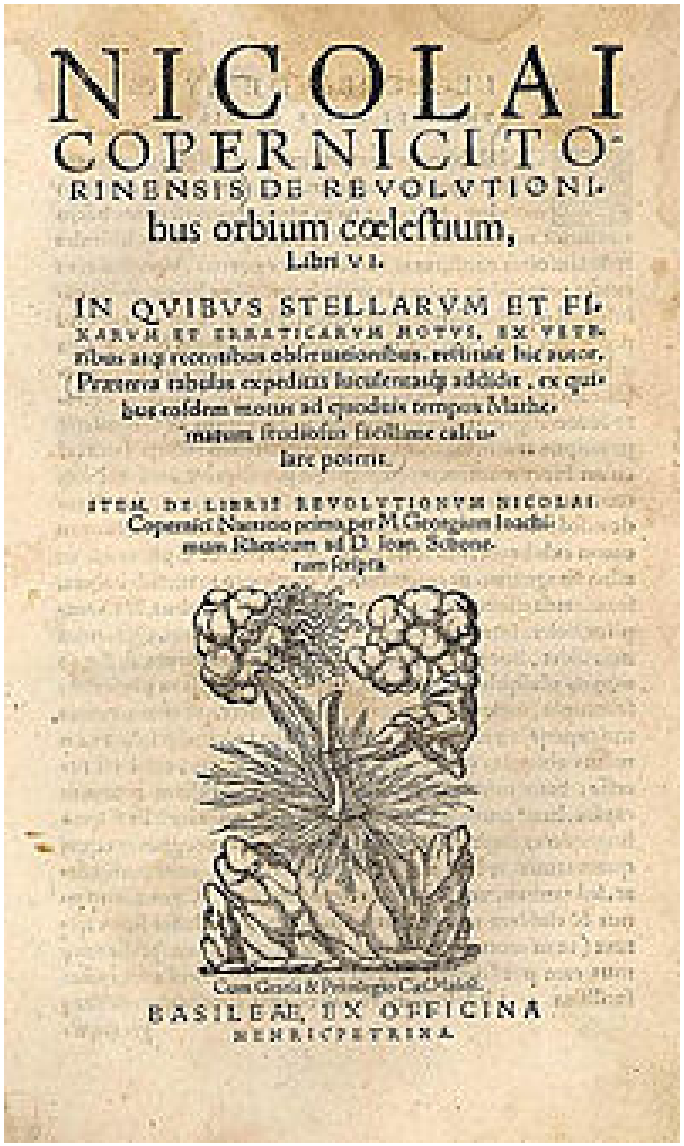
Scientific Revolution

Christian Wüthrich

http://www.wuthrich.net/

Introduction to the history and philosophy of science
Faculté des sciences, Université de Genève

The scientific revolution, 1543-1687

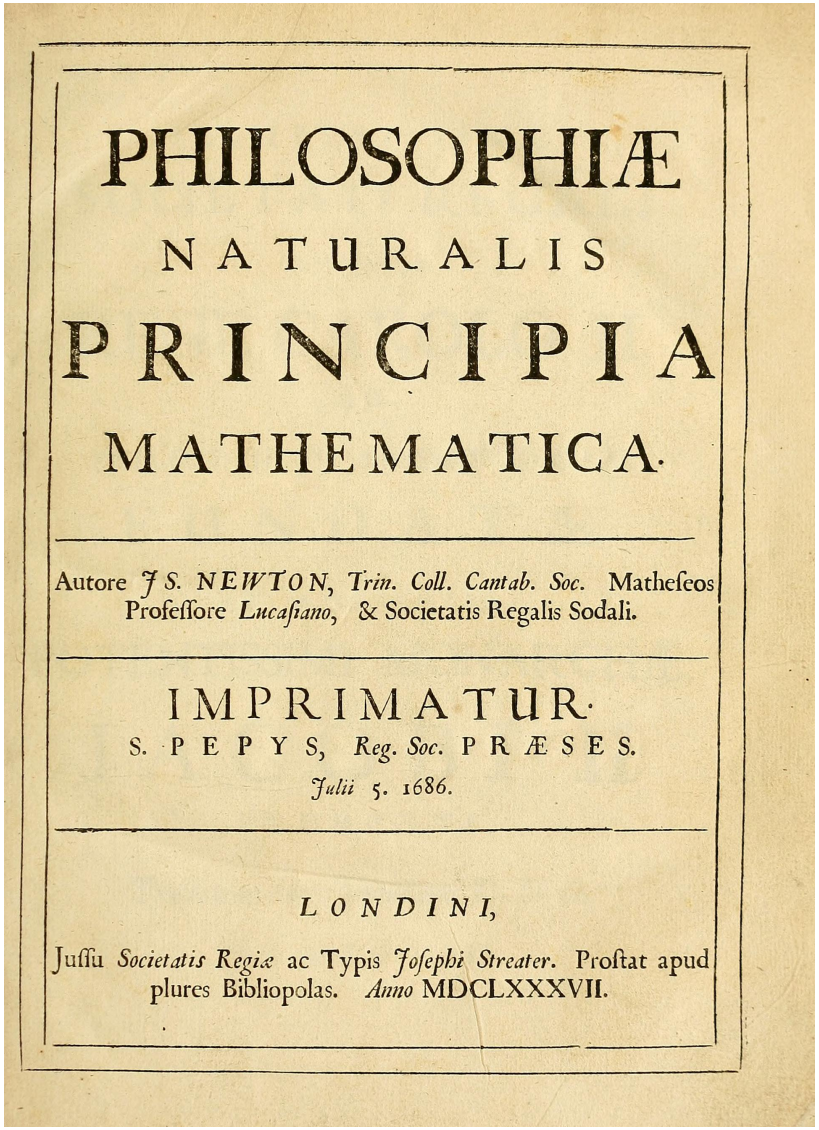


NICOLAI
COPERNICI TO-
RINENSIS DE REVOLVTIONI-
bus orbium cœleſtium,
Libri VI.

IN QVIBVS STELLARVM ET EI-
XARVM ET ERRATICARVM MOTVS, EX VETE-
ribus atq; recentibus obſeruationibus, reſtituit hic autor.
Præterea tabulas expeditas locupletesq; addidit, ex qui-
bus eoſdem motus ad quodlibet tempus Mathe-
matum ſtudioſus facillime calcu-
lare poterit.

ITEM, DE LIBRIS REVOLVTIONVM NICOLAI
Copernici Narratio prima per M. Georgium Ioachi-
mum Rheticum ad D. Ioan. Schone-
rum ſcripta.

Cum Gratia & Priuilegio Cæſ. Maieſt.
BASILEAE, EX OFFICINA
HENRICPETRINA.



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore *J S. NEWTON, Trin. Coll. Cantab. Soc.* Matheſeos
Profeſſore *Lucaſiano,* & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,
Juſſu *Societatis Regiæ* ac Typis *Joſephi Streater.* Proſtat apud
plures Bibliopolas. *Anno* MDCLXXXVII.

Scientific Revolution: thesis

One can reasonably argue that the Scientific Revolution begins with the problem for understanding terrestrial physics set by Copernicus in 1543 and ends with in 1687 with the publication of Newton's *Philosophiae naturalis principia mathematica*, in which the problem is resolved by proposing what we now call Newtonian physics which is fully consistent with heliocentrism.

The scientific revolution in a nutshell

John Henry (2023), The scientific revolution. In Iwan Rhys Morus (ed.), *The Oxford History of Science*. Oxford University Press, 148-180.

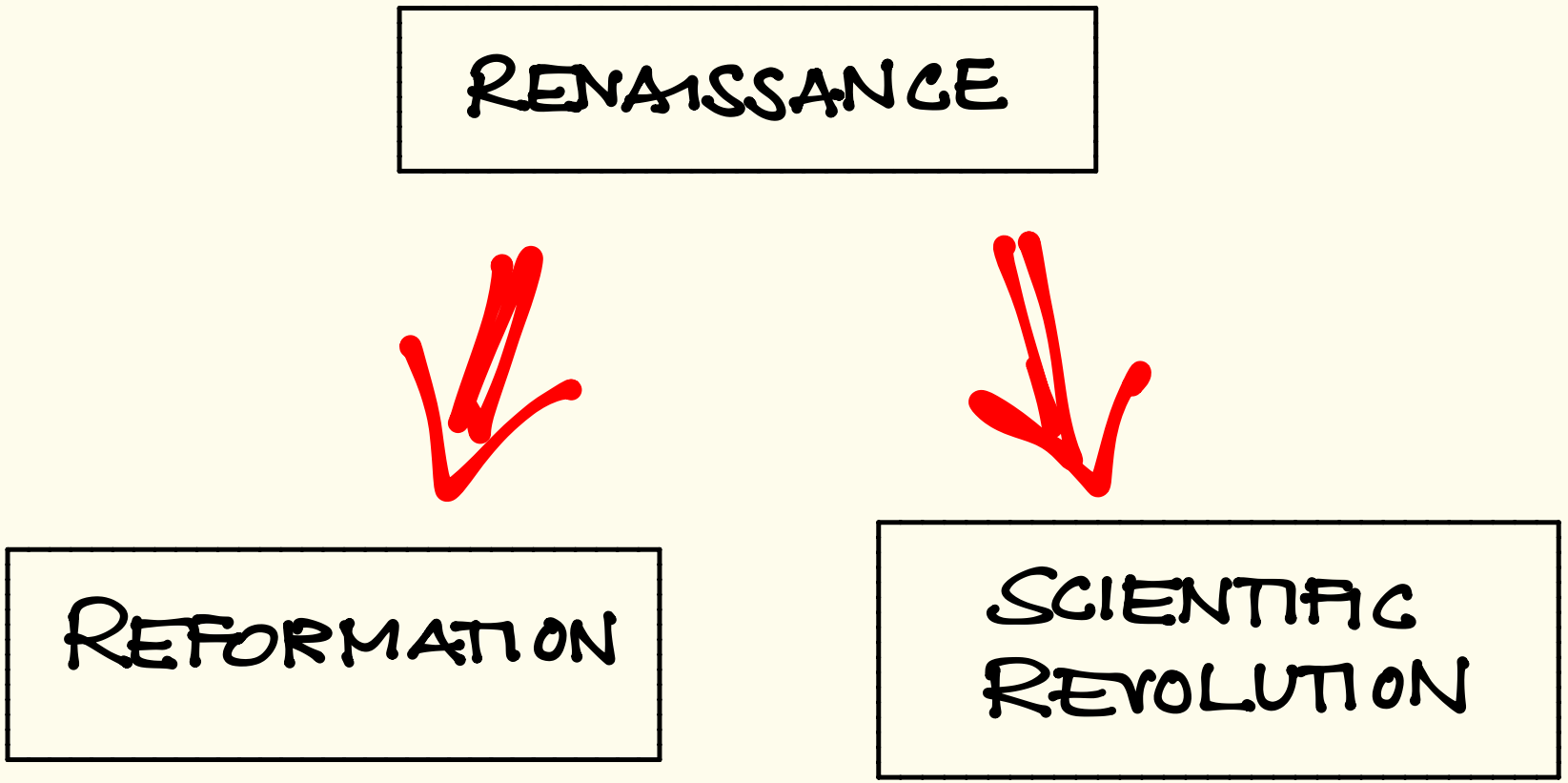
Henry (2023, 148)

Between 1500 and 1700 the world picture shifted from a geocentric finite cosmos of nested heavenly spheres which allowed no empty space, to a heliocentric solar system in an infinite universe that was void except where it was dotted with stars. A prevailing belief in a qualitative dichotomy between the heavens and the Earth [...] gave way to the belief that planets were like the Earth, and stars like the Sun...

