Laws of Motion Revealed: The Age of Enlightenment

John Michael Preston

Welcome to the second session of the *Almost No Math Physics Course*. This week we will explore the dramatic effect of the discoveries of the natural laws of motion on Western thinking from Copernicus to Newton.

New Thinking in Europe

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- Renaissance 1300s-1600s
  - Da Vinci, Mona Lisa, 1503
  - Michelangelo, Vatican Palace, 1589-1700
- The printing press 1436
- Pope approves enslavement of n (1453) in Africa by the Portuguese
- Spanish Inquisition 1478, killed 32 thousand
- Columbus, mid-Atlantic route to the Americas,1492
- Pope:(1493) Doctrine of Discovery

*Rediscovery of the ancient works of the Greeks and Romans found in the captured library at Cordoba contributed to a revival in Europe of the arts called the Renaissance. Examples of renaissance art are *the Mona Lisa by Leonardo da Vinci, and *the Sistine Chapel murals by Michelangelo.

*The invention of the printing press made books widely available in many languages, and many people became literate.

*The Pope issue a bull (ruling) authorizing the king of Portugal to conquer and permanently enslave non-Christians in Africa

*The Pope approved the establishment of an Inquisition in Spain, controlled by King Ferdinand and Queen Isabella, to suppress heresy and to consolidate control by forcing the Jews and Muslims to convert to Christianity or leave the country. In 200 years, the Spanish Inquisition killed about 32,000 people.

*Ferdinand and Isabella fund Columbus' voyage to discover a shorter trade route to China. Instead, he found new lands and people that he called Indians whom he enslaved.

*Pope extends his ruling to include the rest of the world, divided between Spain and Portugal but recognizes claims of other Christian European countries. European Christians rush abroad to be the first to claim non-Christian land.

New Thinking in Europe

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- Reformation 1517- 1600
  - Lutherans – German, 1517
  - Henry VIII – England, 1535
  - Calvinists – French, 1560
- Calendar update commission sought ideas -1517

- Gregorian calendar adopted in Catholic Countries, 1582: Oct. 4, to Oct.15, 1582
- Great Britain and its colonies 1752: Sept. 2 to Sept 14

*Availability of printed bibles and heavy spending on the Vatican palace contributed to independent thinking and breakaway movements from the Catholic church.
*First the Lutherans in Germany, and then by *Henry VIII in England and *followers of John Calvin in France.
*The calendar that had been used from Roman times was slightly inaccurate and the errors had been accumulating for centuries. The Fifth Lateran Council passed a decree in 1517 calling for Pope Gregory to fix the problem. The council sought the opinions of astronomers on how the calendar should be changed. *The new calendar was adopted in catholic countries in 1582. When the new calendar took effect in Catholic countries, ten days were skipped and October 4 1582, was followed by October 15th. Century years were not leap years in the new calendar unless they were divisible by 400, not just 4.
*Protestant countries like England didn't want to follow the Pope's lead, even though it was a good idea. Great Britain and its colonies didn't adopt the Gregorian calendar until 1752. Events in Europe and the Americas between 1582 and 1752, like the Spanish Armada and the founding of Charlestown, had two different dates in Catholic and protestant countries.

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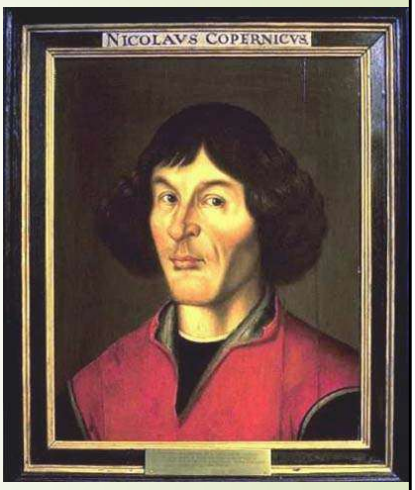
Copernicus: A New Explanation

- Polish (Mikolaj Kopernik) 1473-1543
- Studied astrology and medicine
- Influenced by *Disputations Against Divinatory Astrology (Pico)*
- Doctorate in church (canon) law
- Addressed the church council regarding the new calendar



*Copernicus was from Poland.
*He studied astrology and medicine in Italy and even painted a self-portrait.
*He read Ptolemy's book on planetary motion as part of his training in astrology. An important book in his education was *Disputations against Divinatory Astrology* that criticized astrology for having a weak foundation in astronomy. For example, Ptolemy's system couldn't explain the order of planets from the earth nor explain why Venus and Mercury were never seen opposite the sun.
*He got a Doctorate in church law and then did some administrative work for the church. His reputation as an astronomer was such that his opinion was sought by the Lateran Council on the new calendar.

Ptolemy's Geocentric Model

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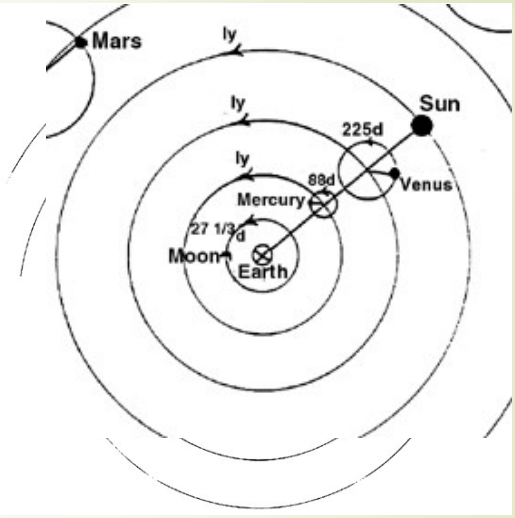
- Planet is on a small epicycle
- Epicycle's center revolves around the earth
- Mercury and Venus
- Mars, Jupiter, and Saturn
- Didn't explain:
  - Order of the planets
  - Size of their orbits
  - Changes in speed



*Recall that Ptolemy proposed a solution to Plato's problem that explained the apparent retrograde motion of the planets by the use of a combination of two circles for each planet, where the planet itself revolves on a small circle called an epicycle while *the center of the epicycle revolves around the earth

*There were some odd, unexplained behaviors in Ptolemy's system. The centers of the epicycles for Mercury and Venus were always aligned between the earth and sun and had different periods, while *the epicycles for Mars, Jupiter, and Saturn all had a period of one year but were not in line with the sun.

*His model didn't provide *an orderly sequence of planets from the earth, *the distance from the earth, *or apparent changes of speed.

