
A tour along the road to modern science…

What are the “hallmarks” of science?
What is the scientific method?
What is a scientific paradigm shift?

Here, we use historical perspective to learn that science is an imperfect human endeavor, and to some degree, is an art form founded upon philosophical principles that permeate our culture and society.

For the most part, science is a painful step-by-step process, marked by creative thought, and small incremental “progress”. Occasionally, a “revolution” occurs, where progress takes a huge leap accompanied by a profound change in our understanding (paradigm shifts).

Science and its history teach us that we can never know the actual “truth” or have the complete and total correct theory. We can only continue to improve on our understanding of nature and the universe.

The Power of the Mind…

Modern Science starts with the Greeks

It was all in their minds… the world could be understand through reason alone. Plato and his student Aristotle believed that the universe beyond Earth was perfect, beautiful, and immutable.

Circle – the most prefect form

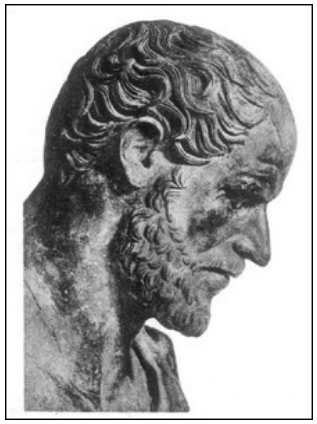
Sphere – the extension of the Circle

Aristotle's model was sophisticated for its time, based upon circles and spheres…

This "model" reigned supreme for 2000+ years- nobody questioned it because they didn't question the notion that reasoning alone *based upon the principles of beauty and perfection* could elucidate the nature of the universe.

Star trails – 6 hour exposure

Aristotle and his Model of the Universe ~350 BC

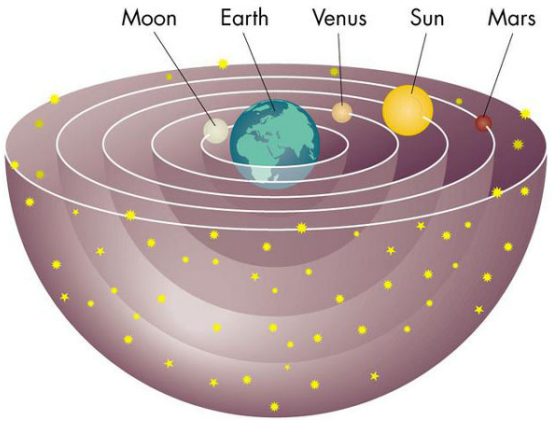


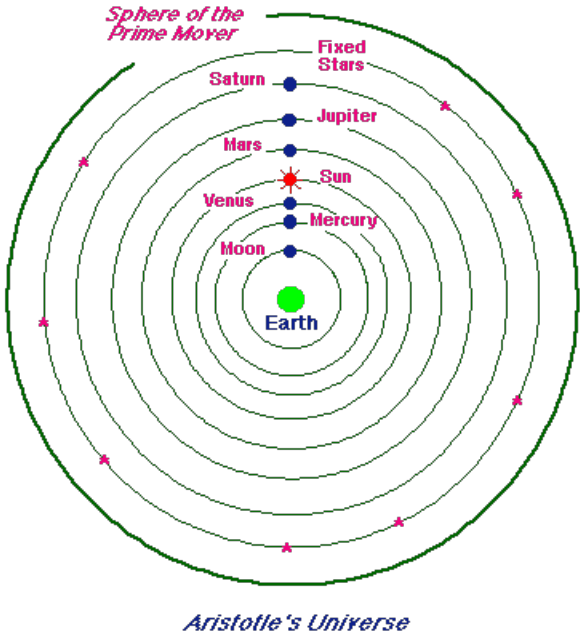
- Earth is at the center and nonmoving.
- Planets locked onto spheres that rotate.
- Stars locked onto most outer sphere- the <u>celestial sphere</u>.

All motions circular- constant speeds.
Everything beyond earth is perfect.
Nothing ever changes.

Aristotle argued there is no other life in the universe beyond earth, but other scholars believed there could be. Aristotle won all debates and his views were adopted for the scientific model that lasted centuries.

