modern physics — indeed, of modern science altogether."

Albert Einstein

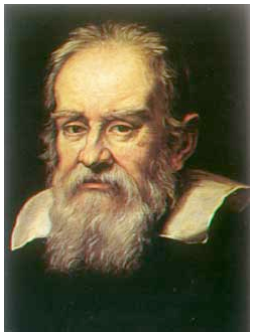
"History plays on the great the trick of calcifying them into symbols. Galileo dropping a cannonball and a musket ball from atop the Leaning Tower of Pisa, thus demonstrating that objects of unequal weight fall at the same rate, symbolizes the growing importance of observation and experiment in the Renaissance. Galileo making the first telescope symbolizes the importance of technology in opening human eyes to nature. Galileo on his knees before the Inquisition symbolizes the conflict between science and religion."

Timothy Ferris

Coming of Age in the Milky Way

Galileo Galilei

1564-1642



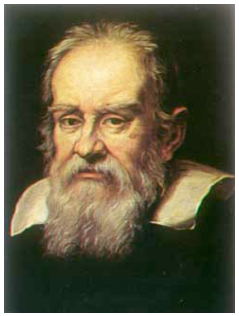
In 1609, Galileo was a professor of mathematics in Padua (then part of the Republic of Venice). He was modestly successful but plagued by financial debts. He needed a lucky break.

But he was brilliant. And he trusted no authority; he trusted only the results of observations and experiments. So he was well prepared to exploit:

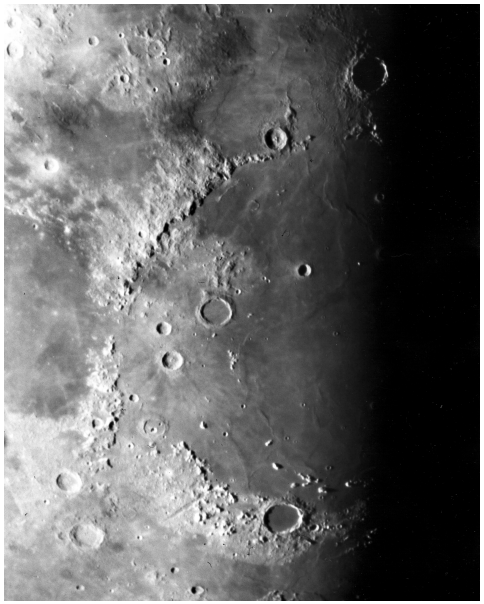
The First Astronomical Use of the Telescope

In 1609, Galileo learned about the invention in Holland of the telescope. He built several telescopes and made himself famous (and got "tenure") by showing Venetians how to use it for military and commercial purposes. And:

Galileo was the first to use the telescope for systematic study of astronomy.



Galileo's Discoveries



- Mountains, valleys, craters on the Moon ⇒
  the Moon is "not a wafer composed of heavenly æther, but a rocky, dusty, sovereign world."

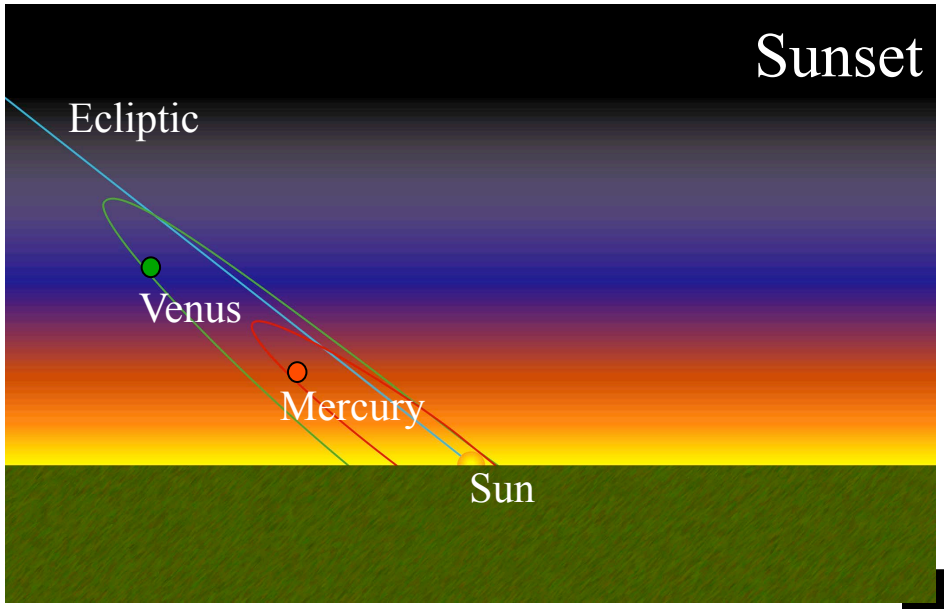
- Four moons of Jupiter, a Copernican "Solar System" in miniature. They showed that other planets, and not just Earth, have moons. Everything does not revolve around the Earth! Also note: Jupiter moves, but it does not leave its moons behind!

- Venus has phases like the phases of the Moon. Venus looks much bigger when it is a thin crescent than when it is full. "These things leave no room for doubt about the orbit of Venus. With absolute necessity we shall conclude, in agreement with [Copernicus] that Venus revolves around the Sun."

- Many stars too faint to be seen with the naked eye, suggesting that the sky has depth.

- Sunspots, indicating that the Sun, like the moon, is not "perfect" or unchanging.