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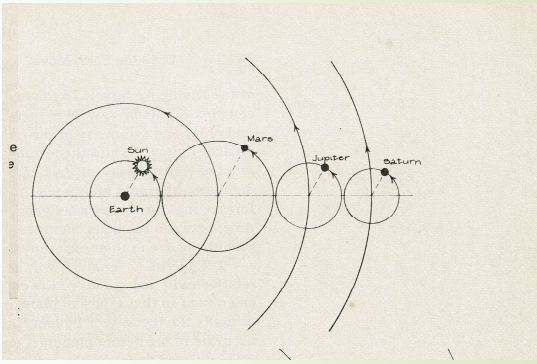
Point of View

- Ptolemy's model uses relative sizes
- Copernicus altered the orbit sizes to make the epicycles the same size as the sun's epicycle
- Change the point of view
- Correct order and distances



*Ptolemy's model gave the relative sizes of the circles but not the actual sizes.
*Copernicus adjusted the relative sizes of the circles and epicycles so that all the epicycles were the same size as the sun's orbit around the earth, and then *removed all the epicycles by placing the sun at the center.
*The sun-centered or **heliocentric** system was simpler and yielded an order of the planets where the periods of their orbits increased with distance from the sun and the distances to the planets could be measured.

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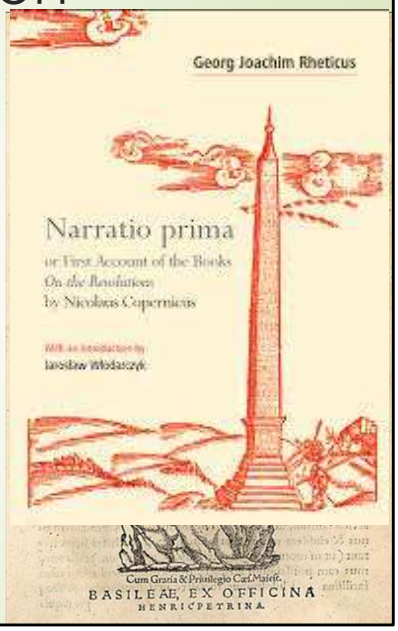
Copernicus: Publication

- Held off publishing for 36 years
- Narratio Prima 1541
- Unauthorized "letter to the reader"
- Published just before his death in 1543



*Copernicus was hesitant to publish his ideas and delayed publication for 36 years.
*First, he co-authored a book with Georg Rheticus titled *First Narration* that was a summary of his work. It was a type of trial balloon to see how his ideas would be received. He knew that it contrasted with the accepted teachings of the church that were based on Aristotle and Ptolemy.
*Copernicus and Rheticus turned the final manuscript over to a theologian named Andreas Osiander to manage the publication. Osiander added an unsigned letter to the reader which explained that the book made no pretense to the truth and was just an aid to calculation.
*The book was finally published just before Copernicus' death in 1543. It was up to those who came after him to deal with its consequences.

8

Inquisition and Giordano Bruno

- Giordano Bruno, 1548-1600
- Stars were like the sun with planets and people
- Discussed forbidden ideas
- Fled Naples Inquisition
- Taught in England, France, Germany, and Venice
- Arrested, tried, and executed, February 1600

*Giordano Bruno was a Dominican friar whose metaphysical view was dramatically changed by Copernicus.
*The idea that one's point of view was important led him to conclude that the stars were also suns with their own planets which also must have people and that space was infinite.
*He freely discussed the belief of the Arian sect which was banned by the church in 325 CE, whose position was that Jesus was not divine. *He was accused of heresy by the Inquisition and fled his native town in Naples which was controlled by Spain in 1576.
*He taught at several universities in Europe seeking one where freedom of thought was available. He ridiculed those who still believed in Aristotle and was unwelcome. In Germany, he was excommunicated by the local Lutheran church. In 1591, he accepted an invitation to return to Venice which was thought to be the most liberal of Italian states.
*In 1592, his Italian mentor in Venice denounced him to the Inquisition and he was transferred to Rome and put on trial for heresy. The trial lasted for seven years but he still refused to retract what he had written. Pope Clement VIII ordered his death, and he was gagged and burned alive in 1600. In 1889, a defiant statue was erected at the **Campo de' Fiori** in Rome facing the Vatican by Italians who wanted independence from the church.

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Vincenzo Galilei: 1520-1591

- Salon in Florence
- Played the Lute
- Pythagorean tuning
- Question authority
- Tuning assumptions
- Tensions of 4:1 required for an octave
- Oldest son was Galileo Galilei

*Giovanni de Bardi was a wealthy Florentine who established a salon for intellectual discussions on topics of mathematics, astronomy, and music which eventually led to the development of the opera. *One of the men he supported was a young lute player named Vincenzo Galilei (not him in the picture). Bardi paid for Vincenzo to take lessons in music theory where he learned the *Pythagorean method of tuning using ratios. Vincenzo later studied under another teacher who taught him to tune by ear using a sequence of notes that sounded right which seemed to work better.
*Vincenzo learned from this experience to question established assumptions.
*As shown in this woodcut from 1492, it was thought that Pythagoras could produce an octave using different size hammers, bells, water glasses, flutes, and string tensions.
*Because Vincenzo was familiar with tuning a lute by tightening the strings, he doubted the values shown in one of the panels.
*Vincenzo tested these values with strings and weights similar to the illustration and found that it took a tension of 4:1 to produce an octave, not 2:1.
*Vincenzo might have been assisted with this experiment by his oldest son, Galileo Galilei, whom he probably taught to question established thought and test it with experiments.

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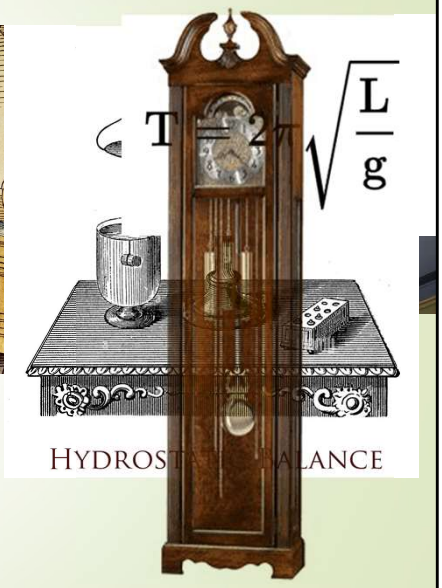
Galileo (1564-1642)

- 1583: pendulum
- 1586: Hydrostatic balance
- 1589: Professor of mathematics at Pisa
- Arabic/Hindu numbers
- Kitāb al-muḫtaṣar fī ḥisāb **al-ğabr** wa-l-muqābala
- Algebra



*As a young man of 19, Vincenzo's son, Galileo Galilei, observed that a chandelier swinging in the breeze in a church took the same time to swing back and forth regardless of how large the swing might be. [Demonstration]
*When he heard the famous story of how Archimedes tested the King's new gold crown to see if some of the gold had been stolen and replaced with lead by observing how much water it displaced compared to an equal weight of pure gold, he claimed that the displacement of water would have been too small to measure accurately and that the story was wrong. *He thought Archimedes probably used a special balance where an object on one side is submerged in water. This method is far more accurate at comparing densities, and Galileo proposed that this was how Archimedes actually made his determination.
*In 1589, he got a job as a professor of mathematics. *Italy had replaced the old Roman numerals with the Arabic and Hindu numbering system around 1200 CE. The Europeans learned about the Persian system of solving equations from a book written in 820 CE but not widely available in Europe until the library of Cordoba was captured in 1236 CE *titled *Kitāb al-muḫtaṣar fī ḥisāb **al-ğabr** wa-l-muqābala. The system became known by one of the words in its title, *algebra.
*Galileo determined that the period of a pendulum was proportional to the square root of its length. He made use of algebra with its equal sign to express how the period of a pendulum, T, was equal to the square root of the ratio of the length to the acceleration of gravity times 2 pi. The advantage of using an equation was that the period was equal to an

exact value, not just proportional. It was also easy to see what factors were not important such as the amplitude of its swing back and forth *which is why a pendulum clock keeps time well.