Geocentric Model



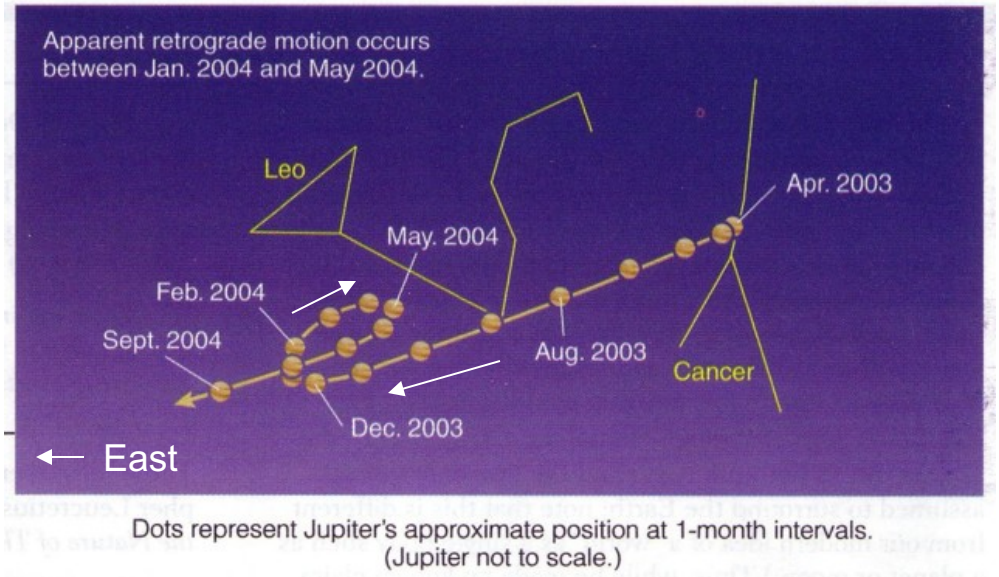


Ptolemy and his Fine Tuning of Aristotle ~ 150 AD

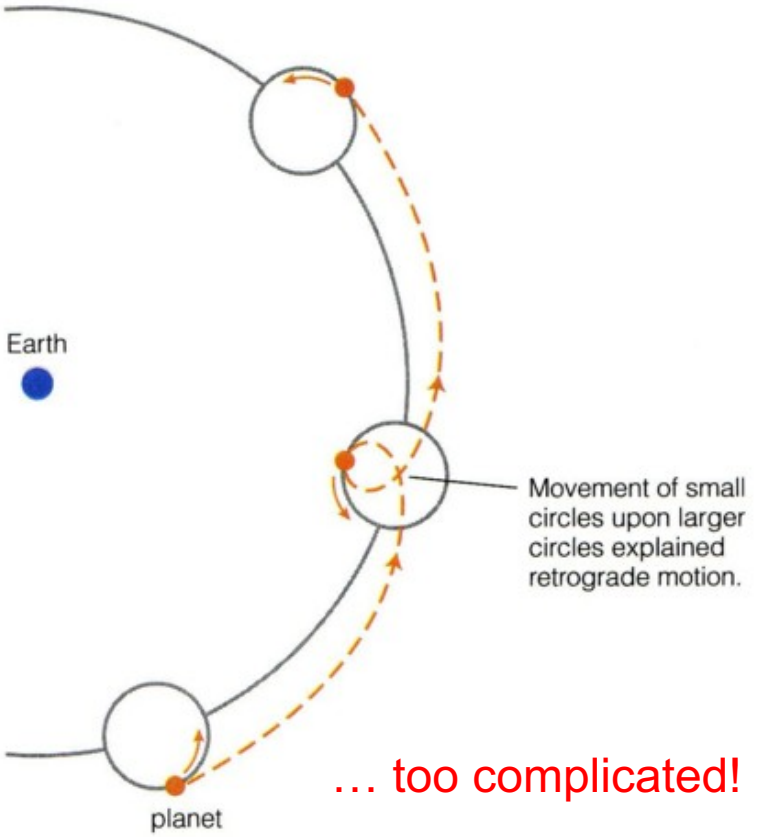
Apparent motion of planets is sometimes "backwards" - called Retrograde Motion – westward motion.

Aristotle strikes again!

Ptolemy explained this with smaller circular motion, also moving at constant speed; the combined speeds of the circles are tuned to the observed periods of retrograde motion



Dots represent Jupiter's approximate position at 1-month intervals. (Jupiter not to scale.)



… too complicated!

Link to see Video Demonstration: 3:57 http://youtu.be/GevV1yvMJbc

Copernicus and his Model of the Universe ~ 1500 AD

Sun at the center (heliocentric) with a rotating Earth!

showed it was a *simpler model* that explained the motions and behaviors of the planets (including retrograde motion)

Aristotle strikes again!

Still, used circles for orbits and this still required *fine tuning*…

Copernicus risked his life to publish this book, for the Vatican had adopted Aristotle's model – it was a capital crime to express ideas counter to their doctrine.

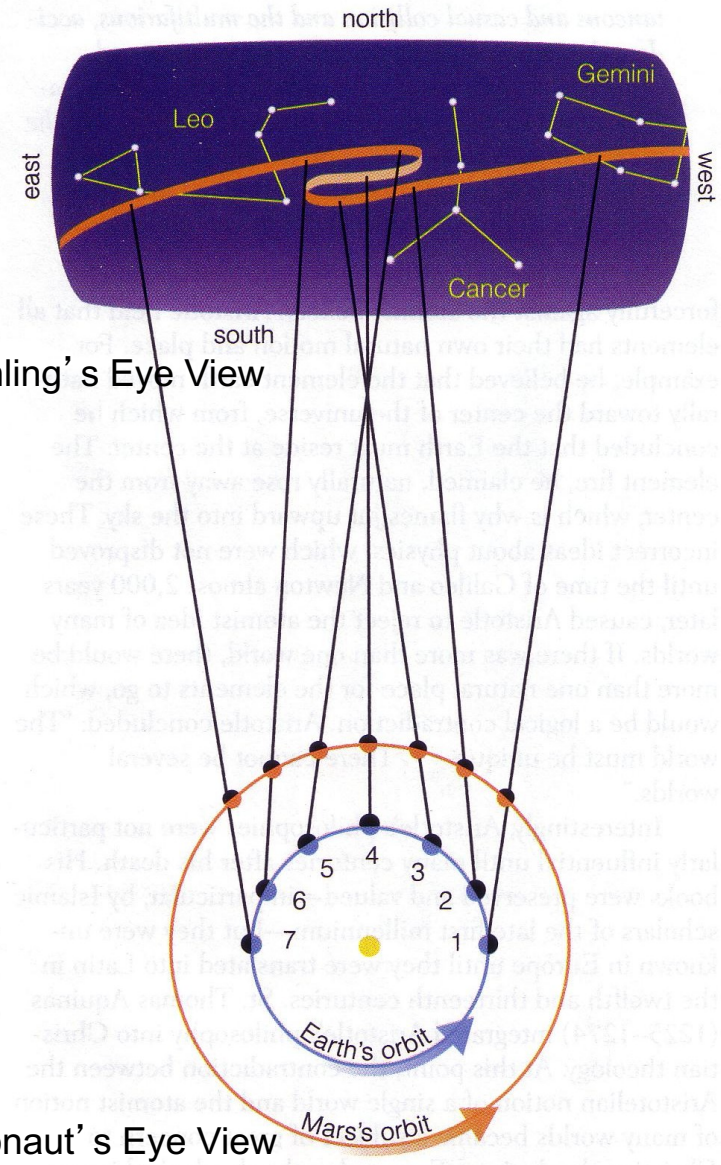

NICOLAI COPERNICI

net, in quo terram cum orbe lunari tanquam epicyclo contineri diximus. Quinto loco Venus nono mense reducitur. Sextum deniq; locum Mercurius tenet, octuaginta dierum spacio circu currens. In medio uero omnium residet Sol. Quis enim in hoc

I. Stellarum fixarum sphæra immobilis.
II. Saturnus anno. XXX. reuoluitur.
III. Iouis. XII. annorum reuolutio.
IIII. Martis bima reuolutio.
V. Telluris
terra
cum orbe lunari
VI. Veneris nouem mensibus.
VII. Mercurius octuaginta
Sol.

pulcherimo templo lampadem hanc in alio uel meliori loco po neret, quàm unde totum simul possit illuminare. Siquidem non inepte quidam lucernam mundi, alij mentem, alij rectorem uocant. Trimegistus uisibilem Deum, Sophoclis Electra intuentē omnia. Ita profecto tanquam in solio re gali Sol residens circum agentem gubernat Astrorum familiam. Tellus quoq; minime fraudatur lunari ministerio, sed ut Aristoteles de animalibus ait, maximā Luna cū terra cognationē habet. Concipit interea à Sole terra, & impregnatur annuo partu. Inuenimus igitur sub hac

Copernicus and his Model of the Universe ~ 1500 AD



Retrograde Motion explained…

In a heliocentric model, the RGM is simply an *apparent motion*…

EXAMPLE: apparent backward motion of the car next to you when you go around a long curve on the inside lane and pass the other car.