The scientific revolution in a nutshell

- acceptance of the universal applicability of natural laws
- laws understood not as mere regularities, but as precise quantitative, predictive statements capturing causal relations between phenomena
- new theories of motion, of the generation and the organisation of life, a revised human anatomy, new physiology
- introduction of the experimental method, wide and powerful application of mathematical analysis
- knowledge should be put to use for the benefit of humankind
- new forms of institutional organisation, formation of scientific societies

Enabling condition: Renaissance



The relevance of the Renaissance

- The new exploitation of gunpowder and the magnetic compass showed usefulness of natural knowledge.
- The invention of printing enabled the mass dissemination of knowledge and ideas.
- The exploration of the new world led to an awareness of cultural relativism.
- Emerging powerful and wealthy individuals and families, such as the Medici in Florence, acted as patrons of arts and scholarship and sponsored the re-discovery of ancient writers (other than Aristotle) and of Islamic scholarship.

$\Rightarrow$ undermines the authority of Aristotle

The Reformation

- Martin Luther (1483-1546) emphasises the need to go directly to the source of truth, bypassing intermediaries
- new idea that God could be served by reading the 'Book of Nature'

$\Rightarrow$ rejection of human authority as valid source of natural knowledge (and to some degree even of theology)

$\Rightarrow$ The time is ripe for a new experiential and empiricist approach to understanding the natural world.

Melissus's paradox

Melissus of Samos (470-430 BCE)

> *And it cannot perish, or become greater, or be rearranged, or feel pain or distress. For if it experienced any of these, it would no longer be one. For if it became different, it is necessary that what it is is not alike, but what previously was perishes, and what is not comes to be.*

$\Rightarrow$ Something must both be the same and different for there to be change: something like X-at-$t_1 = X$-at-t_2 and X-at-$t_1 \neq X$-at-t_2, which is contradictory and hence impossible.

- Aristotle argues in his *Physics* that the puzzle is resolved when one realizes that it equivocates on 'is': 'is' of identity vs. 'is' of predication

What is change?

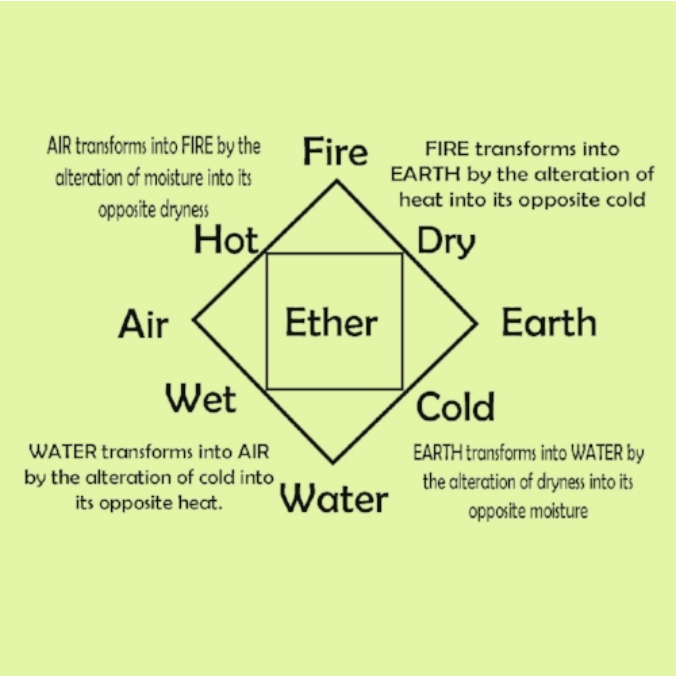
Nick Huggett (2010). *Everywhere and Everywhen: Adventures in Physics and Philosophy*. New York: Oxford University Press.

- Nevertheless, there is a challenge of how to understand change—one of the most central concepts of physics.
- The concept of change, and with it what stands in need of explanation by a physical theory, has itself evolved in the course of history, "with dramatic implications for scientific progress." (Huggett, 3)

Aristotle (384-322 BCE)

- teleological physics: physical world strives toward end ('telos')
- motion as the actuality of a potentiality as such
- natural vs. non-natural or forced motion
- natural motion: motion of a body towards its natural place, following natural law

Aristotelian explanation



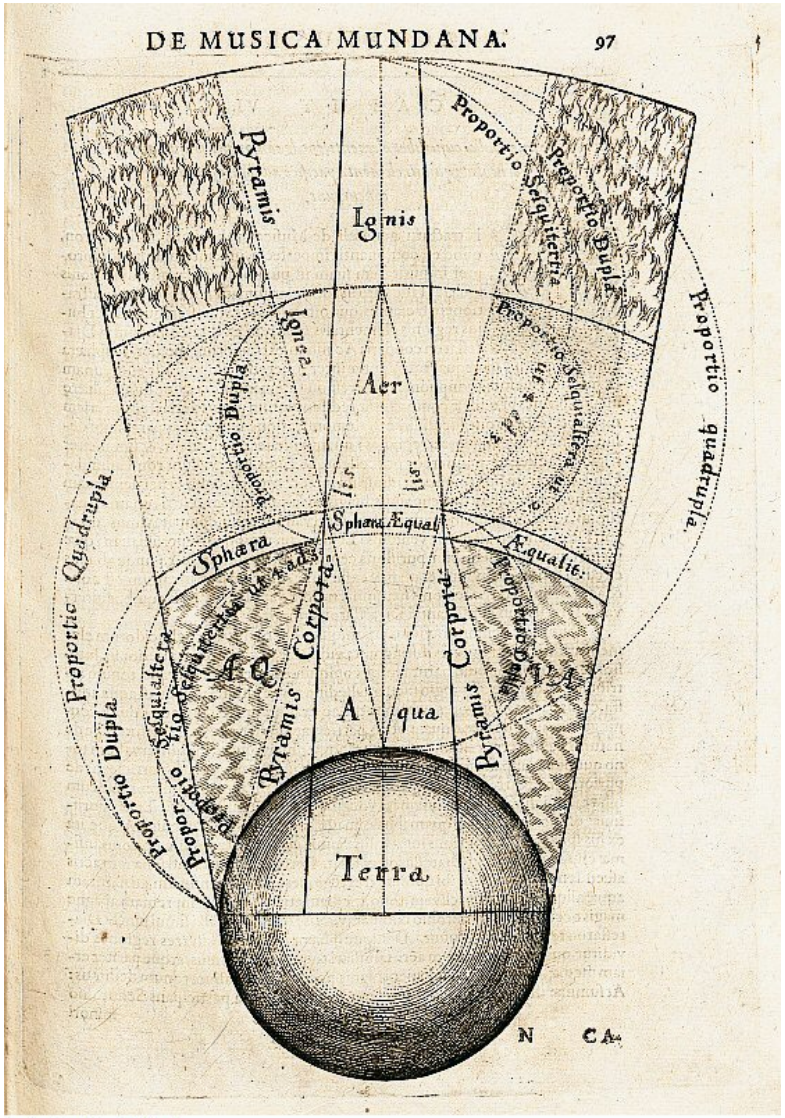
- Aristotle's theory of causality (lecture 2)
- Aristotelian hylomorphism: bodies are made of matter ('hyle') and form ('morphe')
- natural phenomena ought to be explained as consisting of combinations of the four elements (earth, water, air, fire) and exhibiting combinations of the four manifest qualities (hot, cold, dry, wet) by citing their four causes (material, formal, efficient, final)

Failure of reduction

However, more and more qualities (such as magnetic) were discovered which could not be reduced to the four manifest ones. These were said to be 'occult' qualities.

Aristotle's cosmos: sublunar vs. supralunar realm

(1) The sublunar sphere



Quelle: Deutsche Fotothek

- Sublunar sphere: world teeming with life, generation and corruption
- Empedocles's theory of four elements: earth, water, air, fire
- Everything in sublunar realm consists in combinations of those four elements.
- Earth and water are 'heavy' elements tending to centre of world, fire and air are 'light' tending to outer edge of sublunar sphere

$\Rightarrow$ explains 'gravity' e.g. of earth (and 'levity' of fire)

Aristotle's cosmos: sublunar vs. supralunar realm

(2) The supralunar realm

- Supralunar world: 'stationary' state, motions characterized by perfection, repetition, circularity, regularity