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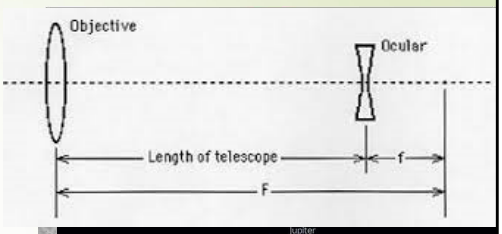
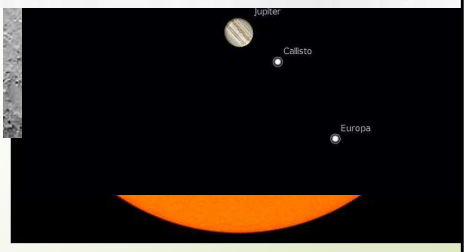
Galileo (1564-1642)

- 1610: Discoveries with a telescope
  - Moon is rough, not smooth
  - Sunspots
  - Moons of Jupiter
  - Phases of Venus





*The telescope was invented in Holland in 1608. It consisted of two glass lenses in a tube. Galileo obtained one and immediately began to make discoveries about the heavens that disagreed with Aristotle and the teachings of the church.
*Even though the moon and sun were thought to be heavenly bodies and therefore perfect, he saw that the surface of the moon was pockmarked with craters and that the *sun had irregular dark spots that moved.
*He discovered that Jupiter had four smaller moons that revolved around it rather than around the earth. He suggested that this demonstrated that smaller objects orbited larger ones and was an argument in favor of a sun-centered system.
His most conclusive discovery whas that Venus had phases like the moon that implied it circled the sun.

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Galileo's Trial

- 1615: Inquisition declares the Copernican view to be heretical
- A Dialog
- Book submitted for review
- 1632: Published in Florence
- 1633: Trial in Rome
  - Recants
  - House arrest for life

Dialog Concerning the Two Chief World Systems

*Galileo's publications, lectures, and private discussions about what he was learning with his telescope caused concern. In 1615, the inquisitors declared the Copernican system to be heresy. The Pope had been a supporter of Galileo and warned him to say that the Copernican system was hypothetical, not real.
*Galileo wrote a book in the form of a dialog, similar to the form used by the Greeks. There were three main characters, Salviati; representing Galileo, Sagredo; an intelligent layman, and Simplicio; an Aristotelean who lost the arguments.
*Galileo submitted incomplete drafts of the book to the Inquisition for its approval and told them that they wouldn't understand it if they didn't know mathematics. *He published the book in Florence in 1632 and when the inquisitors saw that the official church position was represented by Simplicio they ordered him to come to Rome and stand trial.
*The Pope himself attended the trial and Galileo was convinced to take a deal. *He withdrew his claim that the sun-centered system was correct, *and his sentence was commuted from death to life under house arrest.

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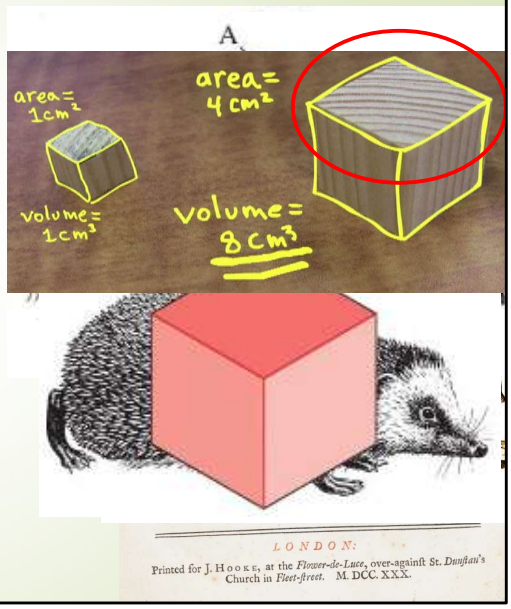
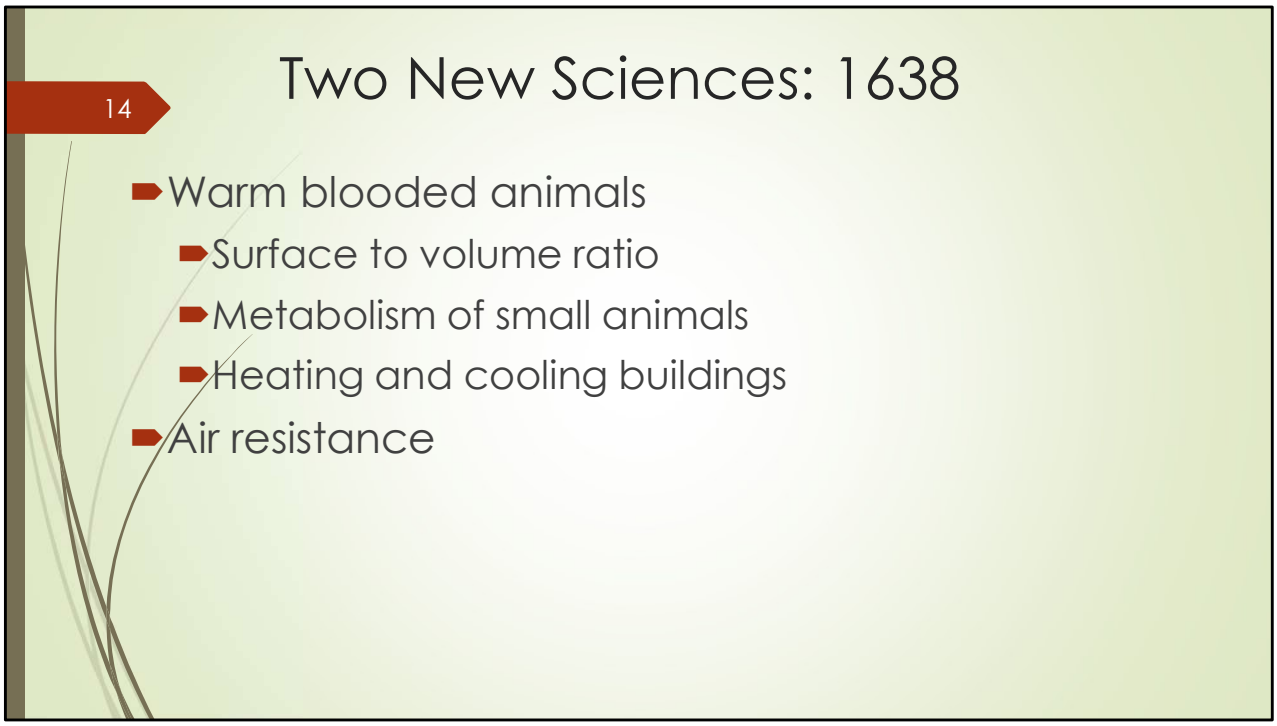
Two New Sciences: 1638

