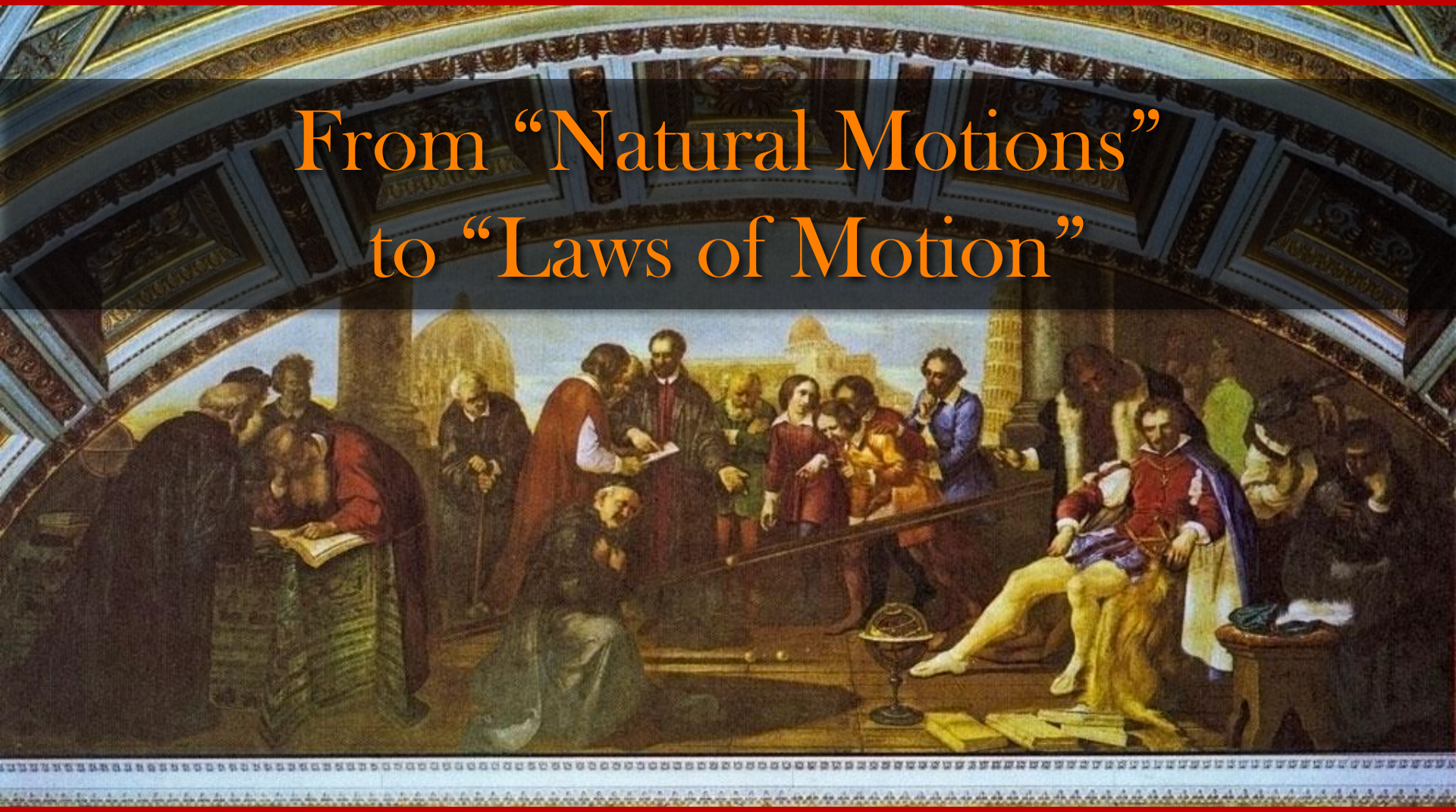
From "Natural Motions" to "Laws of Motion"



Prof. David Kaiser

Motion unit

Overarching questions:

Are the motions of objects subject to universal laws?

Does science drive technology, or the other way around?