During certain alignments, Earth (on the inside lane) "passes" Mars (on the outside lane) and in relation to the background stars (which are so far away the *appear* to not move) Mars appears to "slide backwards" on the sky.

Projected onto the sky, we have RGM!

Link to see Video Demonstration 1:49
http://youtu.be/72FrZz_zJFU

The complicated made more simple…

Part I Summary: Copernicus Stirred a Scientific Revolution

To **Ptolemy**, it became painfully obvious that **Aristotle's** constant motion circle thing wasn't working so well to explain motions of planets as seen on the sky...

After much study, **Ptolemy** added circles on circles on circles to Aristotle's model… modern science was being born… observations were driving the models to complicated extremes and something had to give.

After all, a highly complicated universe is not consistent with **Aristotle's premise of beauty, symmetry, and simplicity**- so which view do you chose to believe?

Copernicus was a game changer… he proposed a radically different universe with a simple and symmetric explanation for the retrograde motion, but he could not explain planetary motion any more *accurately* than Ptolemy because (in reality) planets do not move at constant speeds in circular orbits!.

The change from the geocentric model to a heliocentric model is an example of a **paradigm shift**. Our picture of the universe is completely different than it was.

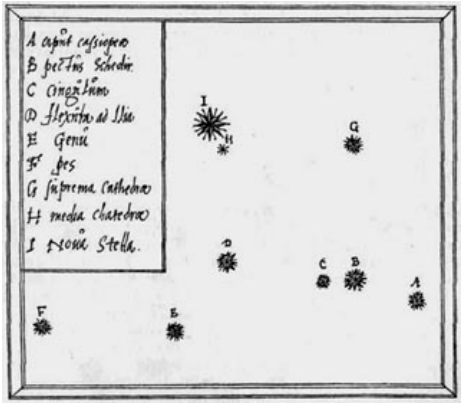
1. Humanity is no longer the center of the universe! *Oh, the implications!*
2. The notion that rational thought alone could unlock nature was dying quickly- but the notion of simplicity and beauty still survives to this day.

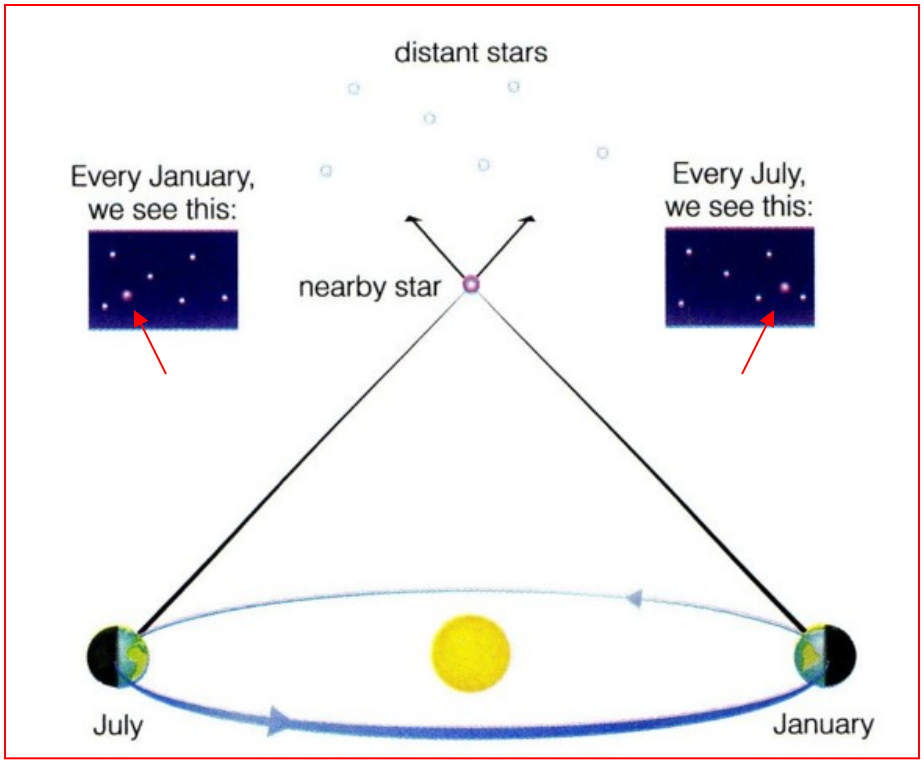
Tycho Brahe ~1575 AD The Heavens are not Unchanging!

Brahe was *the* man of precise measurements…

He use **parallax** to show that a comet (a transient event!) was farther away from Earth than the Moon, and not part of the Earth's upper atmosphere… the comet was heavenly.

Profound Implications:
Objects in the heavens CAN change with time!





WHAT IS PARALLAX?

- the *apparent* motion of relatively nearby objects relative to more distant ones due to the Earth's motion around the Sun…

Works only if Earth moves position with time…

Does not occur in the geocentric model!

Link to see Video Demonstration: 0:43
http://youtu.be/oQYcZvh2JHw

Kepler ~ 1620 AD - God is the Great Geometer

Brahe's decades of precise measurements of the positions and motions of the planets were so good, that Kepler could really make some headway on a model of the "universe".

Kepler believed in Aristotle's simplicity and beauty… but he adopted Copernicus' heliocentric model and then extended Aristotle's "celestial sphere" model to explain the planet's orbits using geometric solids…

Kepler placed a sphere inside a triangle (3 sides), and a sphere outside the triangle, then a square (4 sides) outside that sphere with a sphere outside the square. He placed a octahedron (8 sides) outside that sphere, and on and on, using the five geometric solids to place his spheres around. This gave him six spheres and at the time there were only six planets. He explained why only six planets!