$\Rightarrow$ natural motion is circular

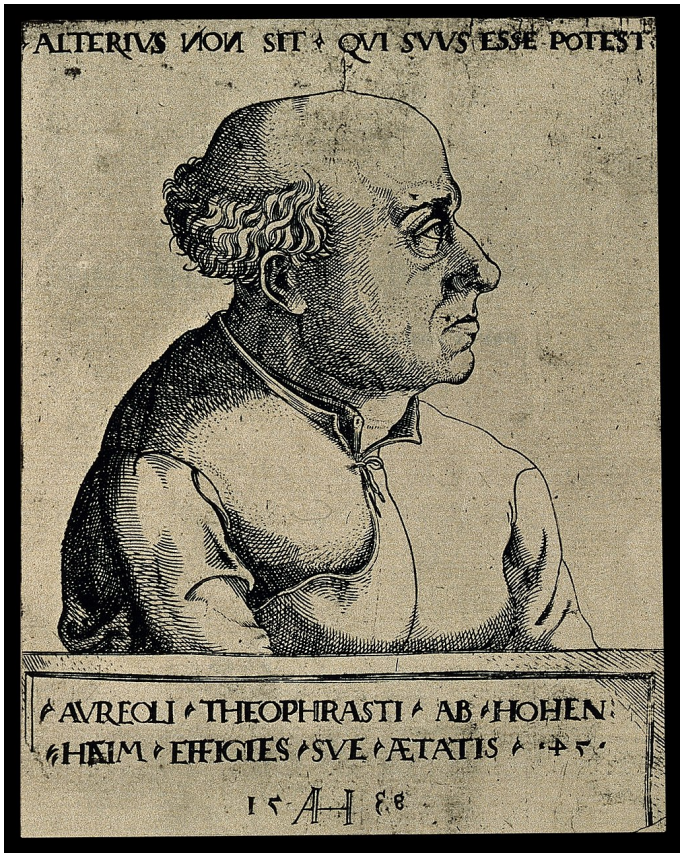
$\Rightarrow$ requires different material—but only one since there are no forced motions ('quintessence')

Aristotelian terrestrial physics

Aristotle, *De Caelo*, Bk. 1, Ch. 6 (273b31-274a2, tr. Richard McKeon)

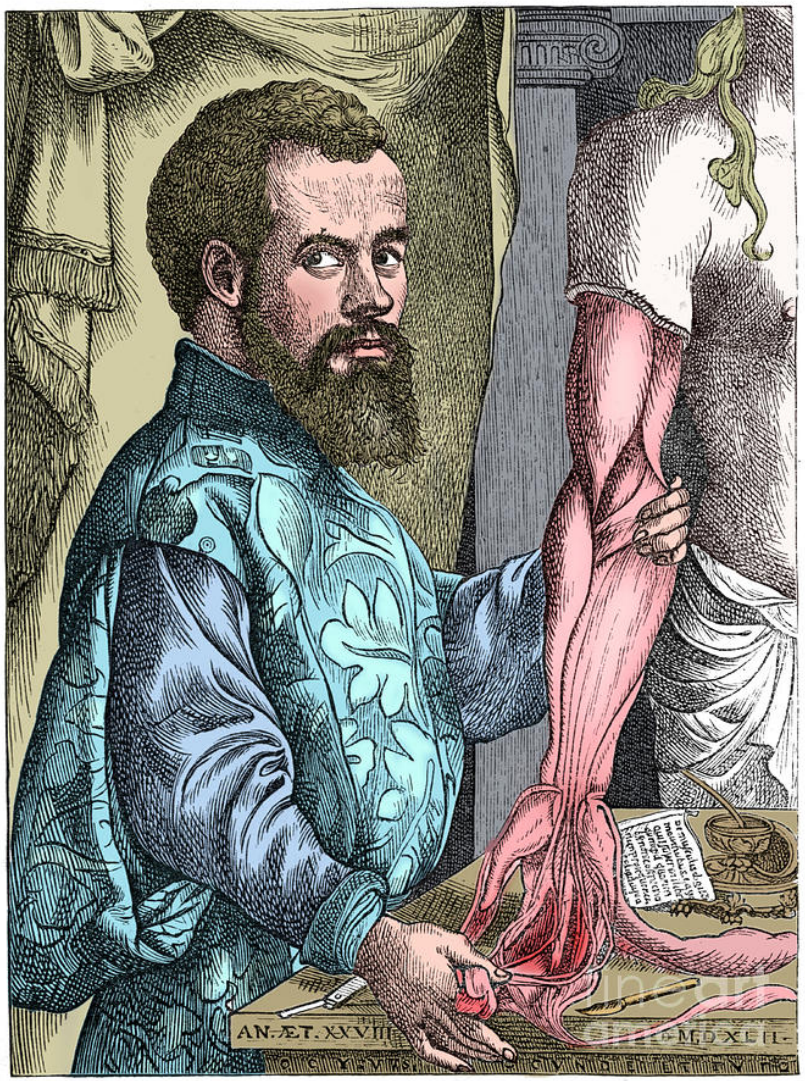
> *A given weight moves a given distance in a given time, a weight which is as great and more moves the same distance in a less time, the times being in inverse proportion to the weights. For instance, if one weight is twice another, it will take half as long over a given movement.*

Paracelsus (1493-1541)



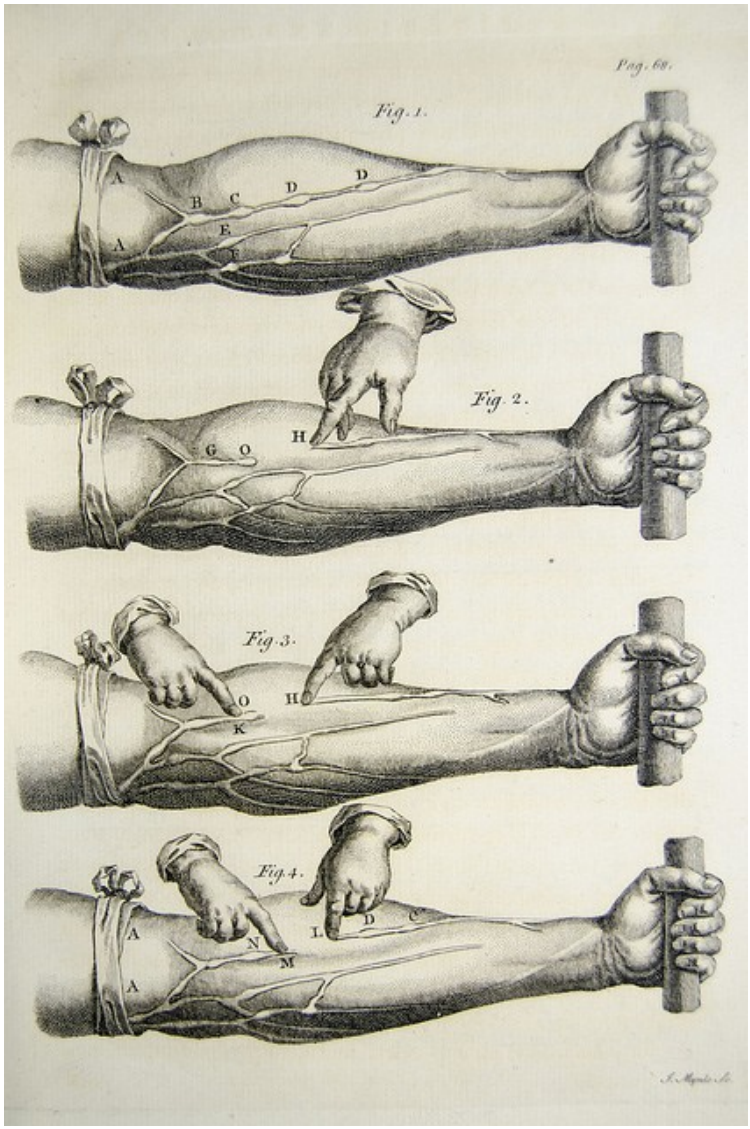
- Swiss religious, philosophical, and medical reformer
- announcement of lecture at the University of Basle in 1527: "Our own observation of nature, confirmed by extensive practice and long experience"
- rejection of ancient authorities of Galen and Avicenna
- Hermeticism, Neoplatonism
- contributions to medicine (introduction of clinical diagnosis, forerunner of germ theory) and toxicology, gave chemistry a new role in medicine
- His methods enjoyed empirical success compared to ancient ones.

Andreas Vesalius (1514-1564)



- Flemish anatomist and surgeon
- new empirical anatomy, new form of lectures
- *De humani corpis fabrica* (1543)
- claims to have found over 200 errors in Galen's work on anatomy

William Harvey (1578-1657)

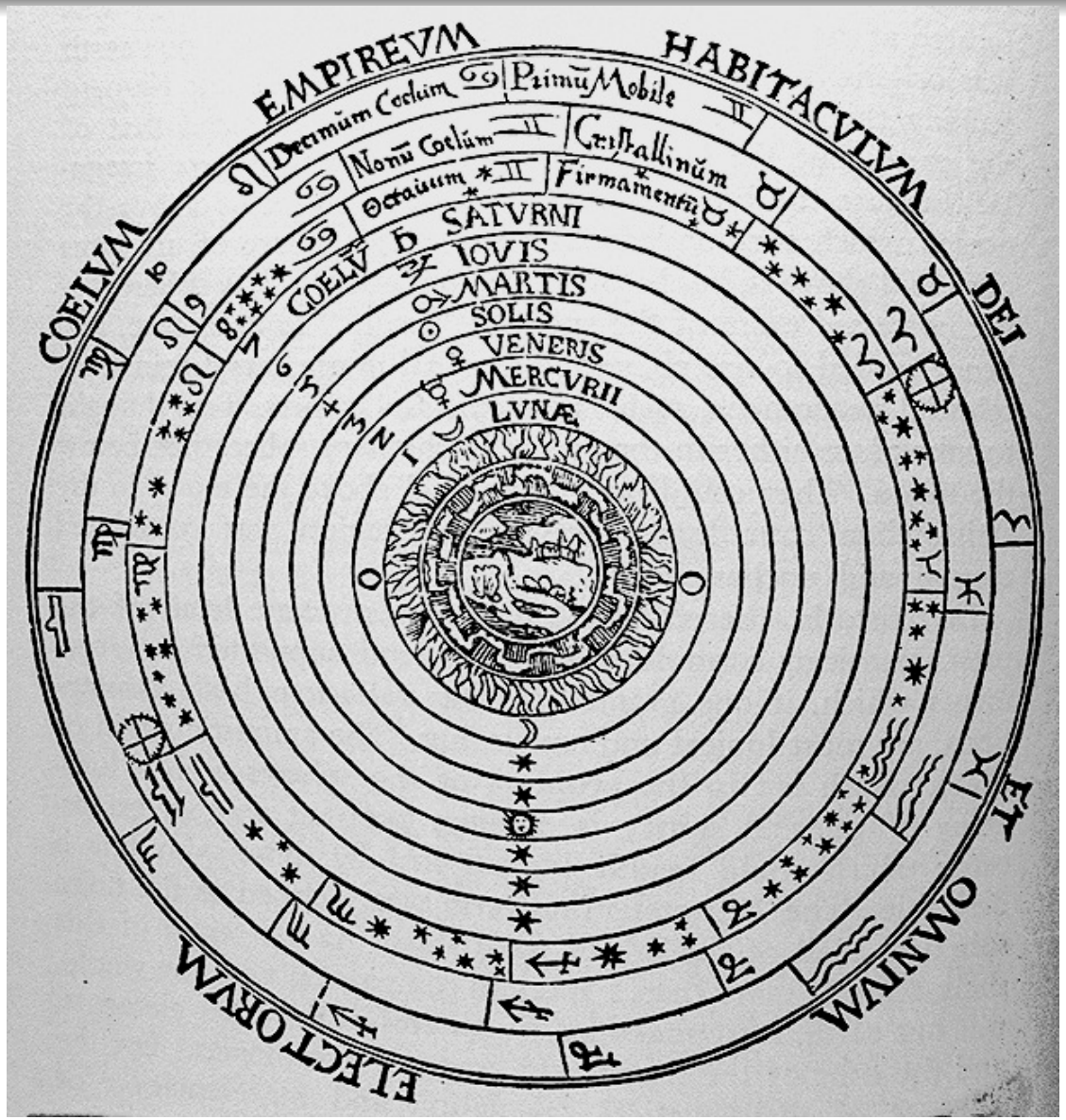


- English physician, contributions in anatomy, physiology
- experimental approach
- discovery of the circulation of blood