- 1638, Second book; Materials and Acceleration of Gravity
- Strength vs. Weight



*While under house arrest, Galileo continued to work. In 1638, he published *Mathematical Discourses Concerning Two New Sciences*. The first new science relates to the strength of materials. He recognized that, unlike similar triangles and circles, *real objects don't maintain the same ratios between strength and weight when they change size. Specifically, the strength of an object like a rope or bone is proportional to its cross-sectional area but its weight increases with its volume. *In this illustration, compare a cube that is one unit long on a side with a cube that is twice as long on each side. The smaller cube has an area to volume ratio of 1:1. The larger cube would have a cross sectional area of 4 and a volume of 8 for a ratio of 4:8 or 1:2. *Consequently, larger animals need proportionally thicker bones and are stockier than their smaller cousins. *Galileo made the case that mythical giants wouldn't exist as simply larger people.

*Size also affects heat production and loss. *The heat produced by an animal is proportional to its volume and the rate at which it can transfer that heat out of its body depends on its surface area. Small animals have a high surface area to volume ratio and have to eat a lot just to stay warm. As size increases the ratio of surface area to volume goes down and larger animals struggle to stay cool. *The same is true for buildings. The interior spaces in large buildings are suppled with 55 degree air year-round to keep them cool, even in winter.



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*Galileo also proposed that the presence of air is the cause of differences in the rate at which objects fall. He observed that the same sheet of paper would fall faster if it were

crumpled up. He predicted that in the absence of air all objects would fall at the same rate. *

15

Acceleration of Gravity

- Air resistance
- Gravity and acceleration
  - Change in speed is **acceleration** (both increase and decrease)
  - Speed is proportional to time
  - Distance is proportional to time^2

*Aristotle observed that heavy objects fall faster than lighter objects, e.g. a piece of paper vs. a book. Galileo observed that shape made a difference, e.g. a crumpled piece of paper fell almost as fast as a book. [Demonstration] He recognized that air slowed the fall of large, lightweight objects and proposed that in the absence of air, all objects would fall at the same rate. *

*The second science had to do with acceleration caused by gravity and the effect of gravity on projectiles like cannon balls. *A change in speed is one type of **acceleration**. Galileo recognized that falling objects accelerate but it happens too quickly to measure. He slowed things down by rolling a ball down a ramp rather than dropping it. *

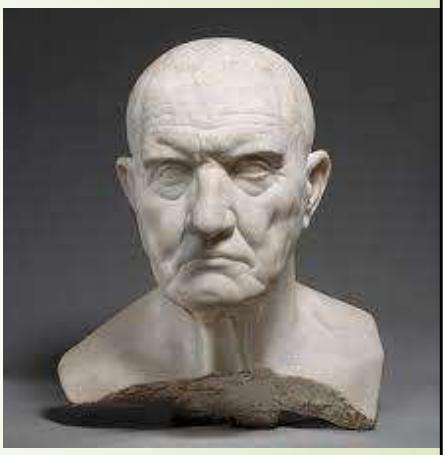
*He found that the speed was directly proportional to the elapsed time and *that the distance was proportional to the time squared.

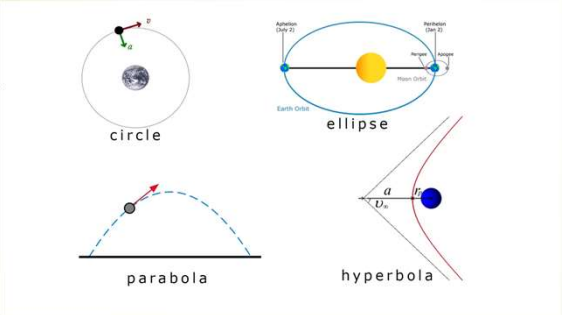
Galileo went blind and died four years later in 1642 at the age of 78.

16

A bit more math: Conic Sections

- Menaechmus 350 BCE





*Menaechmus was a contemporary of Plato. He discovered that a cone could be sliced into four different shapes:
*If it is sliced parallel to the base, a circle is formed
If it is sliced at an angle that does not pass through the base, the shape is an ellipse, aka oval
If it is sliced at an angle that does pass through the base, the shape is a parabola, and if
It is sliced perpendicular to the base, the shape is a hyperbola

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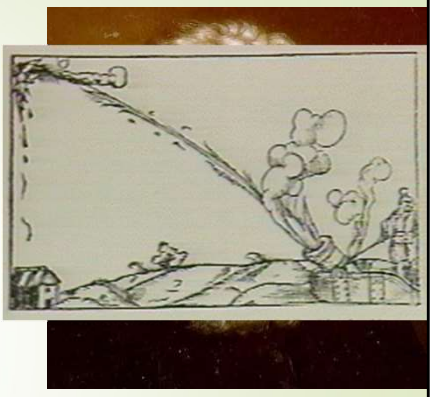
Cannon Balls

- Aristotle, Impetus; straight line, then drops down
- Galileo, two separate motions
  - Constant horizontal speed
  - Accelerating vertical speed
  - Path is a parabola

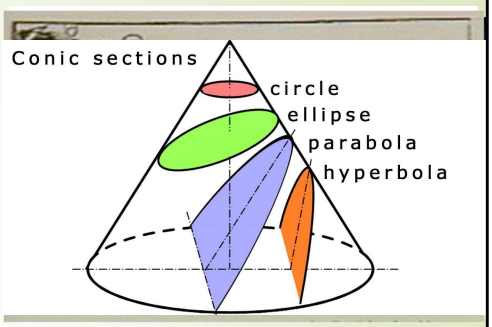


*Aristotle thought that an object could be given *impetus* to make it move against its natural tendency and when the impetus was gone, it would rise or fall to its appropriate level.
*Galileo recognized that the motion of a projectile is a combination of two motions; *a constant horizontal speed, and a changing vertical speed. *The resultant path is a parabola.