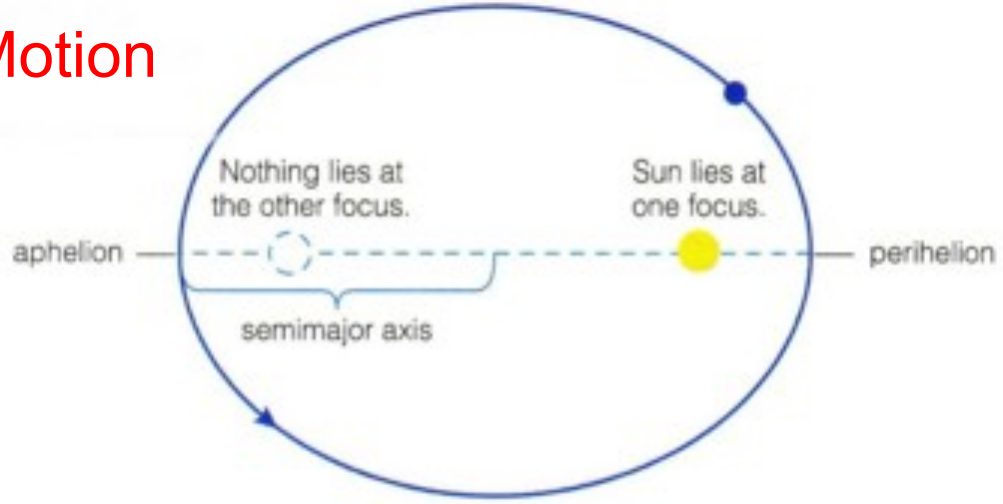
The sized of the planet orbits were very well described by the radii of the spheres! It was a successful model, and was based upon solid scientific data and previous ideas.

But… he was wrong. For one, there are more than six planets!

He got something else very right, though!

Kepler- Laws of Planetary Motion

Thanks to Brahe's awesome data, Kepler is responsible for the death of the circle and constant motion in the heavens.



a Kepler's first law: The orbit of each planet about the Sun is an ellipse with the Sun at one focus.

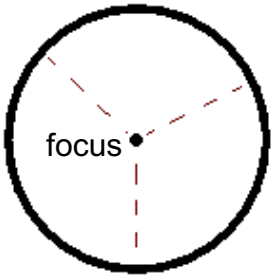
First, Kepler hypothesized that planet orbits trace out the shape of an ellipse, with the Sun at one of the focus points.

Keplers 1st Law:

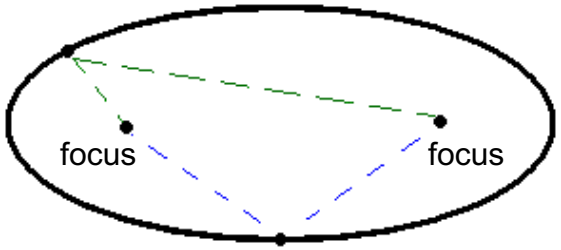
Planet's orbit the sun on an ellipse. The sun is located at one of the focus points.

Circles have one focus in the center
Ellipses have two focus points

Aphelion – farthest reach from the Sun
Perihelion – nearest approach to the Sun



A circle. All lines from the center to the edge are the same length.



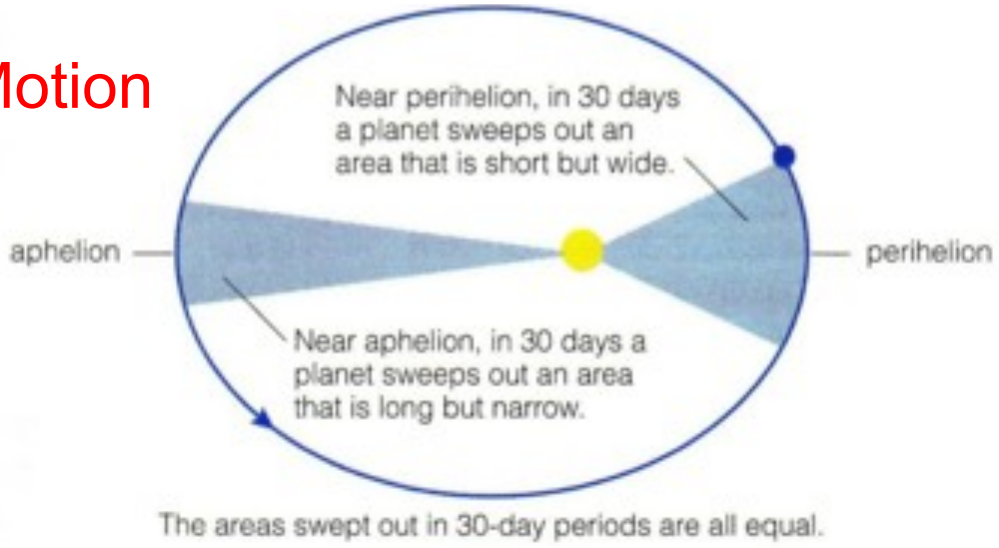
An ellipse. The two green lines, added together, are the same total length as the two blue ones, added together.

Kepler- Laws of Planetary Motion

Second, Kepler saw in Brahe's data that the planets do **not** move in constant motions, but that they move fastest along their orbits at perihelion, and slowest when at aphelion.

The relation between distance and velocity follows from the principle of the **conservation of angular momentum**… the product of the planets velocity times its distance from the sun is a constant at all points along the orbit…

velocity x distance = constant



The areas swept out in 30-day periods are all equal.

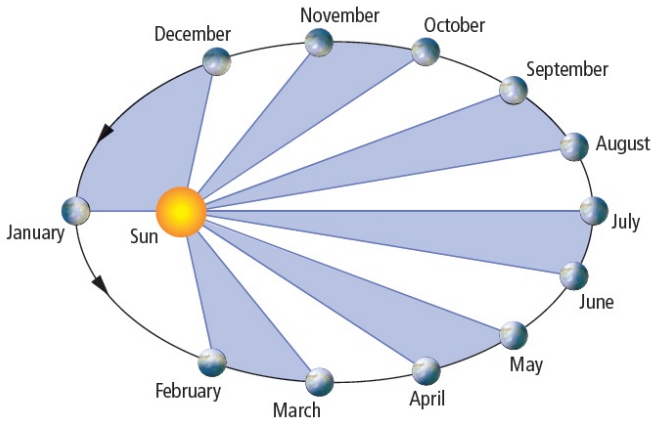
b Kepler's second law: As a planet moves around its orbit, it sweeps out equal areas in equal times. This means that it moves faster when near the Sun and slower when farther from the Sun.