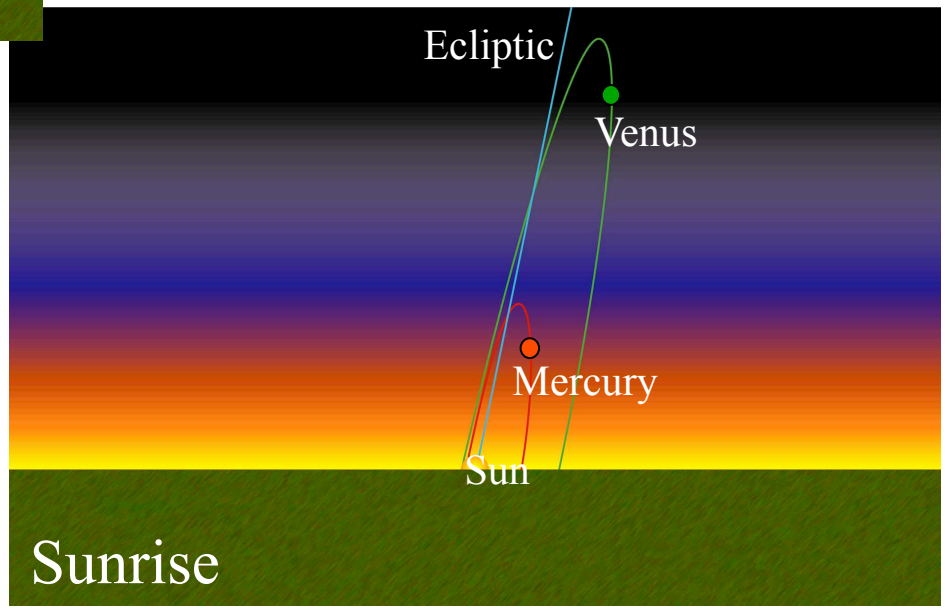
Orbits of Mercury and Venus



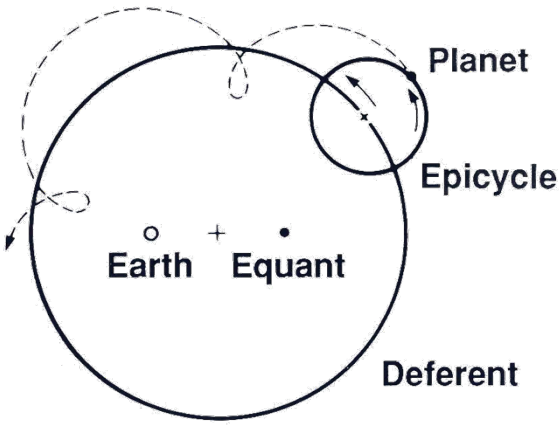
Venus is currently (January 2017) behind Earth in its orbit: It is catching up to us and getting closer to us.

It is easy to see Venus in the evening sky after sunset. Its phase is waning toward new. <u>It is by far the brightest object</u> after our Moon in the evening sky. It is brightest on Feb. 17, 2017.

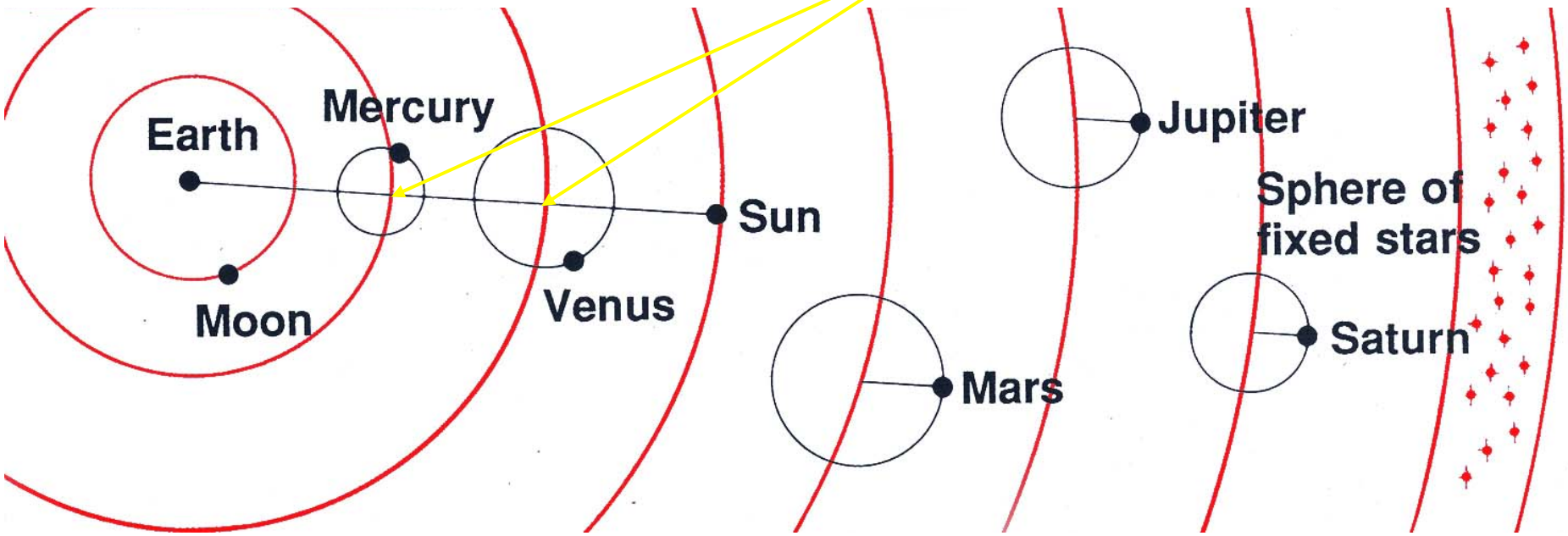
It is almost always hard to see Mercury, because it never gets more than 28° from the Sun.