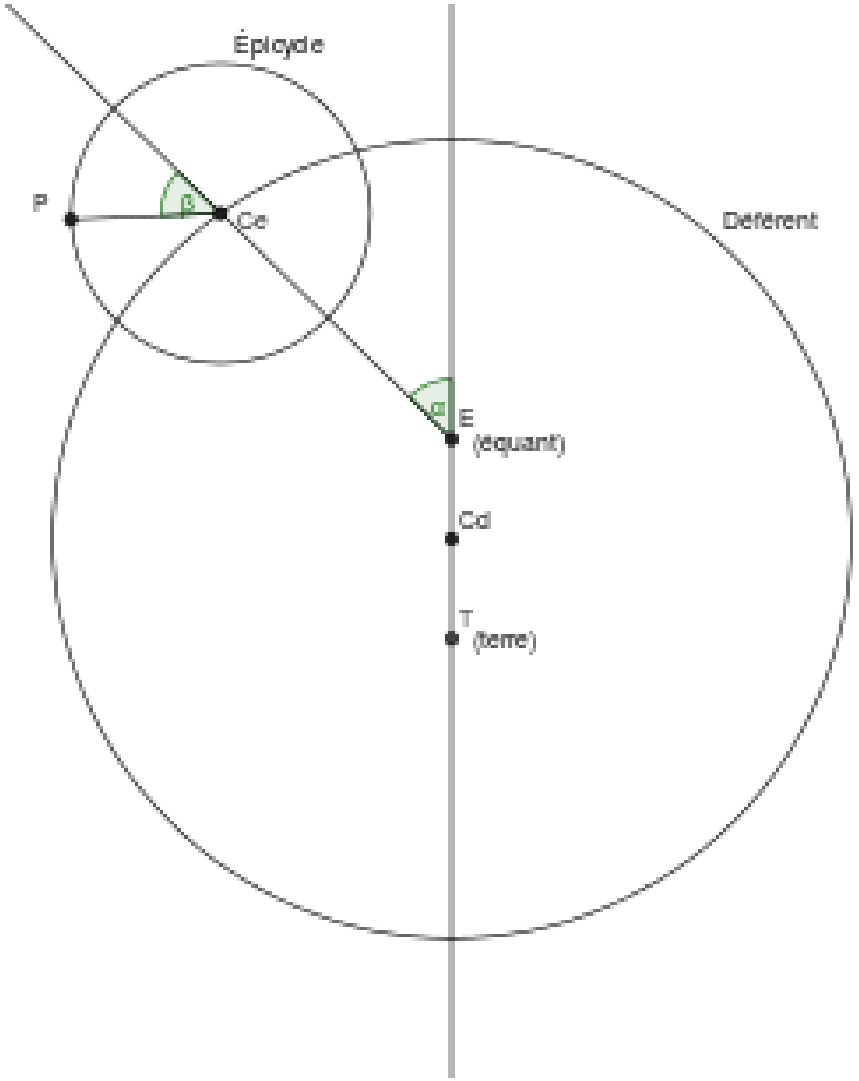
$\Rightarrow$ Galenic assumption of two blood systems (veinous and arterial) is obsolete

$\Rightarrow$ The entire system of Galen's physiology had to be recast.

Ptolemaic astronomy



Deferents, eccentrics, epicycles, equants

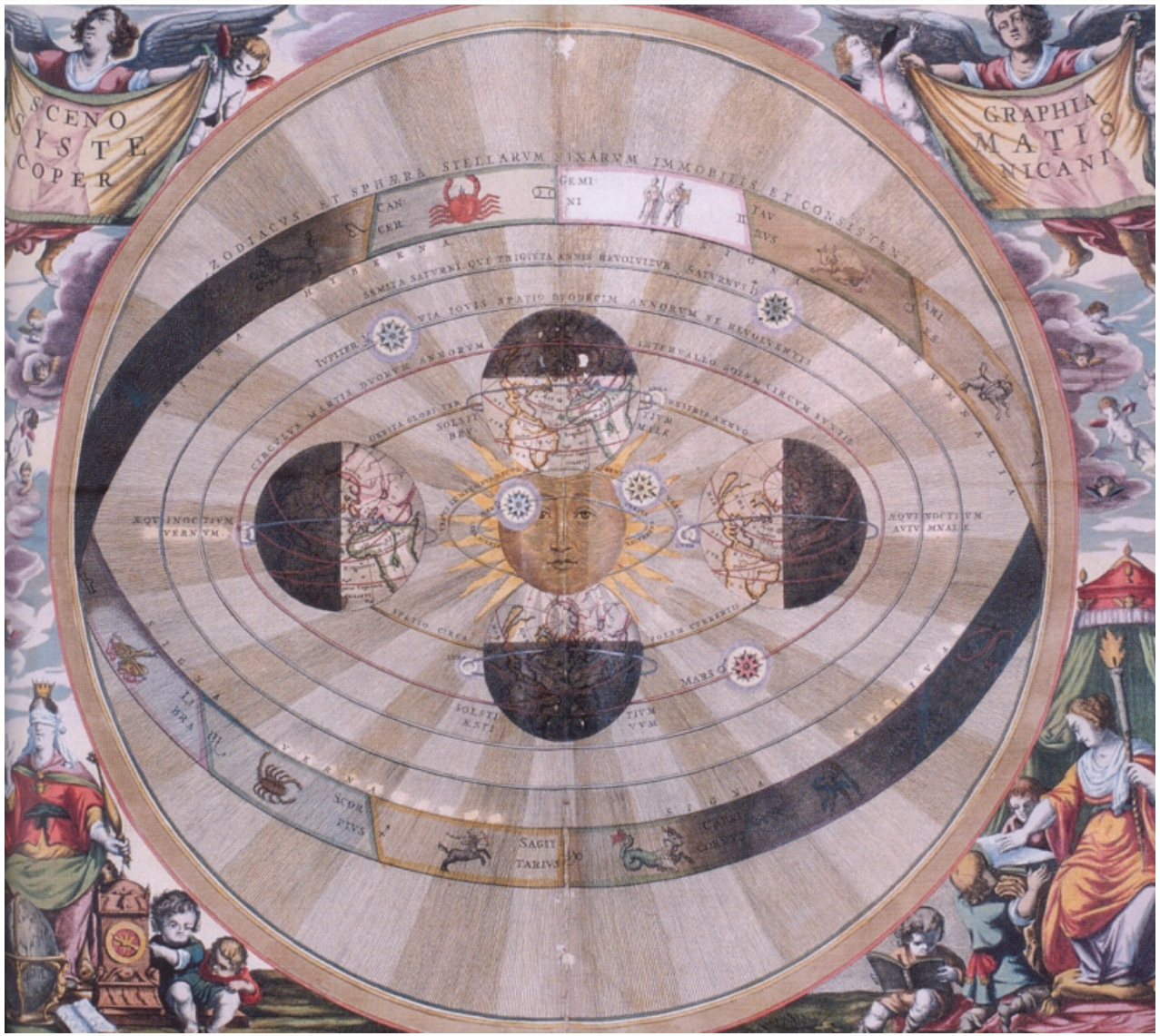


Problems for Ptolemy

- predictively unreliable
- more and more 'bells and whistles' as model is adjusted to fit new data
- Copernicus: equants are particularly unpleasing
- Ptolemaic astronomy was not replaced for long period despite anomalies because there was no credible competitor (we will get back to this point in the module on Kuhn).

Copernican astronomy

Nicolaus Copernicus (1543). *De revolutionibus orbium coelestium*.