Keplers 2nd Law:

A line connecting the sun and planet sweeps out equal areas in equal time intervals.

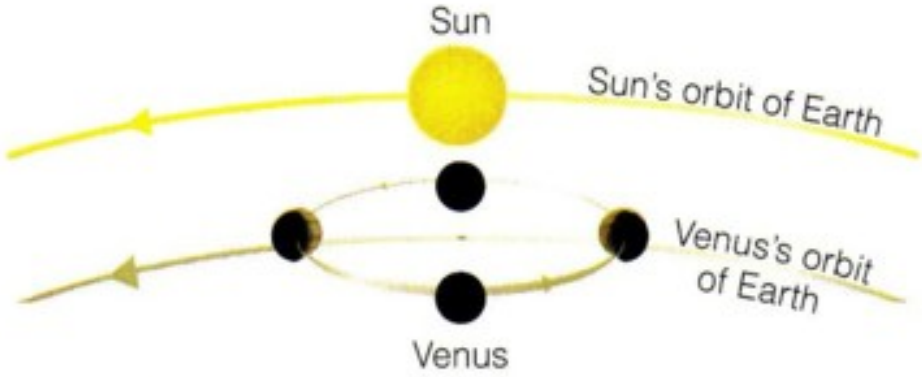
Link to see Video Demonstration: 0:29

https://www.youtube.com/watch?v=rH8ctHu4sLM



Constant Angular Momentum

Galileo ~ 1630 AD Father of Modern Science

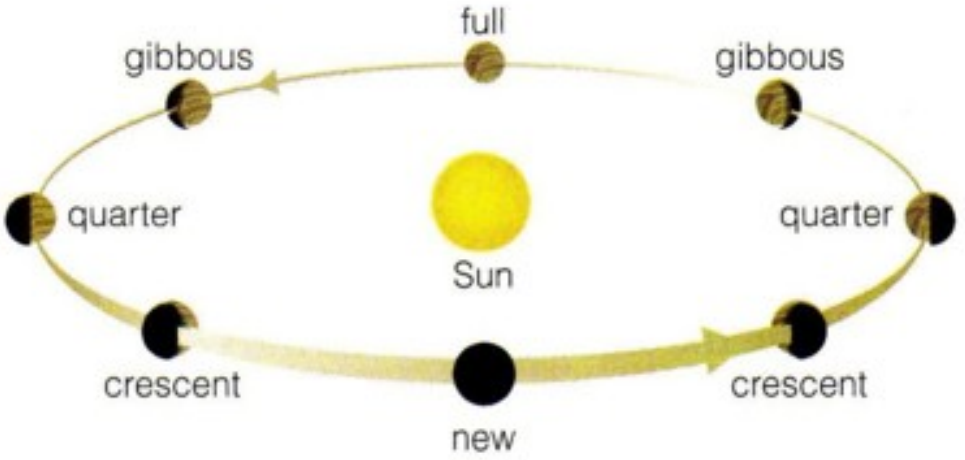


a In the Ptolemaic system, Venus follows a circle upon a circle that keeps it close to the Sun in our sky. Therefore, its phases would range only from new to crescent.

Though Copernicus proposed a heliocentric model, it was not yet accepted as a better model than Aristotle's and Ptolemy's geocentric model…

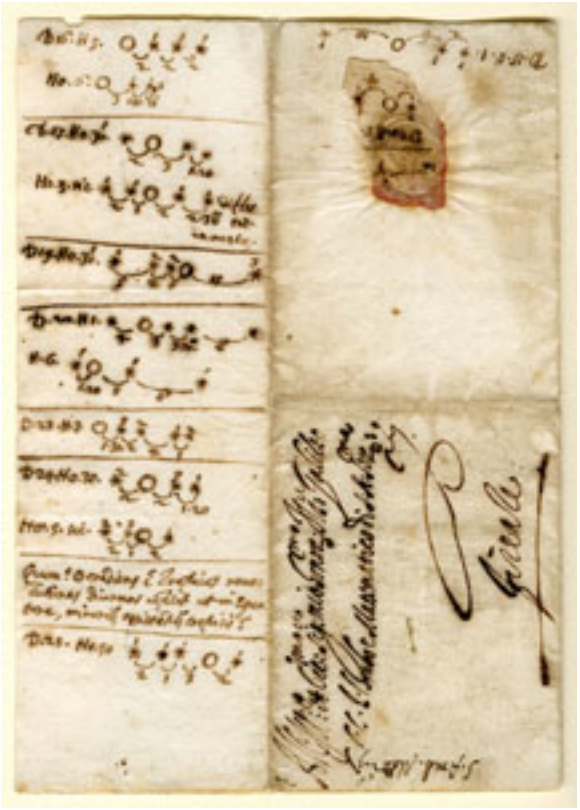
Galileo was the first to use the telescope for astronomy and take careful notes. **Father of Modern Science** bestowed upon him for beginning the era of "observation driven" science.

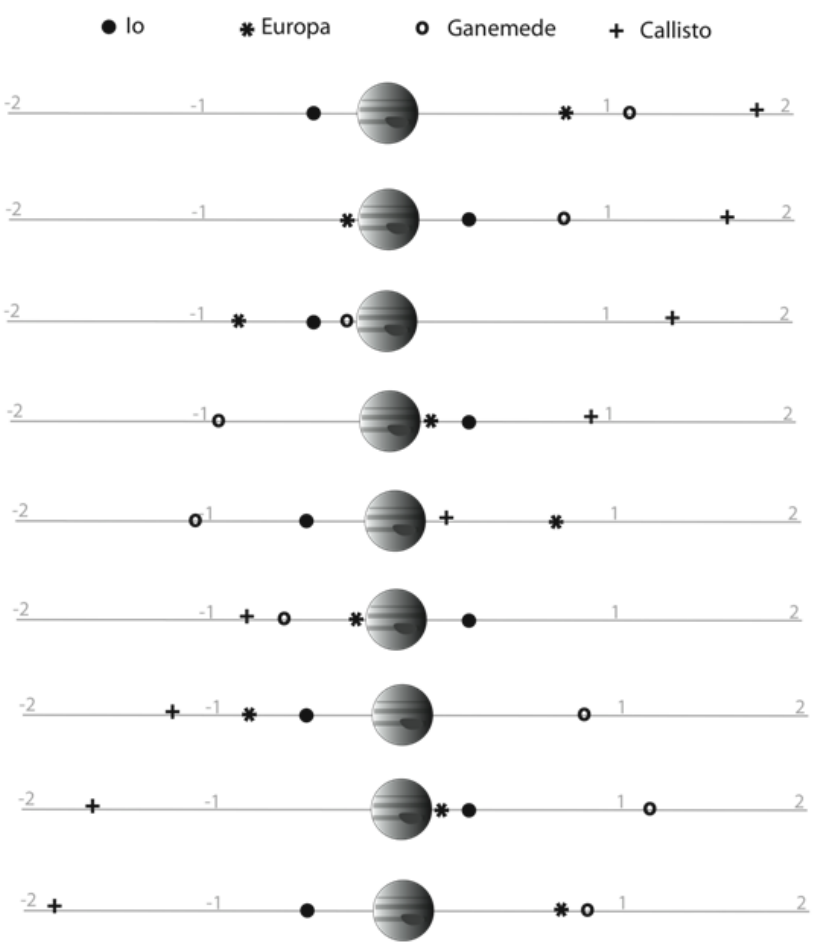
His observations of the phases of Venus disproved the geocentric model once and for all.