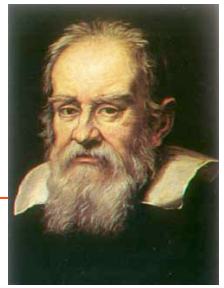
Recall: The Ptolemaic System



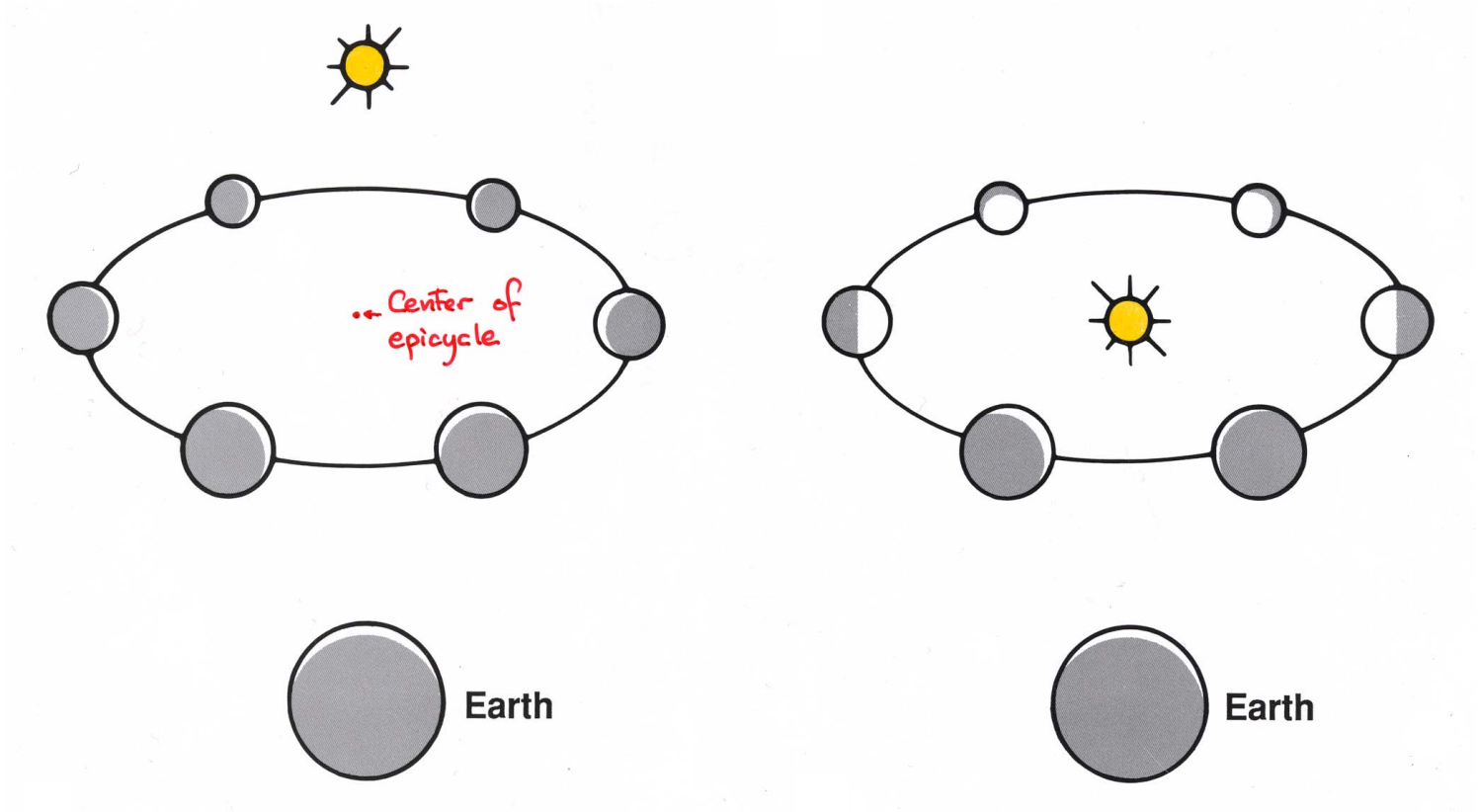
The centers of the epicycles of Mercury and Venus must always lie on the Earth-Sun line.



Disproving a Geocentric Solar System



If Venus traveled around an epicycle that is always between the Earth and the Sun, then it should always be a thin crescent.



But this is not what we see!

Instead, we see this.

Galileo Galilei

1564-1642

Galileo did important work on many problems. For example, he figured out that heavy and light objects fall at the same rate.

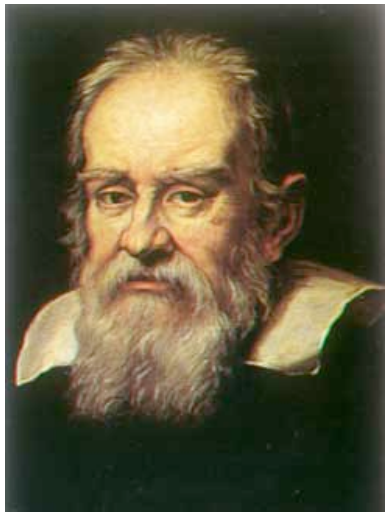
At first, Galileo's relations with the Church were good. Pope Urban VIII was an old friend.

Later, Galileo got power-hungry, and moved to the glorious and wealthy – but politically dangerous – Medici court. He got more and more arrogant. He got overawed with himself as an authority. And he started to ridicule all other authority, especially the Church.

His arrogance, political naïveté, and political blunders got him in trouble with the Church, and he was convicted. On June 22, 1633, on his knees in the great hall of the Santa Maria Sopre Minerva (in Rome), he renounced his "heresies" and promised never to speak or to write about them again.

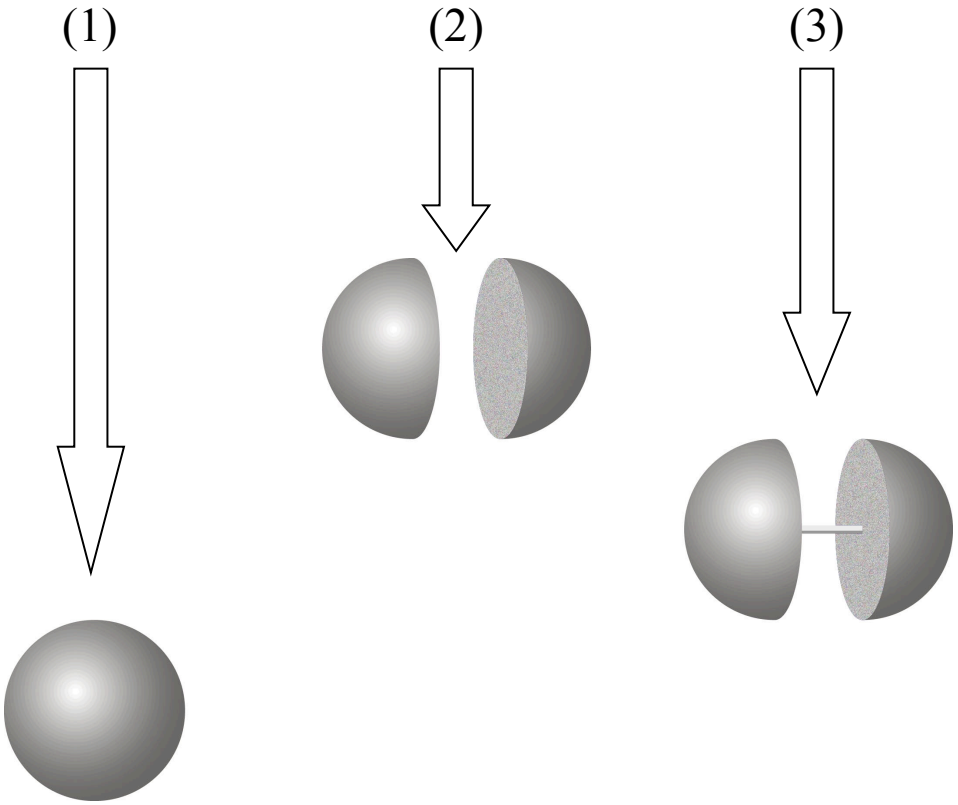
He lived for 8 more years under house arrest in his villa near Florence. He continued his research … quietly.

Galileo was not the last great scientist to suffer from an excess of arrogance.