18

Air Friction

- Laws of motion can be obscured by other factors like friction
- Most of the air is within 10 miles of the surface
- Atmosphere extends to about 300 miles
- Air friction slows projectiles and shortens their parabolic paths
- Without air friction, path can be any one of the conic section shapes



*Some laws of nature are obscured by other factors. Galileo realized that the natural law of motion was obscured by air friction.
*The earth has a layer of air. Most of the air is within ten miles of the surface but some of it can be detected as much as 300 miles up.
*Air friction slows moving objects so their path through the air is not a perfect parabola and the downward part is steeper. *Golfers take this effect into account when choosing how to stop the ball on the green and *the actual path of an ancient cannon ball does resemble Aristotle's idea.
*Without air friction, the mathematics predicts that the path of a projectile that combines linear speed and acceleration can be any of the conic section shapes; circle, ellipse, parabola, or hyperbola

Johannes Kepler 1609

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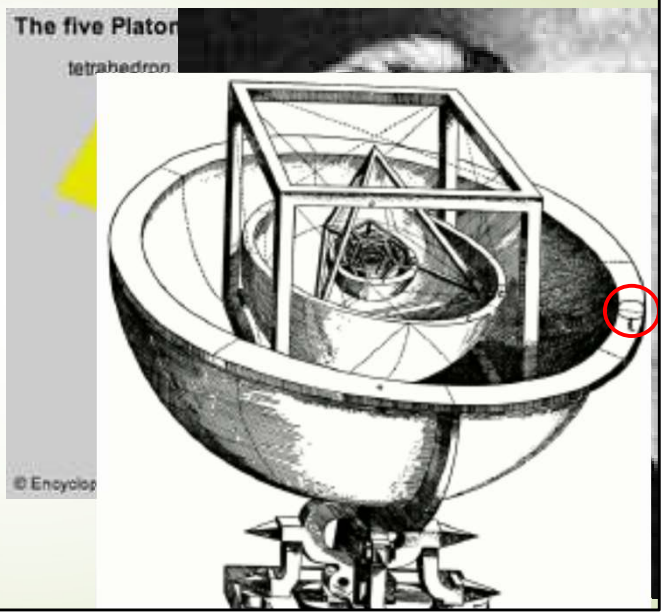
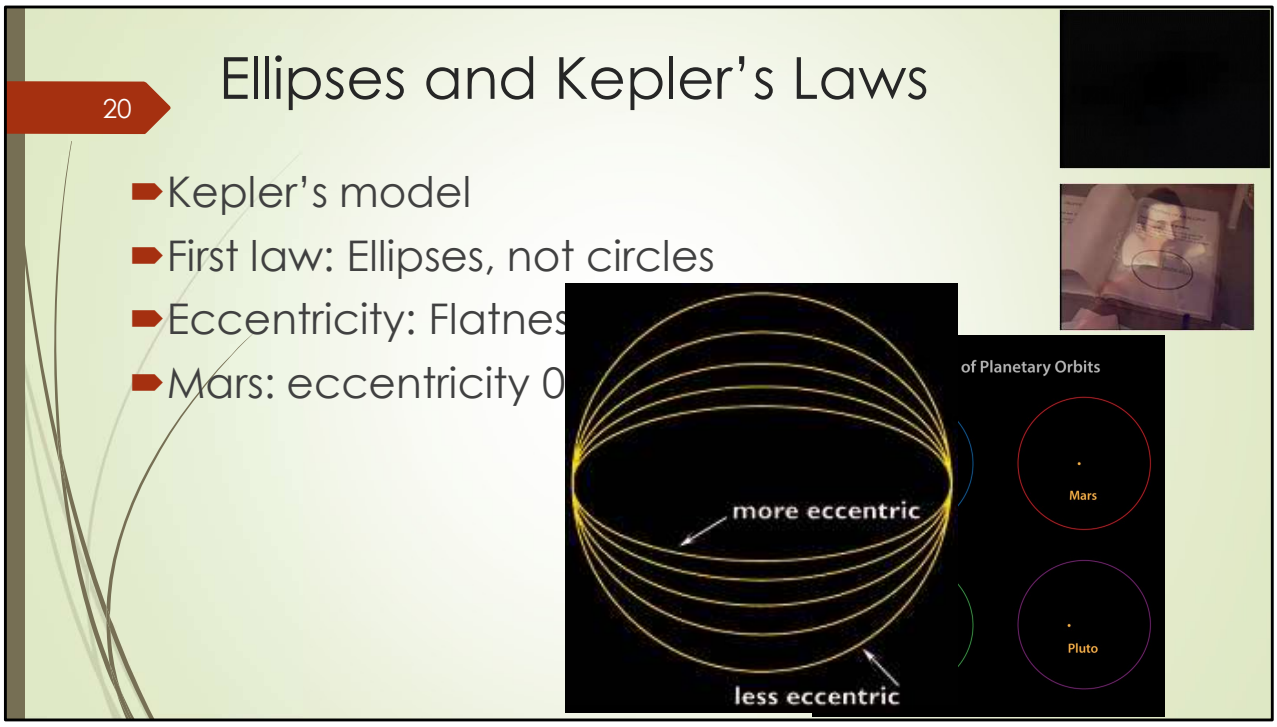
- Johannes Kepler
- Sun-centered
- Perfect solids separate spheres
- Small epicycles
- Too much error



*Johannes Kepler was a contemporary of Galileo who divided his time between Catholic Austria and Protestant Germany. He held the post of Imperial Mathematician in Austria, but he was convinced that Copernicus was right about the *sun being the center. *He also believed that Plato's perfect solids represented Christian ideals. When he discovered an apparent relationship between the perfect shapes and the orbits of Jupiter and Saturn, it inspired him to create a sophisticated model of the solar system.*
This close relationship turned out to be a coincidence and he still had to use *small epicycles to account for apparent variations in the speed of the planets. *Predictions of planet positions could be off by an apparent moon diameter—too much to be dismissed as observation error.



*Kepler was not satisfied with his model. After two thousand years, he decided that Plato's approach was wrong and that no one could explain the apparent motion of the planets using circles and perfect shapes.
He followed Aristotle's approach and discarded a theory that didn't fit the observations and looked for another answer. He found it in the ellipse*
Kepler discovered three laws of nature that accurately describe the orbital motion of planets. The first is that the shape of the orbits are ellipses, not circles.
The second is that the speed of motion is inversely proportional to the distance from the sun.
*After ten more years of examining the data, he discovered that the square of the planet's period is proportional the cube of the orbit's semimajor axis which accurately predicted the orbital periods and distances.
*Kepler avoided prosecution by the inquisition by moving to protestant Germany, but his family was still affected by religious persecution. His mother was accused of being a witch at a time when hundreds of people were executed each year for witchcraft. Kepler dropped what he was doing to defend her at her trial. It took several years for him to clear her of the charge but not until she had spent 14 months chained to the floor in a cell.

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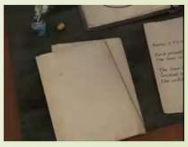
Ellipses and Kepler's Laws

- Kepler's model
- First law: Ellipses, not circles
- Second law: Equal areas measured from the sun
- Third Law: Average radius cubed is proportional to the period squared
- Witchcraft



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Scientific Method: Francis Bacon

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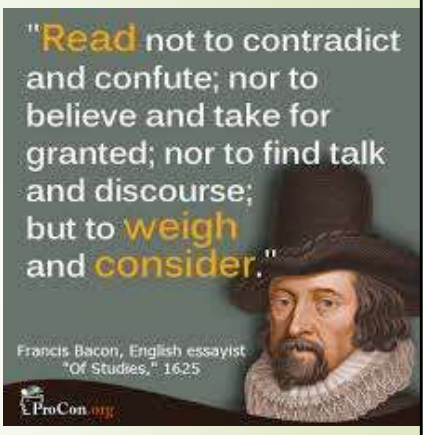
Francis Bacon, 1600 A.D.