I. Aristotle and Natural Motions

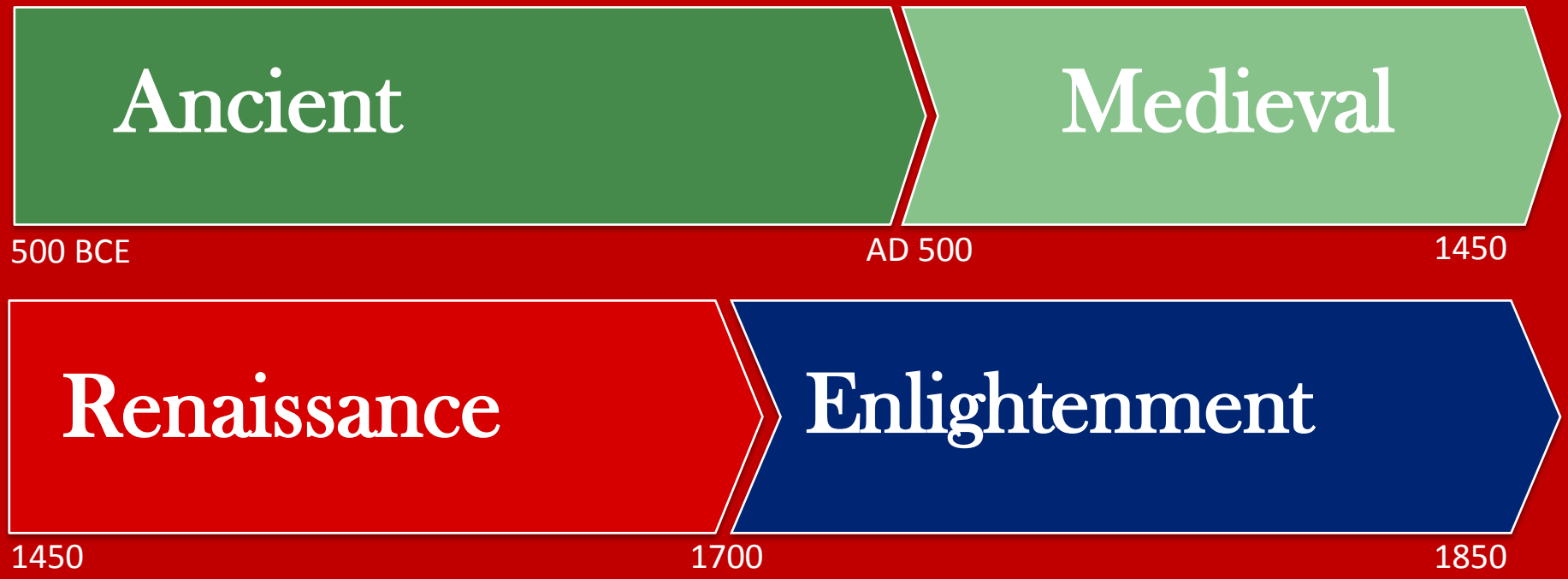
II. Galileo's Mechanics

III. Newton and the *Principia*

Reminder: Paper 2 due in class on Monday, 18 Oct!

Readings: Aristotle, *Physics*, 342-345;
Newton, *Principia*, 221-246;
Dear, *Intelligibility of Nature*, 15-38.

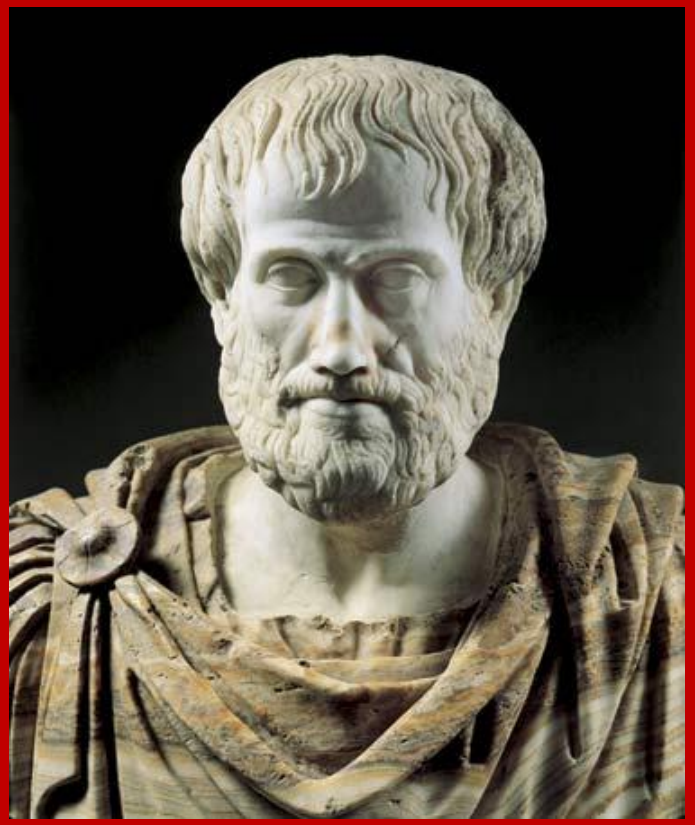
Bend Back the Arc of History...