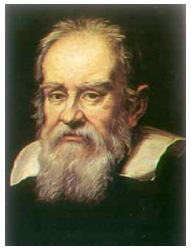


Galileo's Thought Experiment

According to Aristotle, if a one-pound cannonball falls a given distance in a given time (1), then if the ball is cut in half, each half-pound ball should fall less far in the same interval (2). But, reasoned Galileo, what happens if the two half-balls are attached by a thread or a stick (3)? Looked at in this way, Aristotle's ideas about falling bodies start to look absurd.



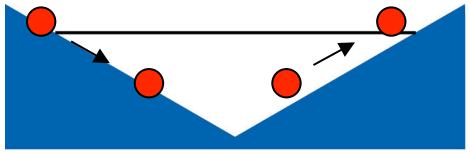
Inertia



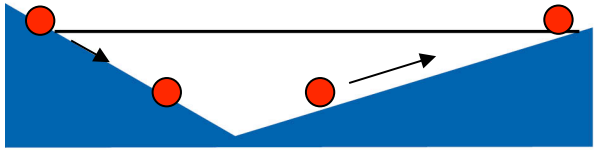
Kepler's laws accurately describe planetary motion, but they do not describe the motion of objects on the Earth. Newtonian physics explains Kepler's laws in terms of more basic principles that apply equally to terrestrial and celestial motion.

Newton's First Law Without Newton

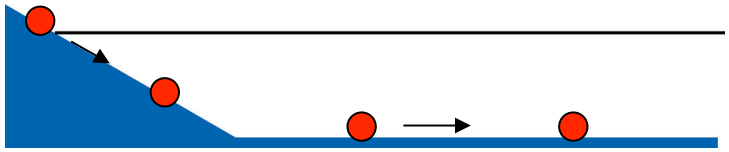
An ox-cart on a dirt track soon stops if the oxen stop pulling. Aristotle concluded that a constant force was needed to keep an object moving. This was disproved by Galileo.



Consider a ball that rolls down one ramp and up another. Galileo noticed that, regardless of the slope of the second ramp, the ball always climbs back up to the level it started from.



What if the second ramp is replaced with a perfectly horizontal track? Galileo concluded that the ball would roll on forever.



Sir Isaac Newton

1642 - 1727

There are 2 kinds of geniuses:

An ordinary genius accomplishes things that we cannot do, but we can imagine that, if we were more intelligent, we could do such things.

A supreme genius does things that look like pure magic. We cannot imagine how he or she did them or how anyone could do them.

Newton was this kind of supreme genius.

[Newton's Law of Gravitation] has been called "the greatest generalization achieved by the human mind."

Richard Feynman

The Character of Physical Law

Sir Isaac Newton

1642 - 1727

Newton has been called "the greatest scientist of his time and perhaps of all time." He was completely absorbed by his interest in how nature works, often to the exclusion of eating and sleeping. His discoveries and inventions include:

- Calculus (which he needed as a tool to study gravity)
- The reflecting telescope
- Splitting of light into its component colors – "spectra"
- Newton's three laws of motion, and
- The law of gravitation

Newton realized that the gravity that holds the Moon to the Earth is the same gravity that holds onto you and me and that makes apples fall. Therefore:

Newton was the first person to realize that the same laws of physics control the heavens and the Earth.

The laws of motion and the law of gravitation were the first mathematical physical laws that were understood to apply to everything. They explained a much wider range of phenomena than the ones that they were derived to explain. They allowed accurate calculations of how things behave. And they allowed us to derive further physical laws.

Newton's laws opened the floodgates of discovery.

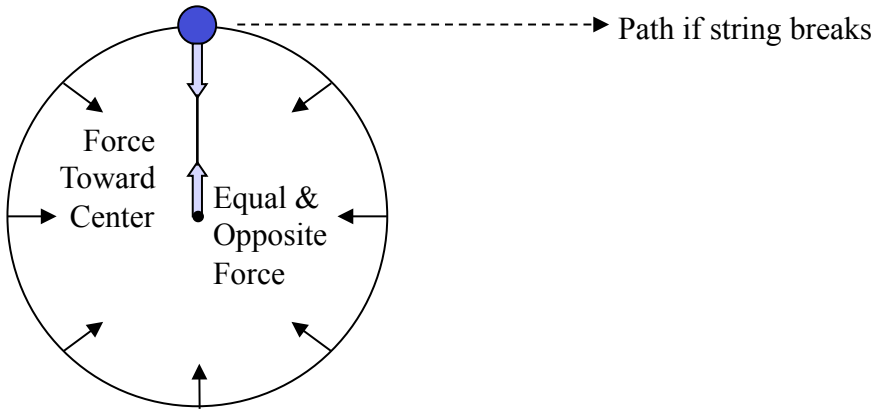
Newton's Laws of Motion

Law 1: A body remains at rest or moves with constant speed in a straight line unless acted on by an outside force.

Law 2: The outside force acting on a body is equal to the body's mass times its acceleration.

Law 3: If two bodies interact, the force exerted on the first body by the second is equal and opposite to the force exerted on the second body by the first.

The circular motion of a weight whirled around on the end of a string illustrates all three of these laws:



What is the "string" that keeps a planet in orbit around the Sun?

Universal Gravity

Newton showed that planets in circular orbits would obey Kepler's third law if they were attracted to the Sun with a force proportional to the inverse square of their distance. Taking this idea further: he postulated that any two bodies attract each other with a force proportional to the product of their masses divided by the square of the distance between them, or