1. Observation and data collection
2. Patterns and correlations
3. Hypothesis, predictions and testing
4. Review by skeptics
5. Rejection, revisions, tentative acceptance

Age of Reason



Galileo and Kepler were pioneers in a new way of seeking knowledge that was based on observation

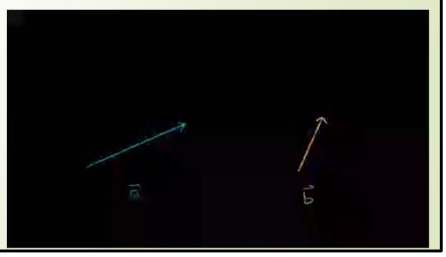
*Sir Francis Bacon, formalized a new method of seeking knowledge which we call *the scientific method*. It has five steps. (read bullet points)

The fourth and fifth steps are especially important. A skeptic is different from a cynic in that a skeptic can be convinced by a good argument. Skeptics play a vital role in science. The last step involves the ability to admit when one is wrong and then make revisions like Kepler did when he rejected circles and found ellipses. The scientific method was a critical component of the Age of Reason.

23

Adding Forces Using Vectors

- Finding the total (net) force
- Vectors: arrows that depict direction and quantity
- Arrow drawn to scale
- Vectors can be added head to tail

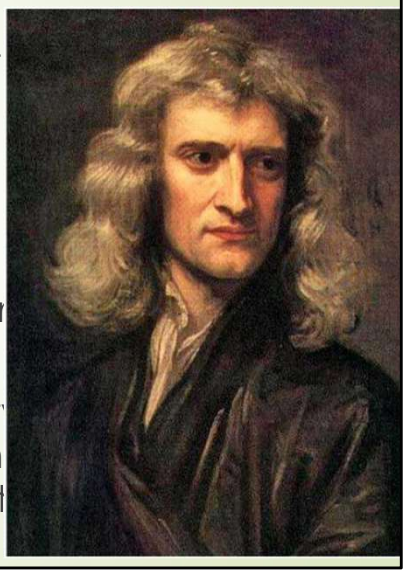


*Forces can be added together, even if they are not in the same direction. There is a simple way to do this graphically with arrows called ***vectors**. A vector can represent anything that has both a magnitude (size) and direction, like a force. *The magnitude is represented by the length of the arrow drawn to scale. *Vectors can be added using a simple graphical method.*

Isaac Newton 1643-1727

24

- One of the great geniuses of science
- All forces come in pairs, equal in strengt
  direction
- If the sum of forces acting on an object
  constant speed and direction
- If the sum of forces acting on an object
  accelerate at a rate inversely proportio
  direction of the force
- The force of gravitational attraction bet
  proportional to both their masses and in
  to the square of the distance between t



*The year after Galileo died in Florence, Isaac Newton was born in England as if the torch of enlightened science had been passed to the next genius. Newton discovered several natural laws, four of which involve force, mass, acceleration, and gravity. His work, combined with the scientific method answered the age-old questions about the planets, comets, and tides and ushered in the age of reason.
Here is a simplified statement of his four laws of motion. We will examine each of them individually in more detail. (Read bullet points)

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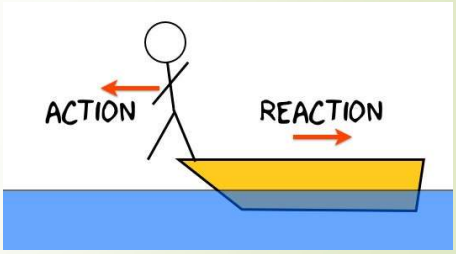
Forces Come in Opposite Pairs

- Newtons third law: All forces come in pairs, equal in strength but opposite in direction

For every action there is an equal and opposite reaction



*I prefer to start with the law that is normally called Newton's Third Law. His statement is shown in the adjacent text box. *

*You've probably noticed that when you step out of a boat the force that you use to push you toward the dock is paired with a force that pushes the boat away from the dock. Here are some other examples: **

Constant Speed and Direction

26

- Newton's First Law: If the sum of forces acting on an object is zero it has a constant speed and direction
- Adding forces

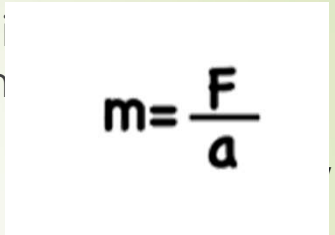
every object will remain at rest or in uniform motion in a straight line unless compelled to change its state by the action of an external force.

*Newton's first Law says that if the total force on an object is zero, it will have a constant speed and direction. *His statement is shown in the adjacent text box.
* Understanding my paraphrasing of this law requires that we define total force which implies that we can add forces to find a total.

Accelerated Motion

27

- Second Law: If the sum of the forces i not zero, the object will accelerate in the direction of the force at a rate that is inversely proportional to its mass.
- The mass of an object is the ratio of the total force and the resulting acceleration
- Inertial Mass: resistance to acceleration



magnitude and direction to the force imposed on it

*His second law is a bit wordier (read bullet). *His version is shown at the right.
*It is usually stated as a formula like this. Notice a small arrow is placed above the a and F to indicate they are vectors and this example uses the term net instead of total.
*This law introduces the concept of mass. *The formula can be rearranged to define mass as the ratio of the net force to the acceleration it causes. Mass doesn't have direction so there is no arrow above it. *This definition of mass is called *Inertial Mass.*

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Mass vs. Weight

- Weight is the force of gravity between an object and the earth
- The force we feel is the reaction force needed to counteract the weight
- Same acceleration
- Inertial mass is an object's resistance to acceleration

$$\vec{a} = \frac{\vec{F}_{\text{net}}}{m}$$

*Weight is the force of gravitational attraction between an object and the earth. Recall that forces always come in pairs. *The force we usually call weight is the force we exert on an object to counteract its weight.
*Recall that Galileo predicted that all objects would fall at the same rate of acceleration in the absence of air friction. *Newton's second law explains this phenomena. The acceleration is the ratio of an object's weight to its mass. Since its weight is due to its mass, this ratio is the same for all objects near the same planet, so they all fall at the same rate of acceleration.
*If the barbell and person are allowed to fall together and shielded from air friction, the person would not have to support the barbell. It would seem to be weightless to the person although the earth is still exerting a force on it.
*Inertial mass is the resistance to acceleration and does not depend on the gravity from a planet. The falling barbell would still be just as difficult to wiggle back and forth. (demonstration with 1L water bottle)

29

International Measurement System

- British Imperial System (feet, seconds, gallons, slugs, pounds)
- Le Système International d'Unités, SI
  - Distance: Meters
  - Time: Seconds
  - Volume: Liter
  - Mass: Kilograms
  - Force: Newtons

*Recall that protestant countries like England continued to use the old Julian calendar for 164 years after the catholic countries switched to the Gregorian calendar even though the new calendar was obviously better. We have a similar situation today where the United States, Liberia, and Myanmar continue to use the old British Imperial system of measurement units even though a better one has been adopted by everyone else, including Great Britain.