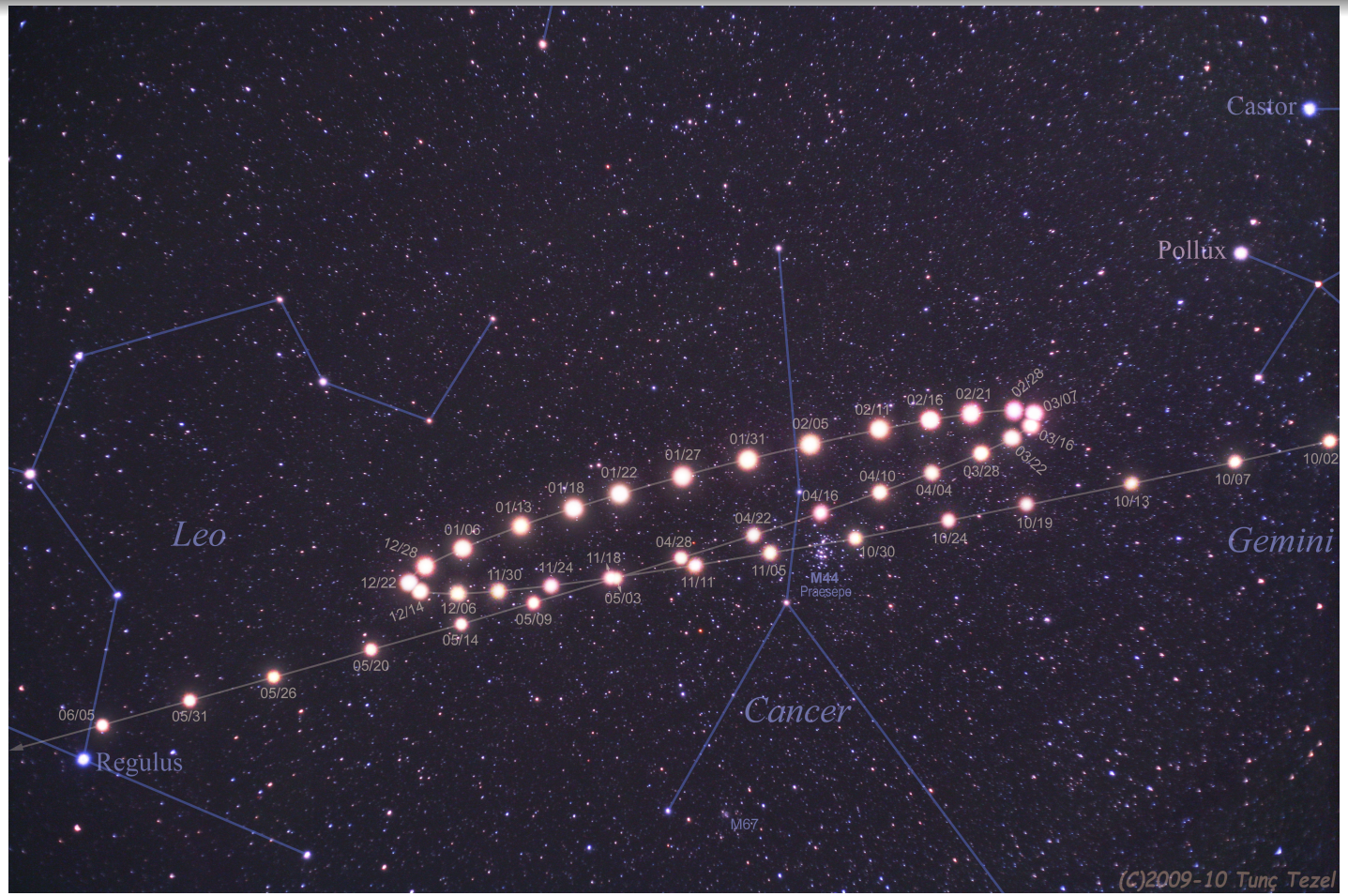
Advantages of the Copernican theory

The advantages of the Copernican theory included:

- Qualitative features of planetary motions can be explained convincingly; for example
  - retrograde motion, and
  - the bounded elongation of inferior planets.
- Variations in brightness of planets can be neatly explained.
- The phases of Venus can also be explained quite naturally.

(a) Retrograde motion: the phenomenon

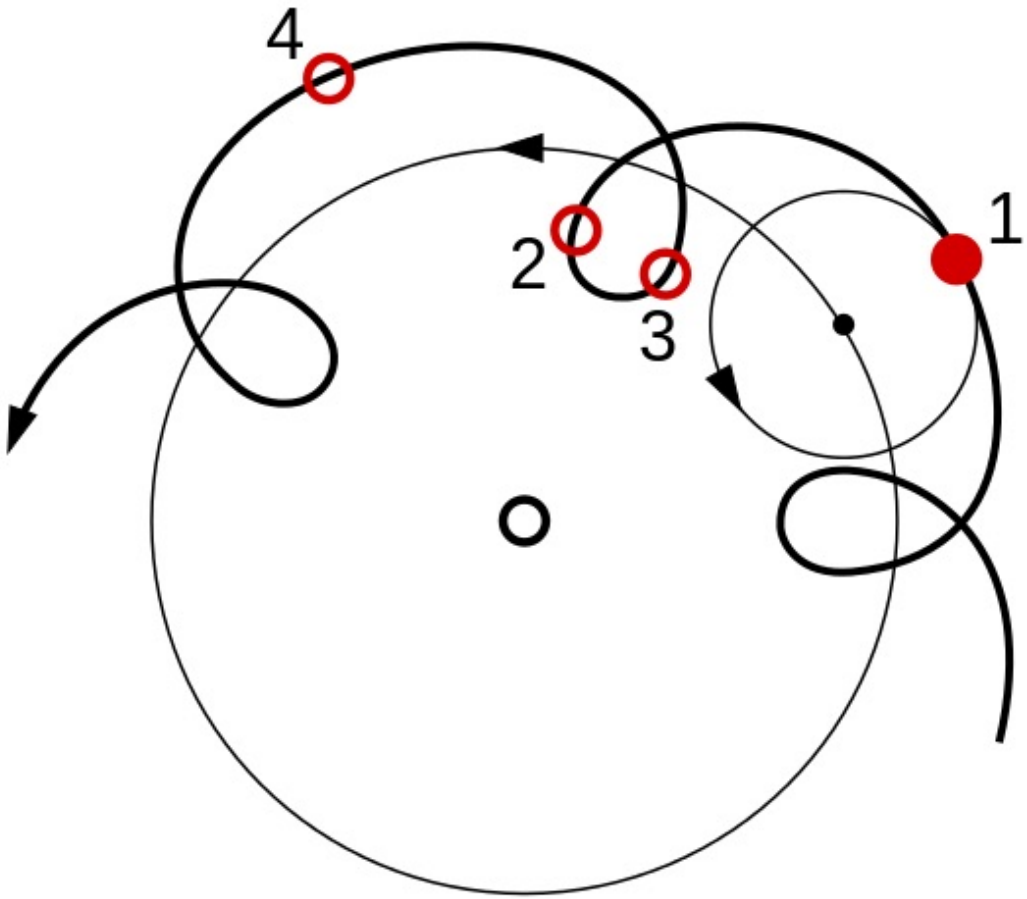
Example: Mars in 2010



Animation:

`https://upload.wikimedia.org/wikipedia/commons/7/70/Apparent_retrograde_motion_of_Mars_in_2003.gif`

(a) Retrograde motion: Ptolemaic explanation



(a) Retrograde motions: Copernican explanation

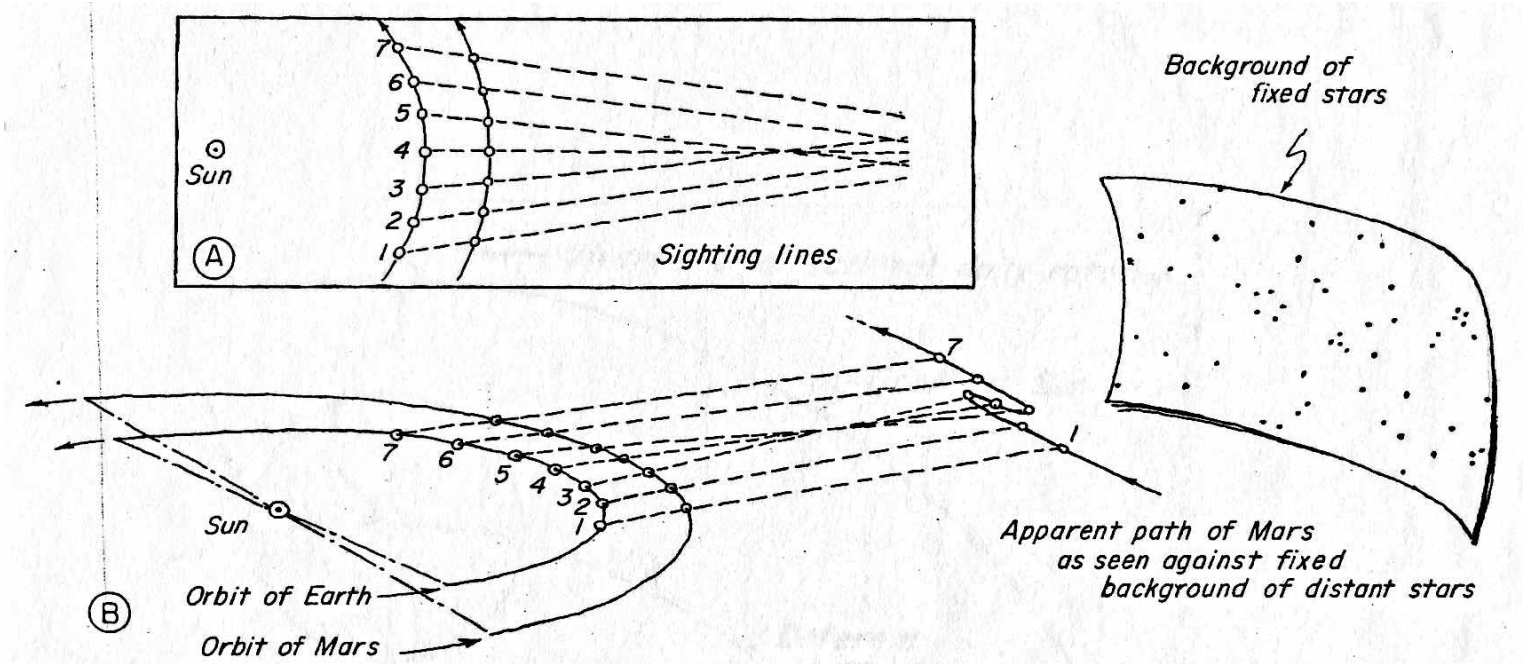
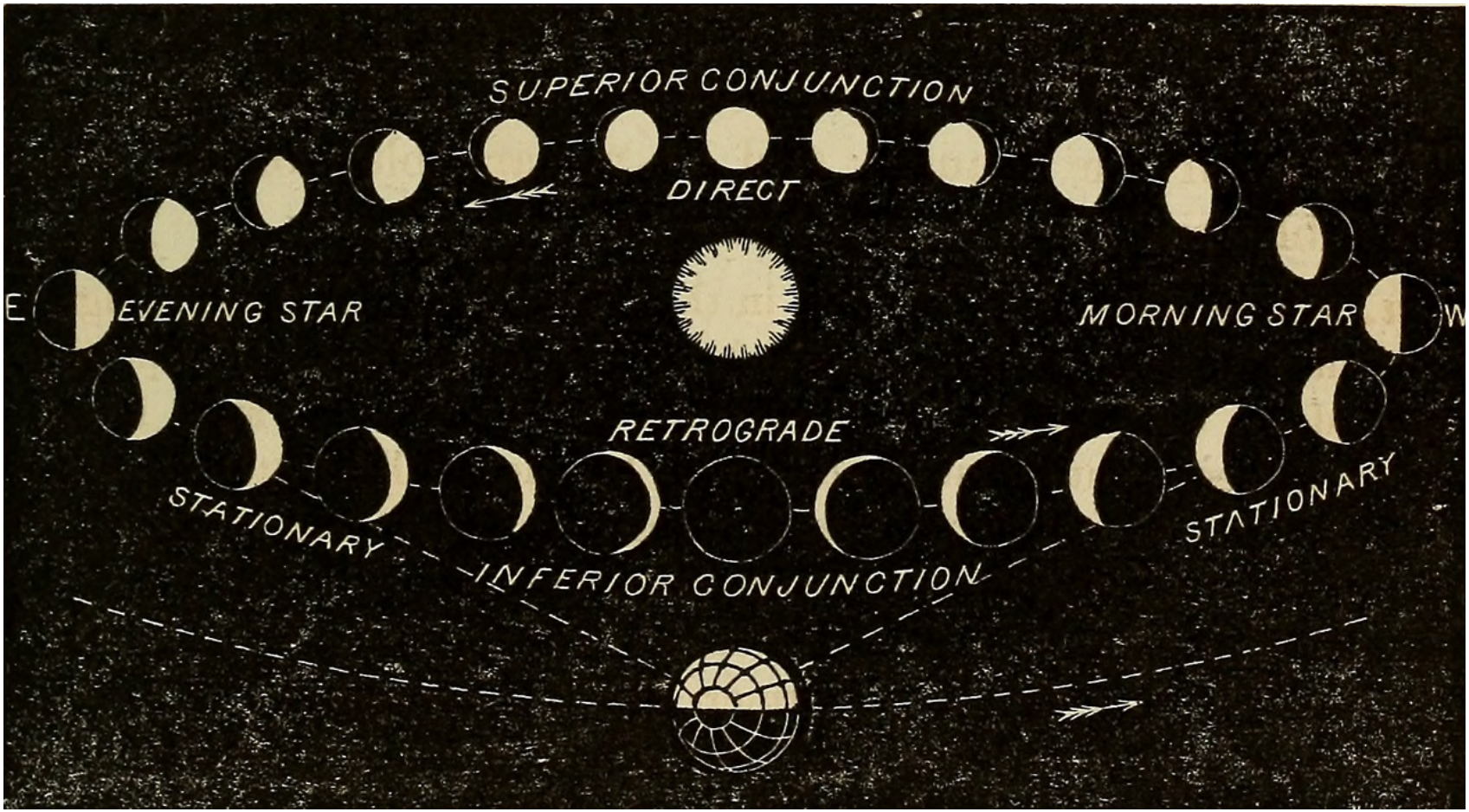