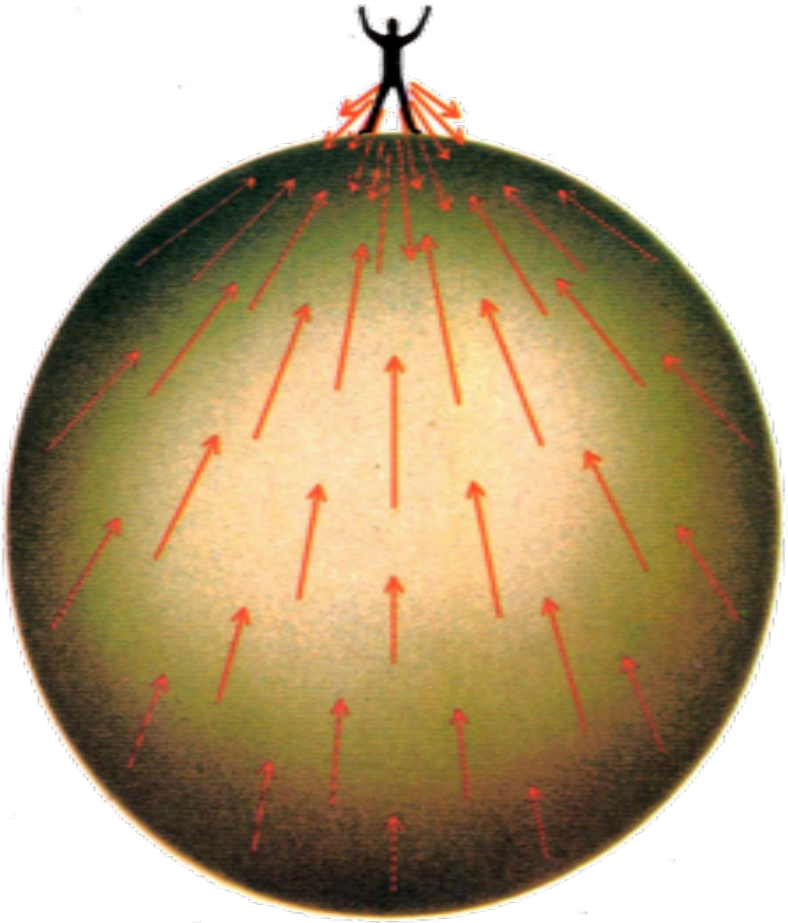
$$\boxed{F = G\frac{Mm}{r^2}}$$

where *M* and *m* are the masses of the two bodies, *r* is the distance between them, and *G* is a constant of nature.

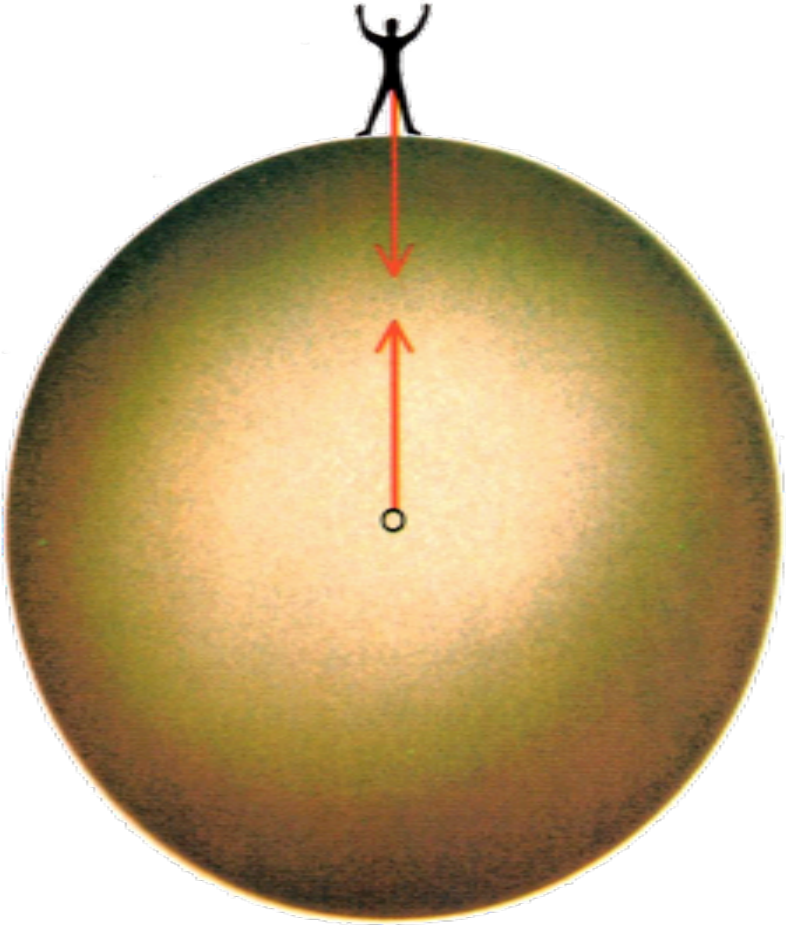
Newton showed that this assumption plus his three laws of motion predict that the planets move according to Kepler's laws. But universal gravity doesn't just explain the motions of planets. It also connects the motion of celestial bodies such as the Moon with terrestrial bodies such as an apple falling from a tree.

G measures the strength of gravity. Nobody knows how to derive G from any theory. G is measured to be 6.67×10^{-11} $m^3/kg\ s^2$.

Everything Pulls on Everything



(a)

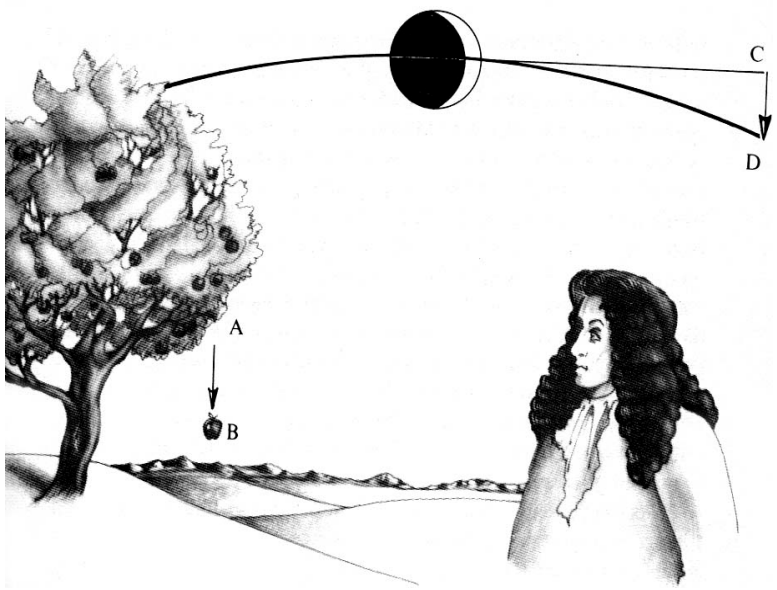


(b)

How Newton connected motion in the heavens with motion on Earth.

I began to think of gravity extending to … the Moon and from Kepler's third law, I deduced that the forces which keep the planets in their orbits must vary reciprocally as the squares of their distances from the centers about which they revolve. I compared the force requisite to keep the Moon in her orbit with the force of gravity at the surface of the Earth and found them … pretty nearly equal.