b Galileo observed Venus go through a complete set of phases and therefore proved that it orbits the Sun.

Galileo ~ 1630 AD Father of Modern Science

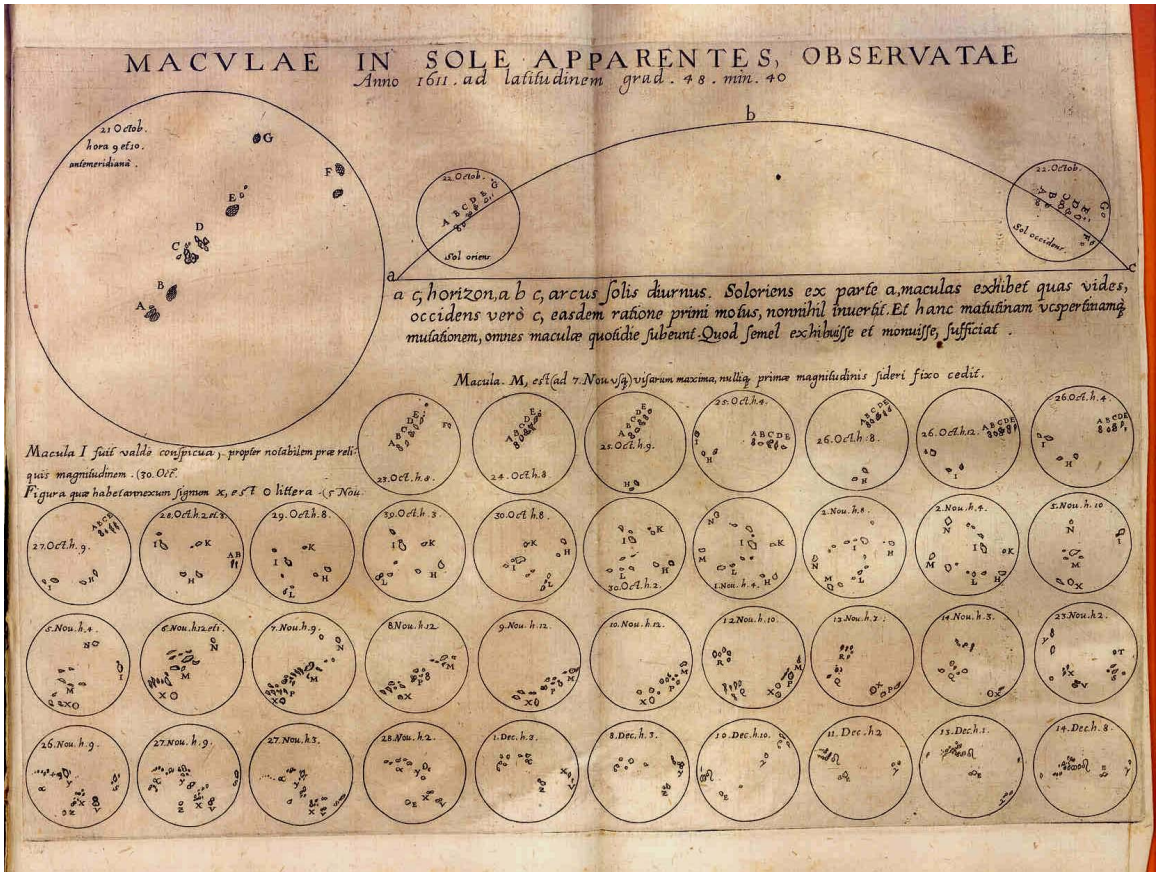




Galileo also discovered moons orbiting Jupiter.

This showed that there are unique systems in the universe that have their own center and this demonstrated that not everything orbited the earth- thereby further challenging the geocentric model

Galileo ~ 1630 AD Father of Modern Science



Galileo also discovered sunspots. He charted how these sunspots changed with time!

This means that objects in the heavens are not perfect and unchanging, which challenged Aristotle's view of a perfect unchanging heavens.

Old Dead Guys that Rock Your World, Part II

Brahe

Kepler

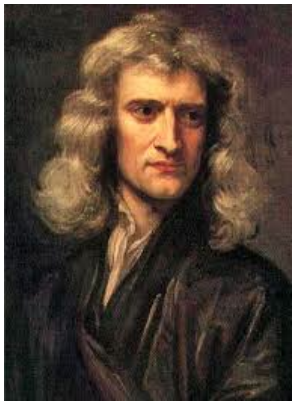
Galileo

Tycho Brahe – used parallax to show comet was outside Earth atmosphere and made 1000s of precise measurements of the positions of astronomical objects

Kepler – adopted Copernican heliocentric model, used Brahe's data to show planets orbit with varying velocities along ellipses (formulated Kepler's Laws of Planetary Motion).

Galileo – first to use telescope on the sky, provided strong support for Copernican model by discovering moons of Jupiter and showing phases of Venus contradict Aristotle's geocentric model; also discovered sunspots

The Story of Space and Time



Isaac Newton

Formulated theory of motion- time is a universal constant across all space

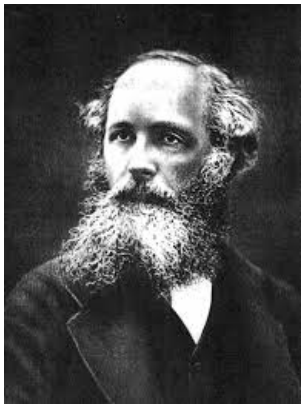
F=ma -> forces (F) cause a mass (m) to accelerate (a)

"Once positions and velocities of all particles in the universe are initialized by God, then forces cause the universe to unfold in a manner completely predetermined."