*In *Le Système International d'Unités,* abbreviated *SI,* uses the following units of measure:

*Distance is meters (about the length of a full-size guitar)

*Time is in seconds (the ancient Babylonians are still laughing)

*Volume is in liters, 1 liter of soda

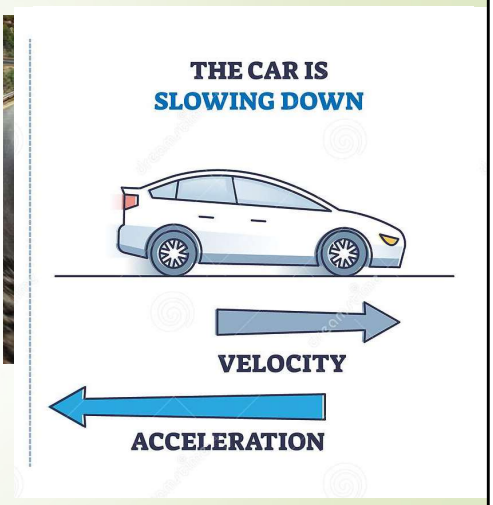
*Mass is in kilograms, 1 liter of water also has 1 kg of inertial mass

*Force is measured in newtons, a medium size apple weighs about 1 newton (more on that later)

30

Acceleration

- Change in speed or direction
- Can be represented by a vector
- Increase in speed
- Decrease in speed (negative acceleration)
- Change in direction, even if the speed doesn't change
- Inertia



*Newton used the term *acceleration* in a very specific way. *Acceleration has both magnitude and direction and *can be represented by a vector. There are three types of acceleration that are all called **acceleration**. *An increase in speed; *a decrease in speed (negative acceleration), *or a change in direction.
*This law is sometimes called the law of inertia. It means that an object will maintain its present speed and direction unless a net force acts upon it.

Newton (1665 A.D)

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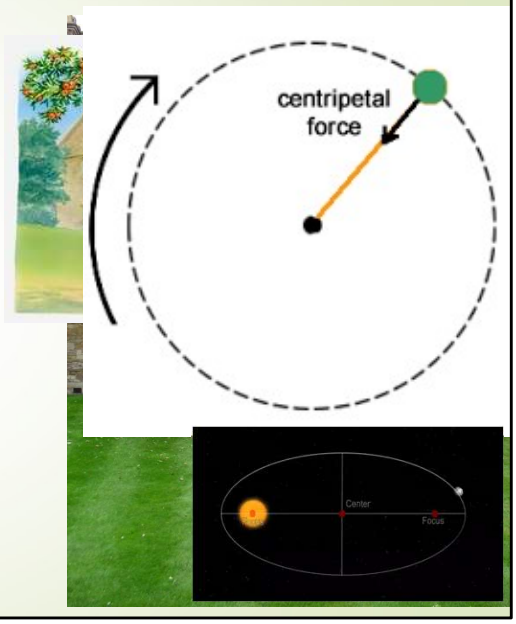
- Circular motion is caused by a force toward the center
- Force of gravity is proportional to square of the distance between objects
- Explained Kepler's laws



Newton didn't *discover* gravity. Everyone knew gravity existed. To understand what Newton discovered, the event needs to be considered with a knowledge of Newton's laws of motion.

*He knew that circular motion was an example of acceleration because the object was not moving in a straight line and that there must be a net force on the object to cause this. The force that causes circular motion is toward the center of the circle. *The athlete exerts a force on the ball toward the center and the ball exerts a reaction force on the athlete away from the center.

*He knew there must be an unbalanced force on the moon toward the center of the earth because it was circling the earth. He noticed an apple falling from a tree and wondered if the same force (gravity) that pulls the apple toward the center of the earth could extend out through space to the moon and cause its circular motion. He applied his mathematical skills to the problem and concluded that it was. *If you go to Cambridge, you can find a direct descendent of the apple tree that inspired Newton. *Newton concluded that the force of gravity spreads out and weakens with the square of the distance which also accounted for Kepler's second law that said planets move slower when further from the sun.

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Law of Gravity

- Law of Gravity: The gravitational force between two objects is proportional to both of their masses and inversely proportional to the square of the distance between their centers
- F is the strength of the force of attraction between the two masses
- G is a very small number
- m is a **gravitational mass**

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

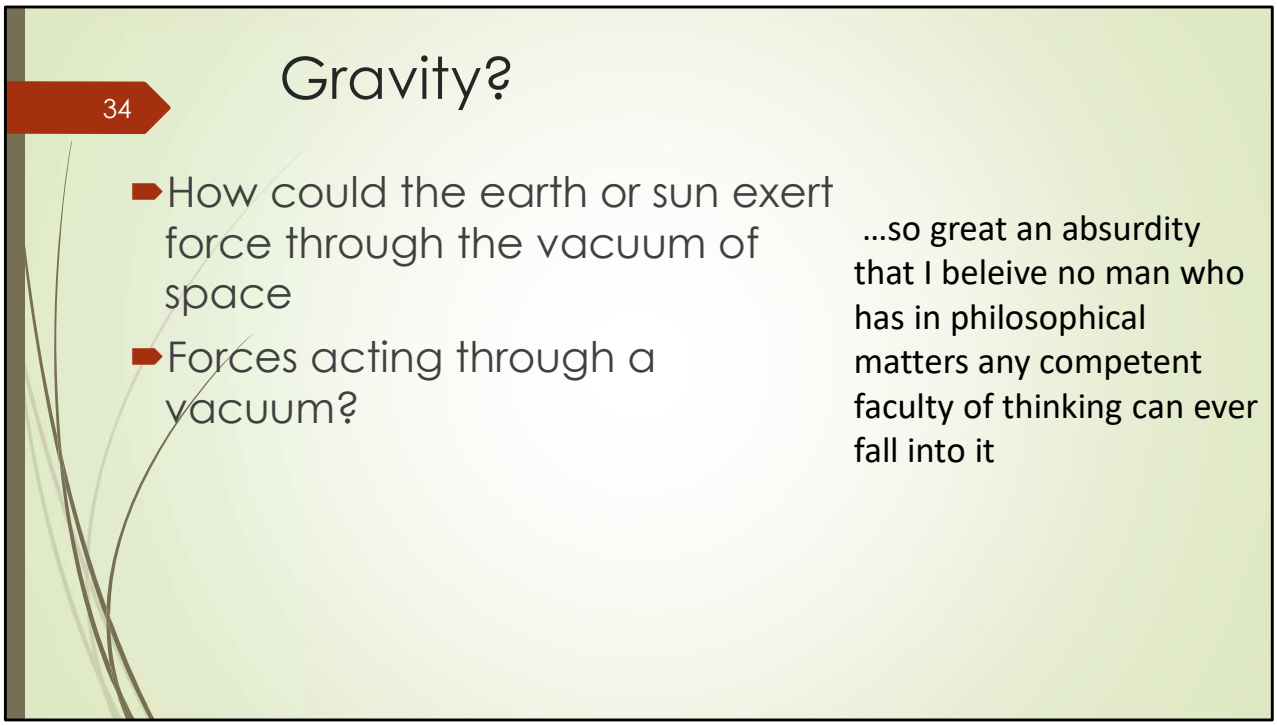
*Newton's law of gravity can be stated in words, or *by a formula.
*F stands for the strength of either of the pair of forces due to gravity that act on the two masses
*The value of G is very small, so the gravitational force is only noticeable if at least one of the masses is very large like the mass of a planet. The lowercase r is the distance between the centers of the two masses.
*This type of mass is called the gravitational mass.