Isaac Newton

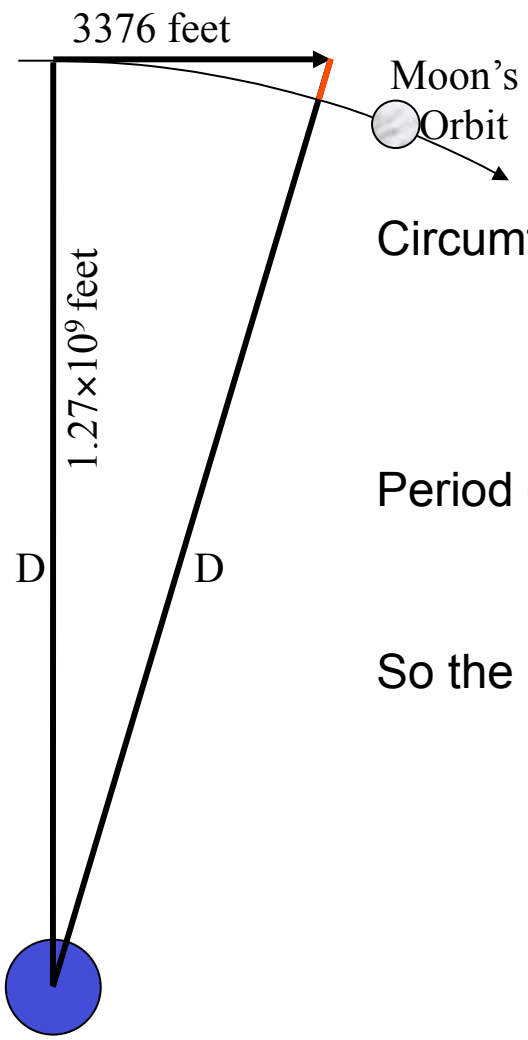


Newton's thinking about universal gravitation went like this: If the Moon is 60 times as far from the center of the Earth as is the apple (4000 miles for the apple, 240,000 miles for the Moon), and gravity gets weaker as the square of the distance, then the apple must feel a gravitational force that is 60^2 or 3600 times stronger than that experienced by the Moon. The Moon therefore should fall along the curve of its orbit $^1/_{3600}{}^{th}$ as far each second as does the apple. And so it does (time AB = time CD).

Timothy Ferris

Coming of Age in the Milky Way

How far does the Moon fall in 1 Second?



Distance to the Moon =

$$D_{Moon} = 240,000 \text{ miles}$$
$$= (240,000 \text{ miles})\left(\frac{5280 \text{ feet}}{1 \text{ mile}}\right)$$
$$= 1.27 \times 10^9 \text{ feet}$$

Circumference of its Orbit =

$$C_{Orbit} = (2\pi) D_{Moon}$$
$$= (2\pi)(1.27 \times 10^9) \text{ feet}$$
$$= 7.96 \times 10^9 \text{ feet}$$

Period of its Orbit =

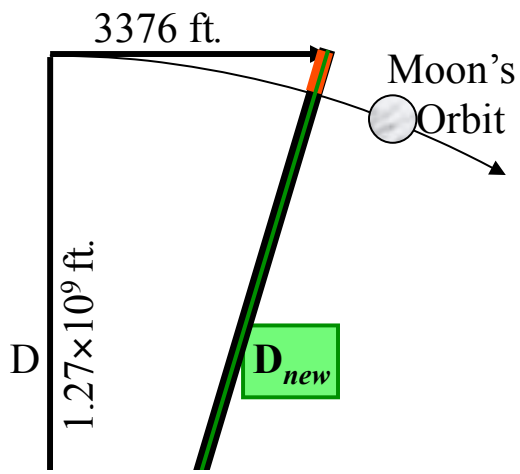
$$P_{orbit} = (27.3 \text{ days})\left(\frac{24 \text{ hours}}{1 \text{ day}}\right)\left(\frac{3600 \text{ sec}}{1 \text{ hour}}\right)$$
$$= 2.36 \times 10^6 \text{ sec}$$

So the moon is moving at

$$Speed_{Moon} = \frac{C_{Orbit}}{P_{Moon}}$$
$$= \frac{7.96 \times 10^9 \text{ feet}}{2.36 \times 10^6 \text{ sec}}$$
$$= 3376 \ \frac{\text{feet}}{\text{sec}}$$

How far does the Moon fall in 1 Second?

If the Moon traveled in a straight line, then after 1 second its distance from Earth would be (from the Pythagorean Theorem):



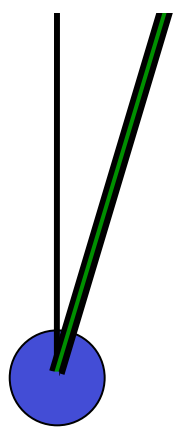
$$\boxed{D_{new}} = \sqrt{D^2 + D_{traveled}^2}$$

$$= \sqrt{\left(1.27\times10^9\ \text{ft}\right)^2 + \left(3376\ \text{ft}\right)^2}$$

$$= 1.27\times10^9\ \text{ft}\sqrt{1+\left(\frac{3376}{1.27\times10^9}\right)^2}$$

$$\approx 1.27\times10^9\ \text{ft}\left[1+\frac{1}{2}\left(\frac{3376}{1.27\times10^9}\right)^2\right]$$

So: to keep the Moon in a circular orbit, i.e. to keep its distance constant at 1.27×10^9 feet, in 1 s the Moon must fall:



$$\boxed{D_{Fall}} = 1.27\times10^9\ \text{ft}\left[1+\frac{1}{2}\left(\frac{3376}{1.27\times10^9}\right)^2 - 1\right]$$

$$= \frac{1}{2}\left(\frac{3376}{1.27\times10^9}\right)^2\ \text{ft}$$

$$= 4.49\times10^{-3}\ \text{ft} \approx \boxed{\frac{1}{18.6}\ \text{inch}}$$

Let's Compare a Falling Apple to a Falling Moon

We conclude: At a distance of 240,000 miles, the Moon falls $^{1}/_{18.6}$ inch in 1 sec.

Is it sensible that this falling could be due to the same force of gravity that pulls on you and me?