The velocity one measures for an object depends upon the velocity of the observer

Formulated theory of light (electromagnetism) - time is a universal constant across all space

$c=(\varepsilon\mu)^{-1/2}$ -> the speed of light is given by the permittivity of space to electric perturbations

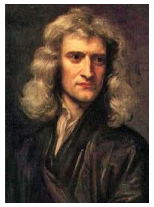


James Clerk Maxell

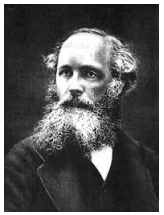
"Light travels at a constant speed throughout all space."

The velocity one measures for light does **not** depend upon the velocity of the observer

The Story of Space and Time



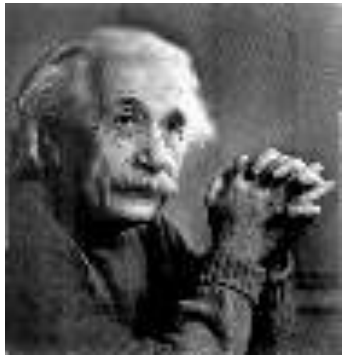
Newton



Maxwell

Newton and Maxwell contradict each other!

"If I travel at the speed of light in the same direction as the light, Newton says I should see light standing still. But Maxwell says that cannot happen!" – Einstein (age 16)



Einstein

Postulates (cannot be proven)

1. Light is a constant speed for all observers
2. The laws of physics are the same for all observers

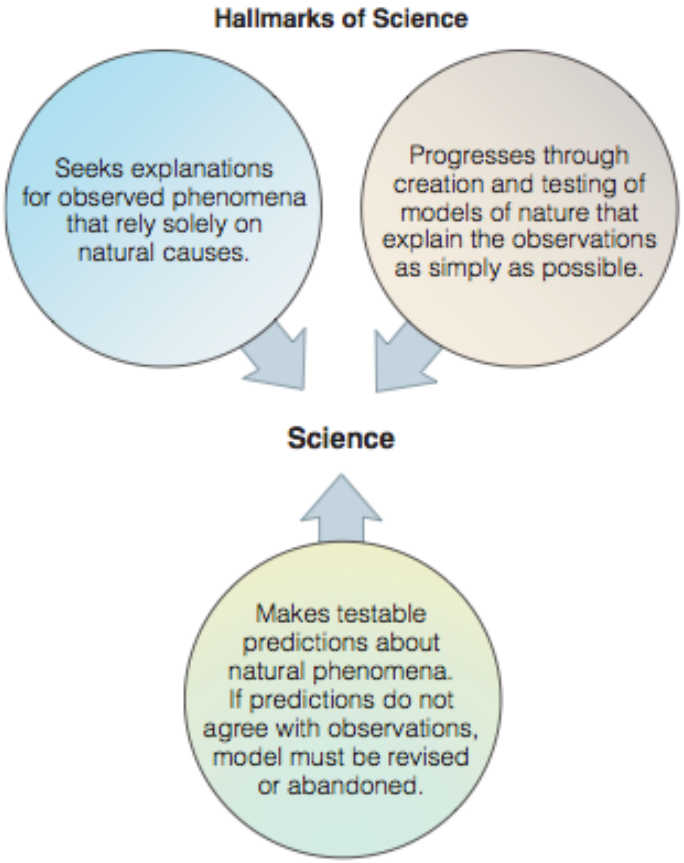
PARADIGM SHIFT:

Einstein finds that time cannot be a universal constant, but depends upon both an observer's velocity and distance to the clock (time is not a constant throughout all space)!

Here is a 10 minute movie illustrating this… (totally worth watching) http://youtu.be/lVuF5zrwMLY

The Three Hallmarks of Modern Science

1. Modern science seeks explanations for observed phenomena that rely solely on natural causes.

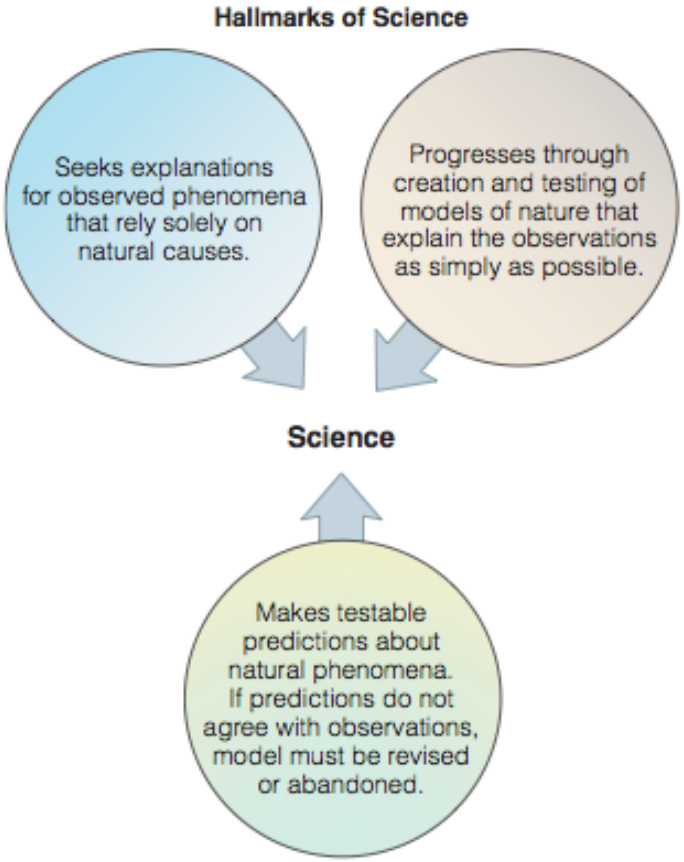


Modern science is also driven by a belief that the world is inherently simple, beautiful, and understandable.