33

Newton: Orbital Motion

- Newton predicts earth satellites
- Rockets rise above the atmosphere
- Accelerate to 17,500 mph
- Takeoff mass to payload ratio for Spac
- Cap re fallin toge

Newton even predicted the behavior of satellites 270 years before Sputnik
Cannon in Newton's day had a range of less than a mile and there weren't any mountains around that he could use. Since 1957, rockets have provided a means to achieve orbital speeds and altitudes. Notice in this video that shortly after the rocket has gained altitude, it changes direction to begin its circular orbit.
*The space craft must accelerate to a speed of 17,500 mph for the curve of its fall to match the curve of the earth.
*To accelerate a kilogram of mass to this speed, it takes 29 kilograms of rocket and fuel.
*Because the spacecraft and everything in it is falling around the earth with the same acceleration, things inside seem weightless.



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*To accelerate a kilogram of mass to this speed, it takes 29 kilograms of rocket and fuel.
*Because the spacecraft and everything in it is falling around the earth with the same acceleration, things inside seem weightless.
*Newton's theory of gravitational attraction described the motion of the planets and comets but it was based on the assumption that gravity could act through the void of space which seemed absurd.

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Summary

- Copernicus 1543: Sun-centered motion
- Galileo 1610: Telescope, supported Copernicus, Friction masks nature of motion, Gravity has constant acceleration
- Kepler 1609: Planets' orbits are ellipses, 3 laws
- Bacon 1600: Scientific method
- Vectors: quantity with direction, can be added
- Newton1660: Three laws of motion, Force of gravity
- Gravity can act through a vacuum

36

What experiences and insights can you share with us?

References

- Spanish inquisition: Link
- Papal bulls of 1452, 1455, and 1493: Link
- Copernicus: Link
- Spanish inquisition: Link
- Vincenzo Galilei: Link, Link
- Galileo: Link, Link
- Newton letter: Link
- Halley: Link

38

Tides

- Equal but opposite forces between the earth and moon
- Earth is 81 times more massive so it would accelerate much less
- The moon's attraction is greater on the side the moon and less on the farther side
- The difference causes tides
- Tidal force locks the orientation of the the earth
- No "Dark Side of the Moon"

*Newton's third law predicted that the earth's gravitational pull on the moon would have a corresponding equal pull on the earth by the moon.
* Since the earth is 81 times more massive, it will accelerate less. The two bodies orbit a point that is between them but which is 81 times closer to the center of the earth which is still inside the earth, just not at its center.
*Newton's law of gravity states that the force of gravity drops off with the square of the distance so the attraction of the moon on the ocean nearest the moon is greater than that on the earth and even less than the attraction on the ocean on the far side. *This difference is the cause of tides. *
*Tides can exist in the rocks as well and the earth produces a tide in the moon. This flexing of the moon slowed it down over time until its rate of rotation matched its revolution. The moon no longer rotates relative to the earth, so the same side always faces the earth. *
*We don't see the far side but the sun does shine on it. There is no "dark side" of the moon.

39

Comets, Asteroids, and Meteors

- Aristotle: Vapors from the earth that ignite
- Edmund Halley: Highly eccentric orbits, 75-year period
- Comets: icy gravel, reflected light
- Comet tails and variable orbits
- Asteroid: solid rock or metal

*Recall that Aristotle thought that comets were vapors from the earth that ignite in the upper atmosphere and were similar to northern lights. Astronomers like Tycho Brahe observed that sightings from different angles placed them beyond the moon.
*Edmund Halley noticed there had been sightings of a bright comet at regular intervals of about 75 years. *He proposed that it was the same object that had a very eccentric orbit and not in the same plane as the planets. The time between sightings wasn't as regular as it should be according to Kepler's law so he sought Newton's advice and help with the mathematics and an explanation of how gravity from the large planets might account for this behavior. He predicted that the comet would return in 1758. When it did, it was named for him.
*We now know that comets are like large icy snowballs filled with gravel. When they are close to the sun, the ice vaporizes creating a cloud of particles that reflect the sun's light making a tail. *The vaporizing ice on the sunward side of the comet can exert a reaction force that would change the comet's orbit. *The force of sunlight pushes the particles in the tail away from the sun, even when it is traveling away from the sun.
*Asteroids are made of rock or metal and don't show a tail like a comet.

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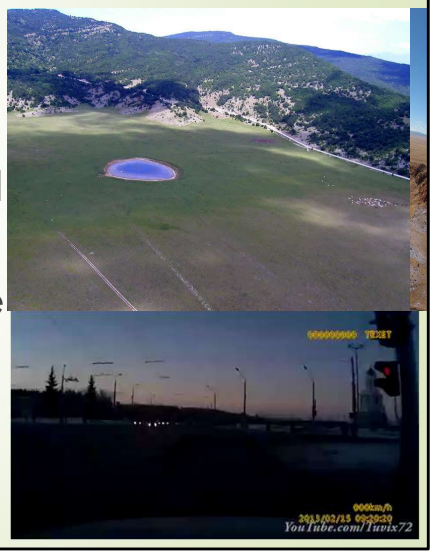
Comets, Asteroids, and Meteors

- Meteors: asteroids, comets, or comet fragments in the atmosphere
- Meteor showers: fragments of old comets
- Meteorites: pieces that reach the ground
- Meteor craters:



When an asteroid or comet encounter earth's atmosphere they heat up from air friction a create a luminous trail or even explode. They are called meteors.
*If the ice in a comet is completely vaporized, it becomes a cloud of small rocks each of which can make a visible trail. If they collide with the earth's atmosphere, we have a meteor shower that is predictable from the path of the original comet.
*If the asteroid or comet is large enough, some of it might reach the ground and create an impact crater like this one in Arizona or this one near Rome that is thought to be the result of a meteor that inspired Constantine's successful conquest of Rome.