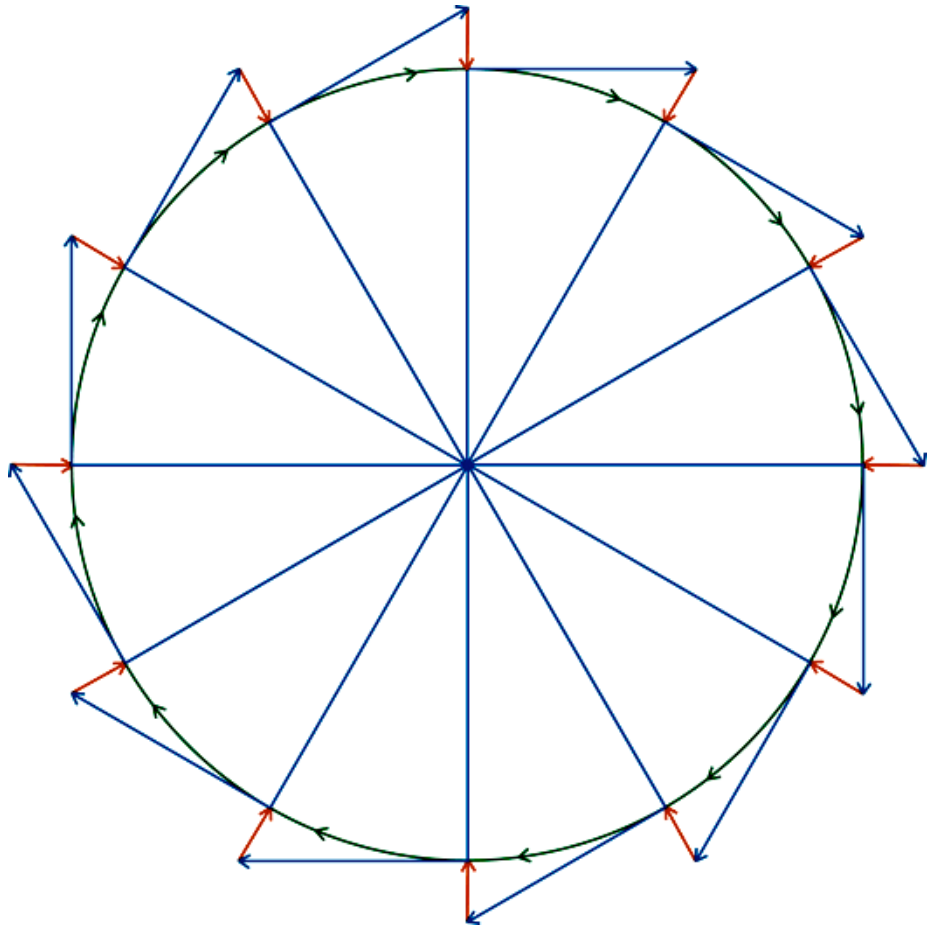
Moon's distance from the center of the Earth =	240,000	miles
Our distance from the center of the Earth =	4,000	miles
Ratio =	60	

If the force of gravity is proportional to $(\text{distance})^2$, then gravity should feel $60^2 = 3600$ times stronger to us than it does to the Moon.

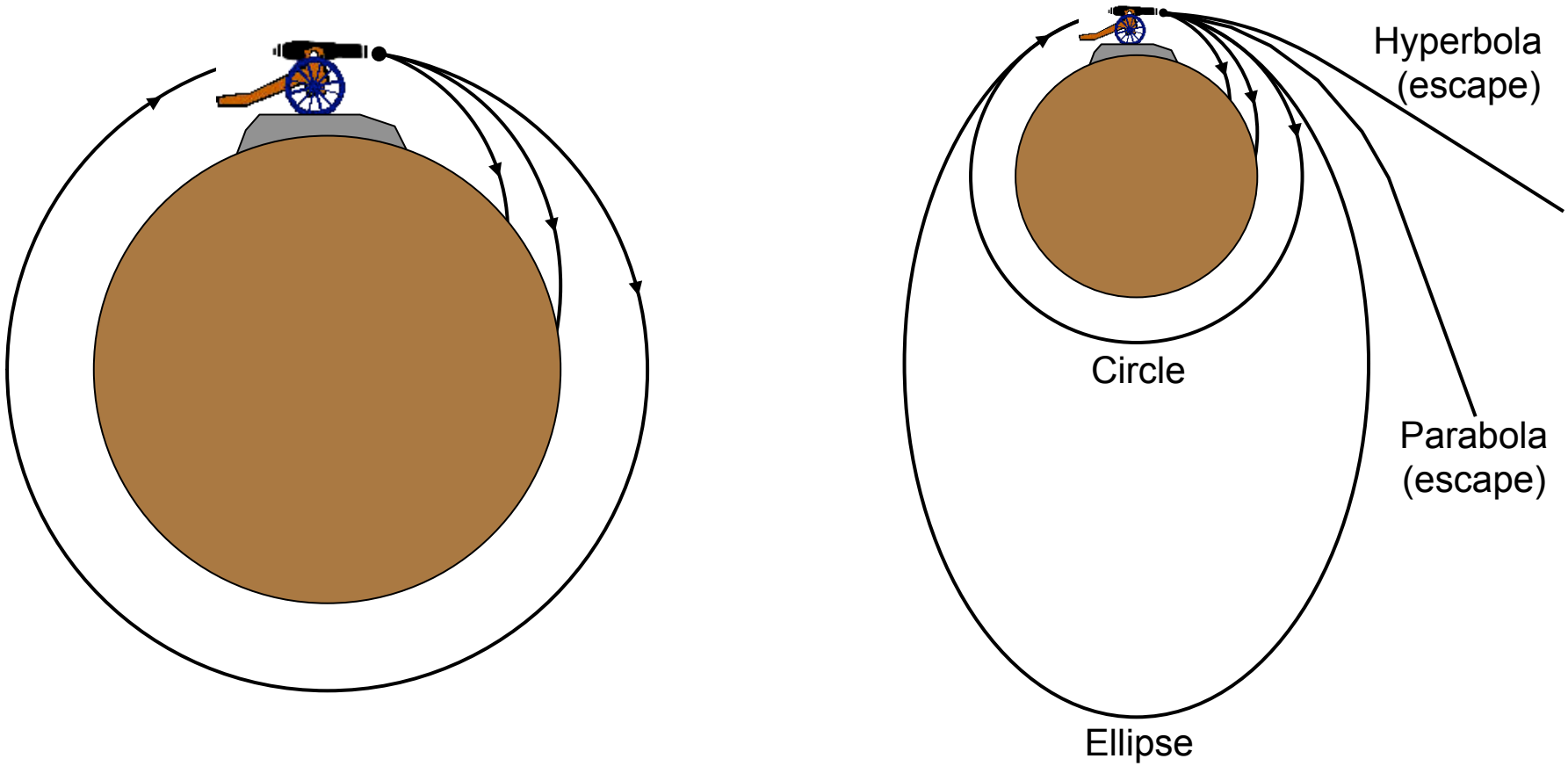
So: objects should fall 3600 times farther in 1 second.
$3600 \times {}^{1}/_{18.6}$ inches = 16 feet.
Galileo had already measured that this is precisely how far things on Earth fall in 1 second!

Newton concluded: The force of gravity that makes apples fall is the same force of gravity that holds the Moon in its orbit around the Earth.