"The most incomprehensible thing in the universe is that it is comprehensible." - A. Einstein

The Three Hallmarks of Modern Science

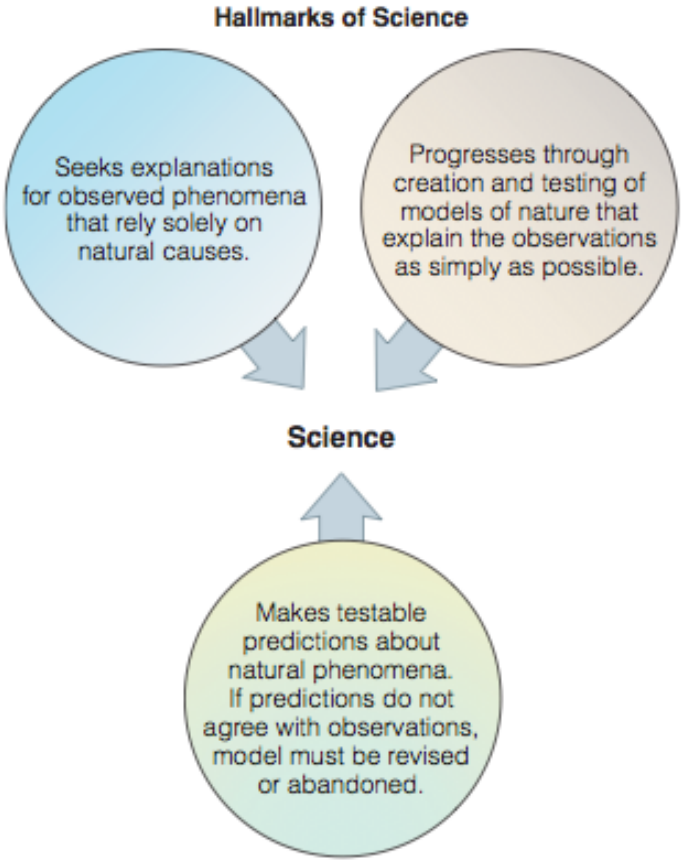
2. Science progresses through the creation and testing of models designed to explain observations, and these models should be as <u>simple as possible</u>, and be as consistent with a rational understanding of other aspects of science



Occum's Razor *– the principle that the simplest hypothesis/model is probably closest to the truth of nature.*

The Three Hallmarks of Modern Science

3. A scientific model should be testable with observations so that we can always envision further ways to check its validity or, if need be, to conclude it is incorrect.



Recall – nothing can be proven correct, only to be consistent with a model or theory

But hypotheses and theories can always be disproven at anytime, once they are shown to be inconsistent with observations.

The Scientific Method

Knowledge is now obtained not by rational thought alone, but by a process of fine tuning that can never end

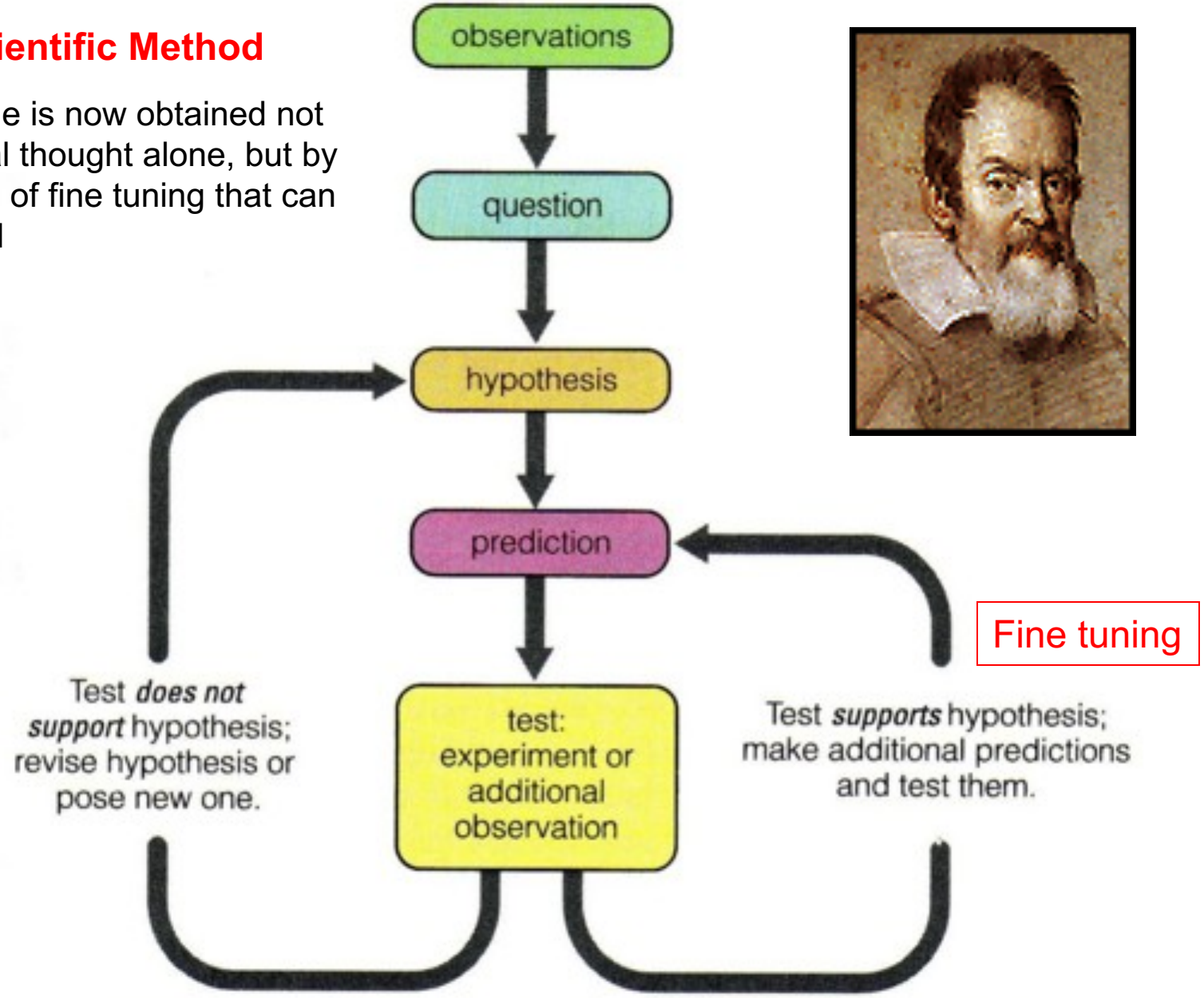


FIGURE 2.11 This diagram illustrates the basic process of hypothesis-driven science.