FIG. 9. In the Copernican system the apparent retrograde motion of planets has a simple explanation; it is a matter of relative speeds. Here the sighting lines show why a superior planet, one farther from the sun than the earth is, seems to reverse its direction. It is traveling around the sun more slowly than the earth is.

Animation:

https://astro.unl.edu/classaction/animations/renaissance/retrograde.html

(b) The phases of Venus



Problems for heliocentrism and discussion

- objections against heliocentrism: unobserved stellar parallax, terrestrial physics, theological and psychological arguments
- also had trouble with predictions and accounting for data (Copernicus noted, not without pride, that his theory accounted for the data just as well as did Ptolemy's theory)
- Despite popular belief, Copernican theory was not much simpler than its Ptolemaic opponent—it also needed eccentrics and epicycles.
- It only became much simpler once ellipses were introduced as planetary orbits (by Kepler).

Osiander's instrumentalism: 'saving the phenomena'

In his anonymous preface to *De revolutionibus*

Andreas Osiander, 'To the reader concerning the hypotheses of this work'

Since the newness of the hypotheses of this work—which sets the earth in motion and puts an immovable sun at the centre of the universe—has already received a great deal of publicity, I have no doubt that certain of the savants have taken grave offense... If, however, they are willing to weigh the matter scrupulously, they will find that the author of this work has done nothing which merits blame. For it is the job of the astronomer to use painstaking and skilled observation in gathering together the history of the celestial movements, and then—since he cannot by any line of reasoning reach the true causes of these movements—to think up or construct whatever causes of hypotheses he pleases such that, by the assumption of these causes, those same movements can be calculated from the principles of geometry for the past and for the future too... for it is not necessary that these hypotheses should be true, or even probably; but it is enough if they provide a calculus which fits the observations...

[A]s far as hypotheses go, let no one expect anything in the way of certainty from astronomy, since astronomy can offer us nothing certain, lest, if anyone take as true that which has been constructed for another use, he go away from this discipline a bigger fool than when he came to it.

Main problem for heliocentrism

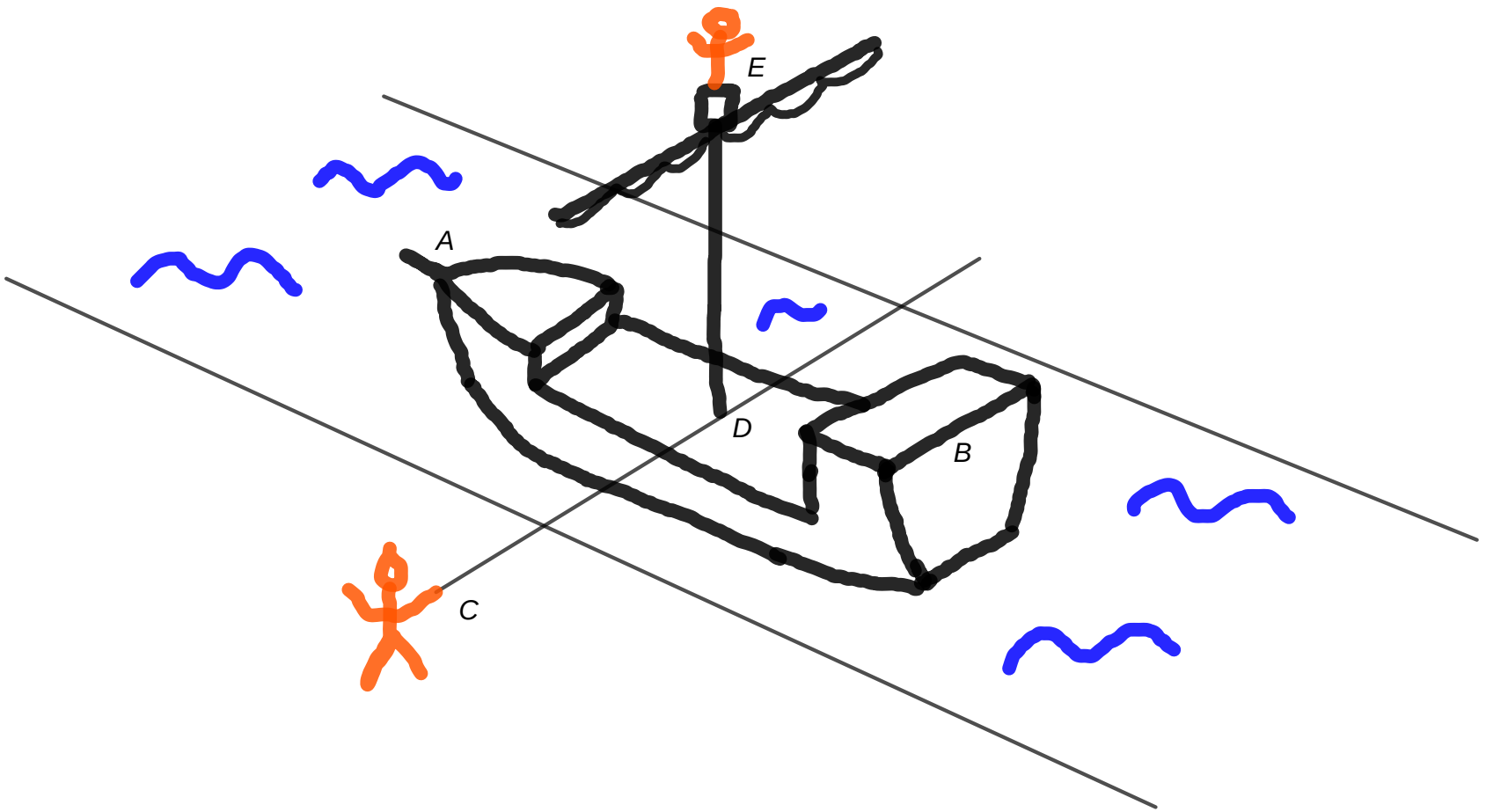
Giordano Bruno (1548-1600)

- Aristotle's view implies that natural motion is toward absolute natural place, and so is not relative to frame of reference
- Although similar, spottier analyses of natural motion challenging Aristotle existed before, we find in Bruno's *La Cena de le Ceneri* (1584) an early version of what we now call 'Galilean relativity':

Bruno, *The Ash Wednesday's Supper*, 3rd dialogue (tr. Stanley L. Jaki, 1975)

With the earth move, therefore, all things that are on the earth. If, therefore, from a point outside the earth something were thrown upon the earth, it would lose, because of the latter's motion, its straightness as would be seen [Fig. 6] on the ship AB moving along a river, if someone on point C of the riverbank were to throw a stone along a straight line, [and] would see the stone miss its course [target] by the amount of the velocity of the [ship's] motion. But if someone were placed high on the mast of that ship, move as it may however fast, he would not miss his target at all, so that the stone or some other heavy thing thrown downward would not come along a straight line from the point E which is at the top of the mast, or cage, to the point D which is at the bottom of the mast, or at some point in the bowels and body of the ship. Thus, if from the point D to the point E someone who is inside the ship would throw a stone straight [up], it would return to the bottom along the same line however far the ship moved, provided it was not subject to any pitch and roll.

Bruno's ship and Galilean relativity



Galileo Galilei (1564-1642)

- developed and defended Bruno's principle of relativity
- systematically challenged Aristotelian physics

Galileo's law of free fall

If the air resistance is negligible, then any two bodies that are dropped together will fall together, regardless of their weights, shapes, and the substances of which they are made.

Galileo, *Dialogues Concerning Two New Sciences*, pp. 66ff (tr. Henry Crew and Alfonso de Salvio, 1914)

> *[It] is possible to prove clearly, by means of a short and conclusive argument, that a heavier body does not move more rapidly than a lighter one provided both are of the same material... If we... take two bodies whose natural speeds are different, it is clear that on uniting the two, the more rapid one will be partly retarded by the slower, and the slower will be somewhat hastened by the swifter... But if this is true, and if a large stone moves with a speed of, say, eight while a smaller moves with a speed of four, then when they are united, the system will move with a speed less than eight; but the two stones when tied together make a stone larger than that which before moved with a speed of eight. Hence the heavier body moves with less speed than the lighter; an effect which is contrary to your supposition. Thus you see how, from your assumption that the heavier body moves more rapidly than the lighter one, I infer that the heavier body moves more slowly... We infer therefore that large and small bodies move with the same speed provided they are of the same specific gravity.*

Johannes Kepler (1571-1630)

Law (Kepler's first law)

The orbit of every planet is an ellipse with the Sun at one of the two foci.