How Orbits Work



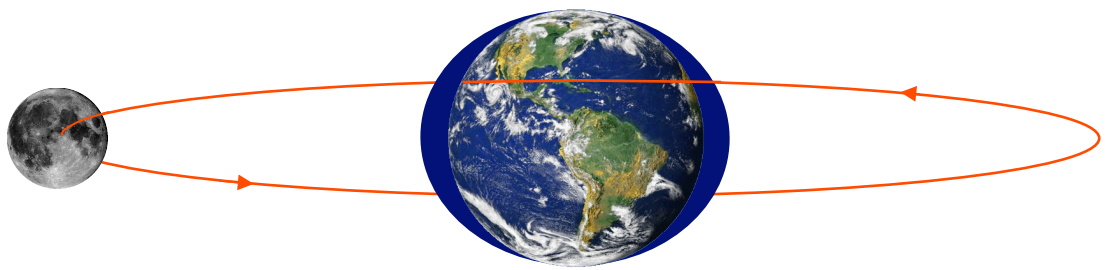
Orbit Geometries



Tides

Using Newton's laws, astronomers rapidly expanded their understanding of the Solar System.

Tides: The twice-daily rise and fall of ocean levels on the Earth is due to the gravitational attraction of the Moon (and, to a lesser degree, the Sun). Because the Earth falls freely through space, the ocean bulges out on the side facing the Moon and on the side facing the other way.



The rotation of the Earth carries you past two high tides and two low tides every day.

Because of the rotation of the Earth, the tidal bulge is dragged slightly ahead of the Moon. As a result, the rotation of the Earth is slowing down and the orbit of the Moon is expanding.

“Weighing” the Planets

Newton’s analysis of Kepler’s third law showed that the constant a^3/P^2 is the mass of the attracting body. If we measure a in AU and P in years, then we get a^3/P^2 in units of the Sun’s mass, $M_\odot$.

Callisto’s orbit around Jupiter has semimajor axis a = 0.0126 AU and period P = 0.046 years. So Jupiter’s mass is

$$M_J = \frac{0.0126^3}{0.046^2} M_\odot = \frac{1}{1{,}000} M_\odot .$$

The Moon’s orbit around the Earth has semimajor axis a = 0.0026 AU and period P = 0.075 years. So the mass of the Earth is

$$M_\oplus = \frac{0.0026^3}{0.075^2} M_\odot = \frac{3}{1{,}000{,}000} M_\odot .$$

To get Earth’s mass in kg, we need to measure the gravitational attraction between two bodies whose masses we know. This gives the mass of the Earth as

$$1\ M_\oplus = 6 \times 10^{24}\ \mathrm{kg}.$$

Interactions Between Planets

Newton's laws predicted tiny violations of Kepler's laws due to gravitational attractions between planets. By comparing the observed violations with predictions, astronomers measured the masses of Mercury and Venus, which do not have satellites.

The gravitational attractions of the other known planets did not explain how Uranus is observed to violate Kepler's laws. Adams and Leverrier showed that these violations could be due to an 8th planet. Neptune, was discovered in 1846 at the predicted position.

Unexplained violations of Kepler's laws by Neptune and Mercury led to predictions of two more planets. Pluto was discovered in 1930, but its mass is too small to affect Neptune's orbit. The slow precession of Mercury's orbit was finally explained by Einstein's theory of General Relativity.

The long-term effects of gravitational attractions between planets are hard to predict. But planetary orbits can be changed dramatically. Any planets that formed (e. g.) between Jupiter and Saturn have been thrown out of our Solar System. Present planetary orbits look stable. But:

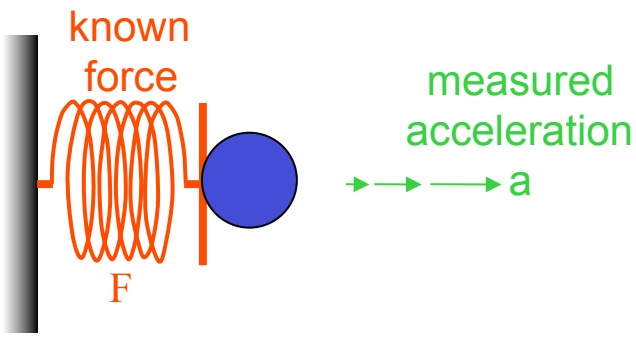
Many planets have been ejected from other Solar Systems. There may be more free-roaming planets in interstellar space than there are stars!

Mass and Weight

Mass

m

Mass is a measure of "how much stuff" you have.



F=ma

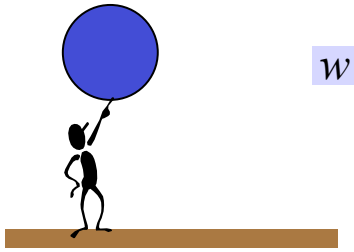
The mass of an object is the same everywhere.

Weight

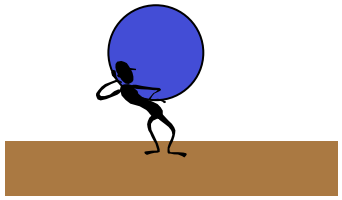
w

Weight is the amount of force needed to keep an object from falling in a particular gravitational field

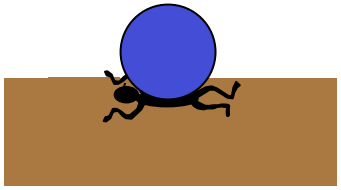
$$w = \frac{GMm}{r^2}$$



Low-gravity planet
(small M or big r)



Medium-gravity planet



High-gravity planet
(big M or small r)

Weight depends on where you are.

Four Kinds of Forces

1. Gravity
2. Electromagnetic Force
3. Strong Nuclear Force
4. Weak Nuclear Force

Gravity is the weakest force.

Put two protons 1 mm apart:

- They attract each other gravitationally.
- They repel each other electrically.
- Electrical repulsion is 10^{40} times stronger than gravitational attraction.

You would have to move the protons more than a light year apart to make the repulsion there equal to the attraction at 1 mm.

You are attracted gravitationally by the person sitting next to you.

But you are attracted 5 billion times more strongly by the Earth.

Four Kinds of Forces

Gravity — holds together the Earth, the Solar System, and the Galaxy.
— holds you to the Earth.

Electromagnetic Force — Holds you together.
— Holds together most objects in your daily lives.

Strong Nuclear Force — Holds the atomic nucleus together.

Weak Nuclear Force — Is involved in some radioactive decays.

Gravity is the weakest force.

Gravity and electomagnetic forces are long-range; the others are important only on tiny scales (smaller than an atom).

Ninety-Nine Years that Changed Astronomy