Law (Kepler's second law)

A line joining a planet and the Sun sweeps out equal areas during equal intervals of time.

Law (Kepler's third law)

The square of the orbital period P of a planet is directly proportional to the cube of the semi-major axis a of its orbit, $P^2 \propto a^3$.

Occult powers: magnetism

- During the Renaissance, we see a trend of increasing exploitation of occult qualities, both theoretical (explanatory) and practical.
- emergence of 'Hermeticism', natural magic (which is based on occult powers of things) and alchemy (and metallurgy)
- William Gilbert (1544-1603), *De magnete* (1600): investigation of magnetism (lodestones, Earth), argued that Earth's motion is explained by magnetism

$\Rightarrow$ 'occult' explanation of gravity, explains its nature of 'action at a distance'

The rise of the 'kinematic' approach

Characterisation (Kinematic explanation)

The kinematic approach to explanation seeks to eliminate all explanations of natural phenomena based on occult powers and to replace them with explanations exclusively in terms of bodies in motion.

- advocates: Galileo, Descartes, Isaac Beeckman (1588-1637), Thomas Hobbes (1588-1679)
- Galileo: kinematic explanation of the tides, tried to explain acceleration in free fall without recourse to occult idea of gravity

René Descartes (1596-1650)

- replaced Aristotle's theory of scientific explanation by his mechanical philosophy

$\Rightarrow$ Rather than in terms of the 'natures' of things, Descartes used Archimedean simple machines (lever, wheel/axle, pulley, inclined plane, wedge, screw) as models of explanations.

$\Rightarrow$ All physical change (including living things) is explained in terms of intermeshings, friction, collisions of material parts.

- Change is not a result of forms or natures, but of geometrical changes in the shape or spatial arrangement of things.

$\Rightarrow$ mechanical and atomistic

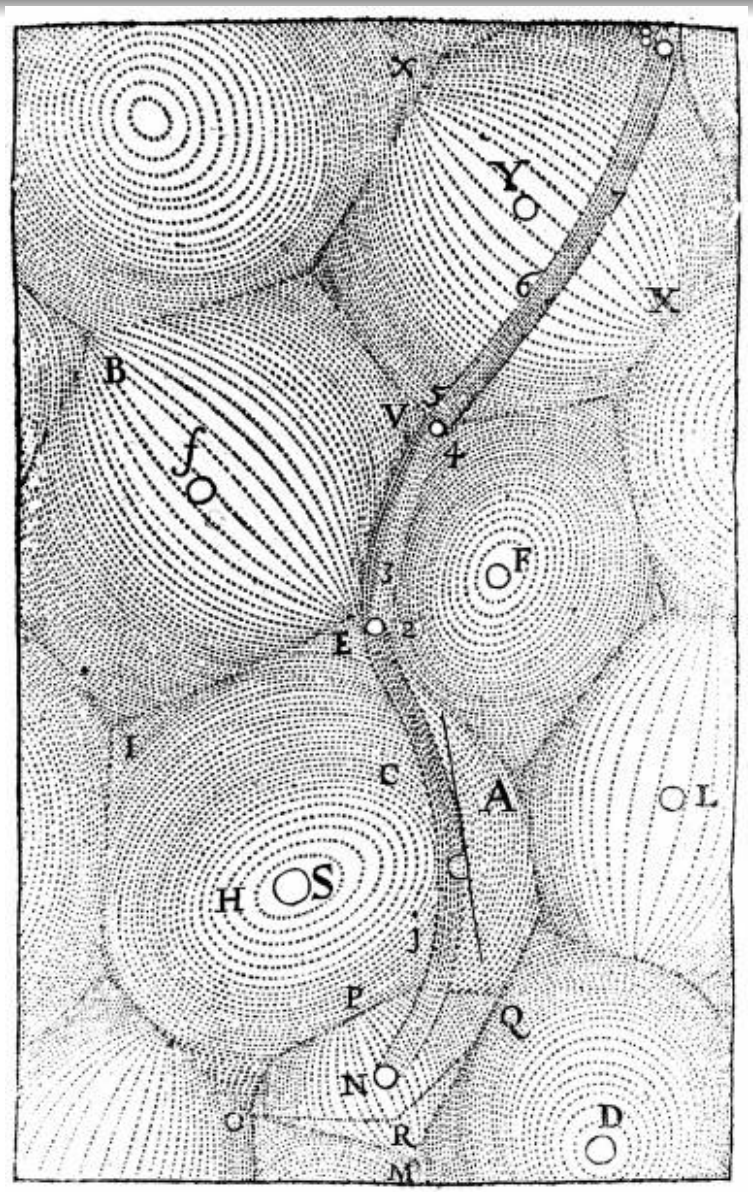
Cartesian physics: basic principles

1. The universe is completely full of matter (plenum universe).
2. All matter is essentially the same.
3. The only fundamental properties of matter are its size, shape, and relative position. All other properties arise solely from the fundamental geometrical properties of bodies

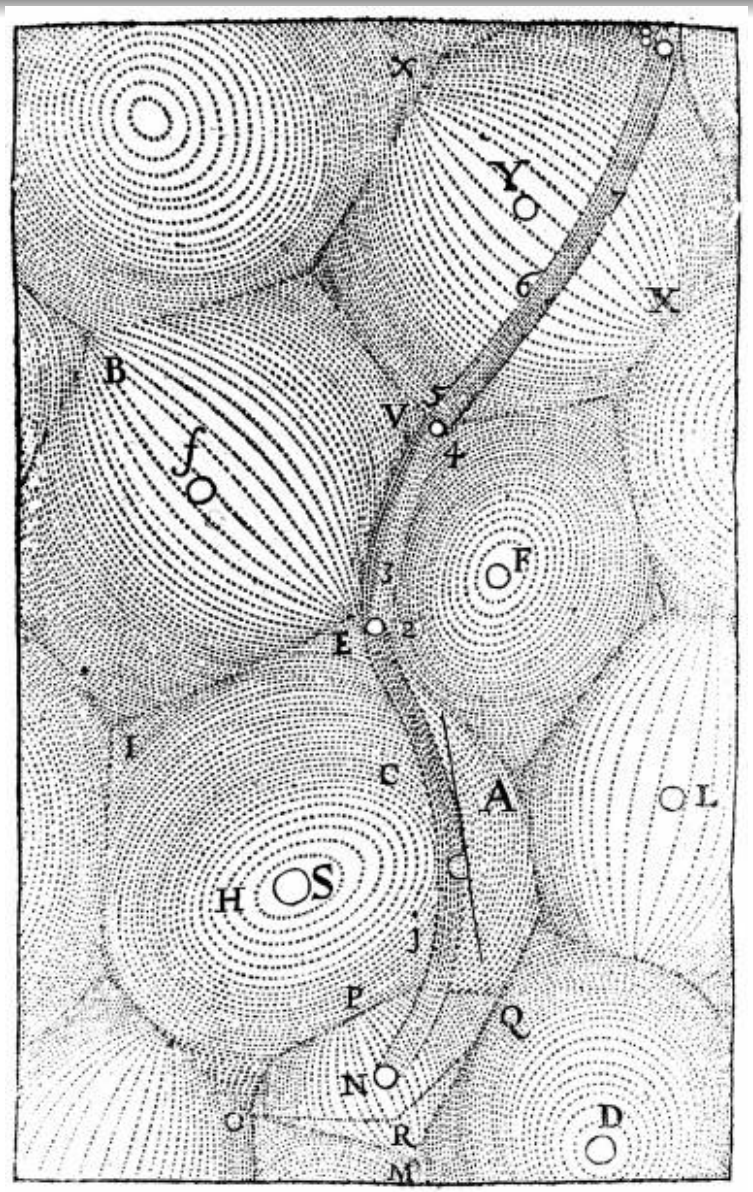
Descartes, *Principles of Philosophy*, part II, sections 23 and 64 (Reidel 1963)

> *Therefore, all the matter in the whole universe is of one and the same kind; since all matter is identified solely by the fact that it is extended. Moreover, all the properties which we clearly perceive in it are reducible to the sole fact that it is divisible and its parts moveable... I know of no kind of material substance other than that which can be divided, shaped and moved in every possible way, and which Geometers call quantity and take as the object of their demonstrations. And that there is absolutely nothing to investigate about this substance except those divisions, shapes and movements.*

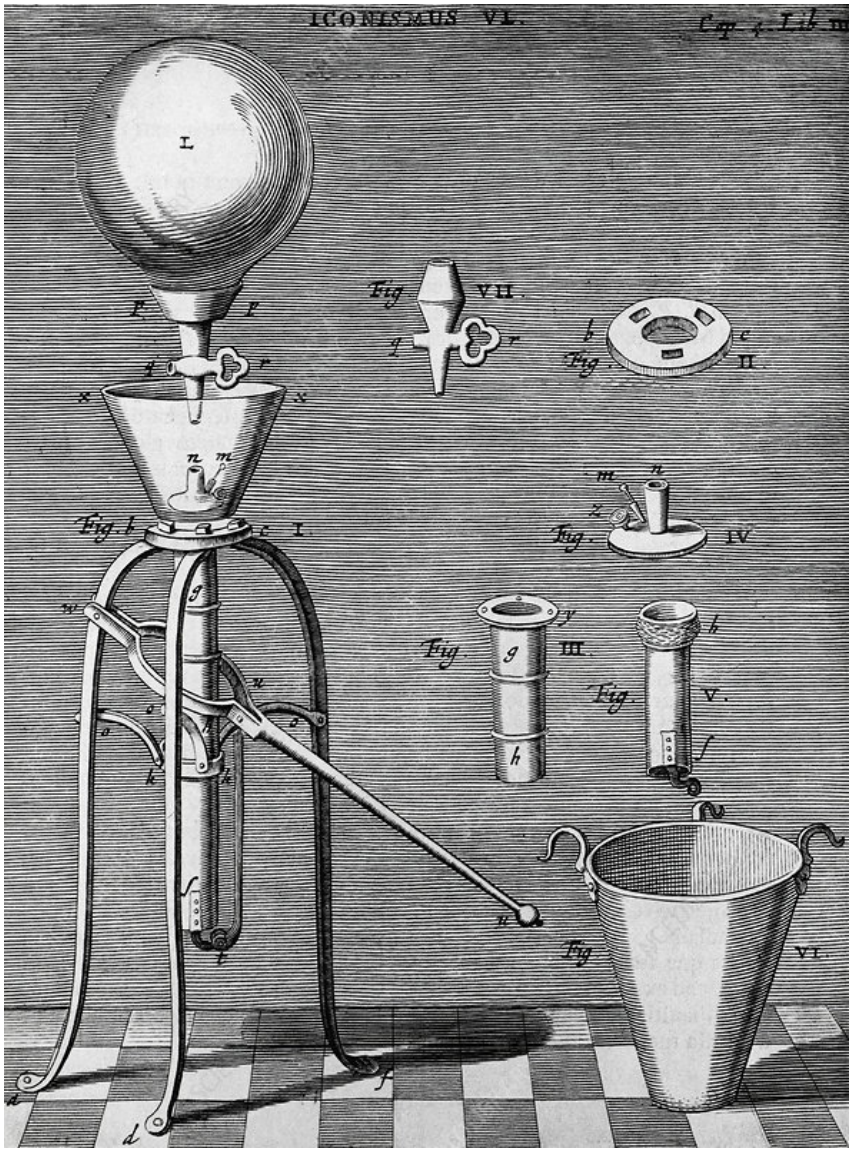
Cartesian universe



Cartesian universe



The physics of the void

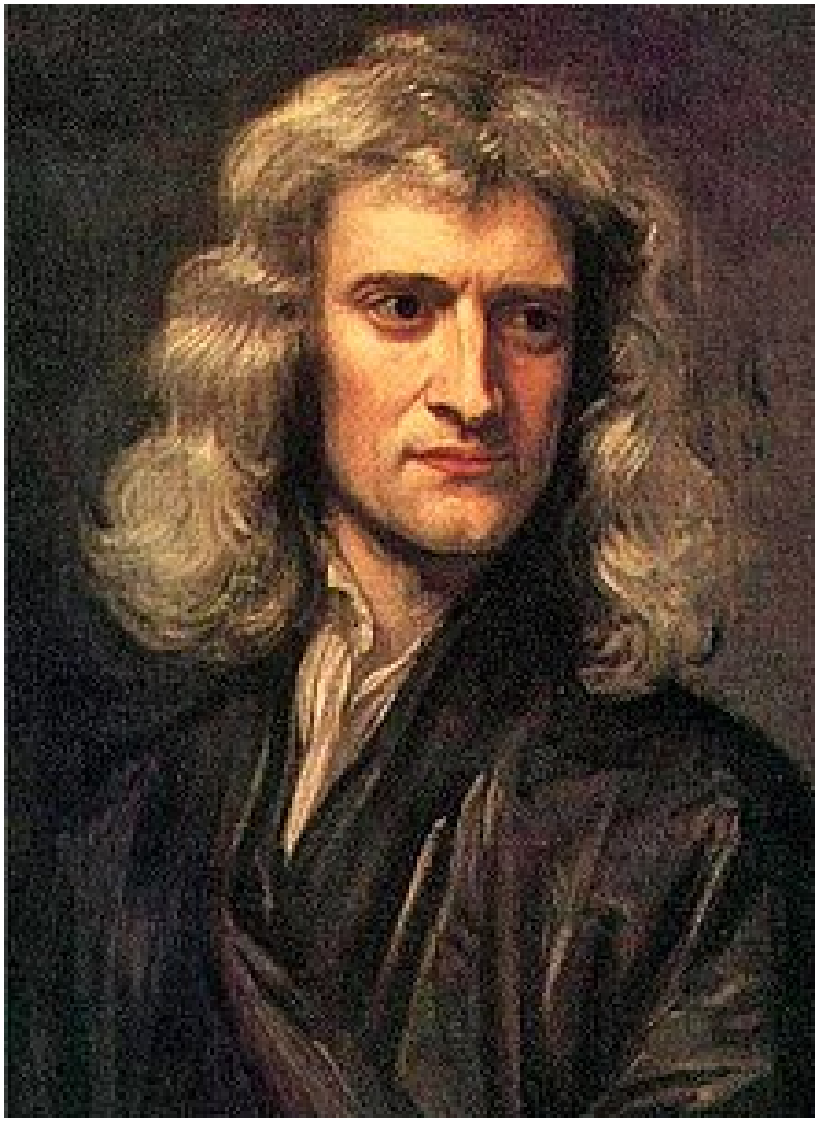


- Otto von Guericke (1602-1686): air pump 1650

$\Rightarrow$ possibility of void space

- Blaise Pascal (1623-1662): role of atmospheric pressure in various phenomena
- Robert Boyle (1627-1691) and Robert Hooke (1635-1703): experiments on void

Isaac Newton (1643-1727)



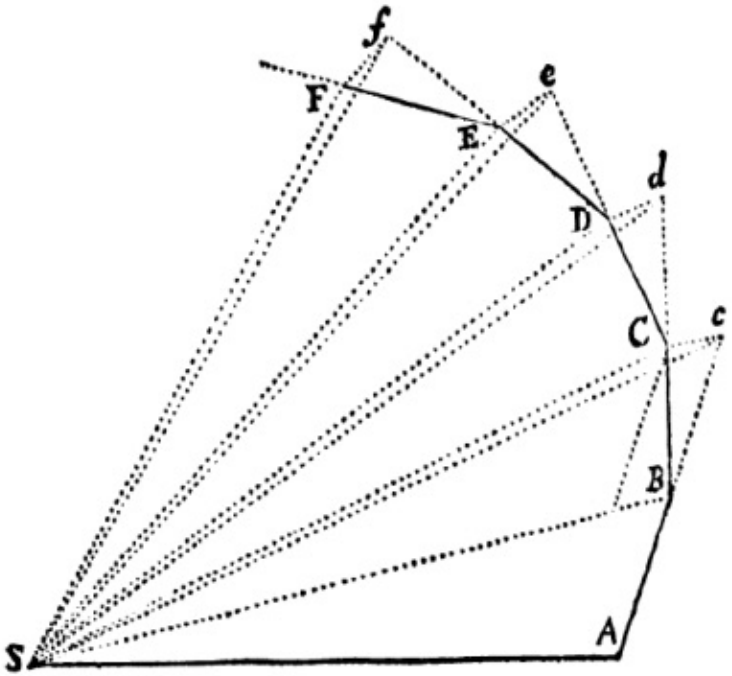
- problem for Descartes: no one ever discovered mechanical account of motion of planets

$\Rightarrow$ Descartes was unable to transform his qualitative account into an empirically successful quantitative theory

- Newton did just that with his law of universal of gravitation

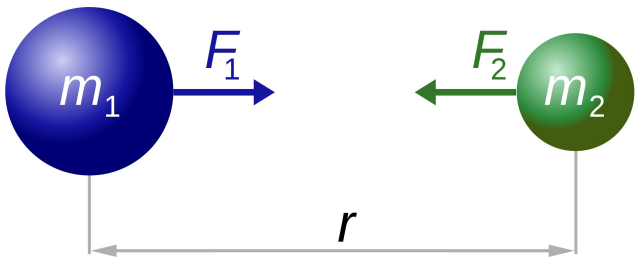
$\Rightarrow$ theory of planetary orbits; Kepler's laws can be recovered to good approximation

Universal gravitation



- natural motion: If no force acts on body, then the body moves at constant velocity in straight line
- gravity acts on planet at points, gives it jerk toward sun; rectilinear inertial motion in between jerks
- motion of planet is "constant falling forward around the sun"
- approximation of ever smaller intervals: motion gets smoothed out to form elliptical orbits

Newton's law of universal gravitation



$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

Proposition 75, Theorem 35

If to the several points of a given sphere there tend equal centripetal forces decreasing in a duplicate ratio of the distances from the points; I say, that another similar sphere will be attracted by it with a force reciprocally proportional to the square of the distance of the centres.

Isaac Newton (1687), *Philosophiae Naturalis Principia Mathematica*. Translated by Andrew Motte.

Universal gravitation

- Newton's law of gravity is truly universal: unification of sublunar and supralunar physics (though already in Descartes)
- He is unable to give mechanical explanation of gravity, and so gravity needs to be added to mechanical universe as nongeometric power

Newton, in a letter to Robert Hooke, 1676 (and almost verbatim in *Principia*):

> *I have not been able to discover the cause of those properties of gravity from phenomena, and I frame no hypotheses; for whatever is not deduced from the phenomena is to be called a hypothesis, and hypotheses, whether metaphysical or physical, whether of occult qualities or mechanical, have no place in experimental philosophy.*

Newtonian physics: laws of motion (*Principia*, different translations)

1. Every body persists in its state of being at rest or of moving uniformly straight forward, except insofar as it is compelled to change its state by force impressed.
2. A change in motion is proportional to the motive force impressed and takes place along the straight line in which that force is impressed.
3. To every action there is always opposed an equal reaction: or the mutual actions of two bodies upon each other are always equal, and directed to contrary parts.

Derivation of Kepler's third law from Newton's laws

Source

https://phys.libretexts.org/Bookshelves/University_Physics

- We assume that a planet of mass m orbits the Sun (with mass M) on a circular orbit of radius r, held in by gravity as the centripetal force acting on m.
- Newton's second law when applied to circular motion of velocity v on the orbit gives us
$$F = ma = m\frac{v^2}{r}.$$
- Gravity is the external force acting on m, so we use Newton's law of universal gravitation:
$$G\frac{Mm}{r^2} = m\frac{v^2}{r},$$
where G is Newton's constant.
- Canceling m (all masses fall with the same acceleration at a given location) and r, we obtain
$$\frac{GM}{r} = v^2.$$

- Thus, at a given orbital radius r, all masses orbit at the same velocity.
- By definition the orbital period P is the time it takes the planet for one complete revolution.
- The average velocity v is the circumference divided by the period,

$$v = \frac{2\pi r}{P}.$$

- We substitute v into the previous equation to obtain

$$\frac{GM}{r} = \frac{4\pi^2 r^2}{P^2}.$$

- Solving for P^2 yields

$$P^2 = \frac{4\pi^2 r^3}{GM}.$$

- Two planets (of the same sun), indexed by subscripts 1 and 2, are compared by their ratio of the last equation to obtain

$$\frac{P_1^2}{P_2^2} = \frac{r_1^3}{r_2^3},$$

  which is Kepler's third law.
- Note that this is valid only to an approximation, as the orbits are not precisely circular—see the first law!