"For the Most Part"

"Among things which are, some are always in the same state [...], and some are not of necessity nor always, but for the most part. [...] There is, then, besides these, something which is fortuitous and accidental. [...] That there is no science of the accidental is obvious; for all science is either of that which is always or of that which is for the most part."

Aristotle, *Metaphysics*, IV 2



Aristotle (384 – 321 BCE)

Aristotle did not believe in universal *laws*, of the kind we might seek today. He built his project around *regularities* and *tendencies*: what happens in nature "always or for the most part."

Aristotle's Elements

Photo courtesy of Blaž Vizjak on Flickr.

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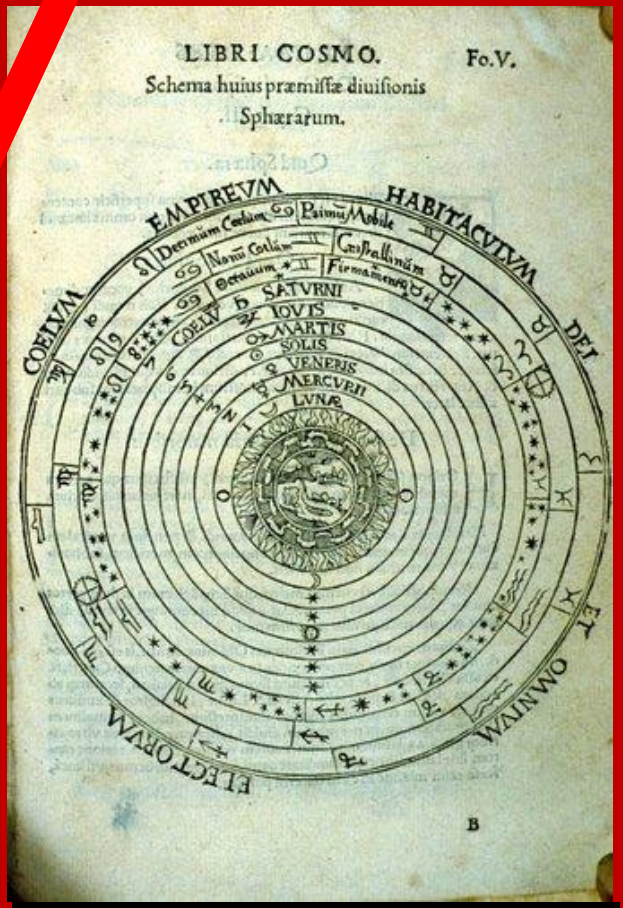
Terrestrial

Celestial

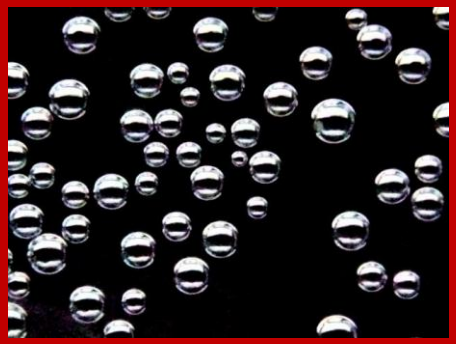


Peter Apian, *Cosmographia*, 1524

Natural Motions

To Aristotle, each element had one “natural motion” or tendency.

Photo courtesy of kevindooley on Flickr.



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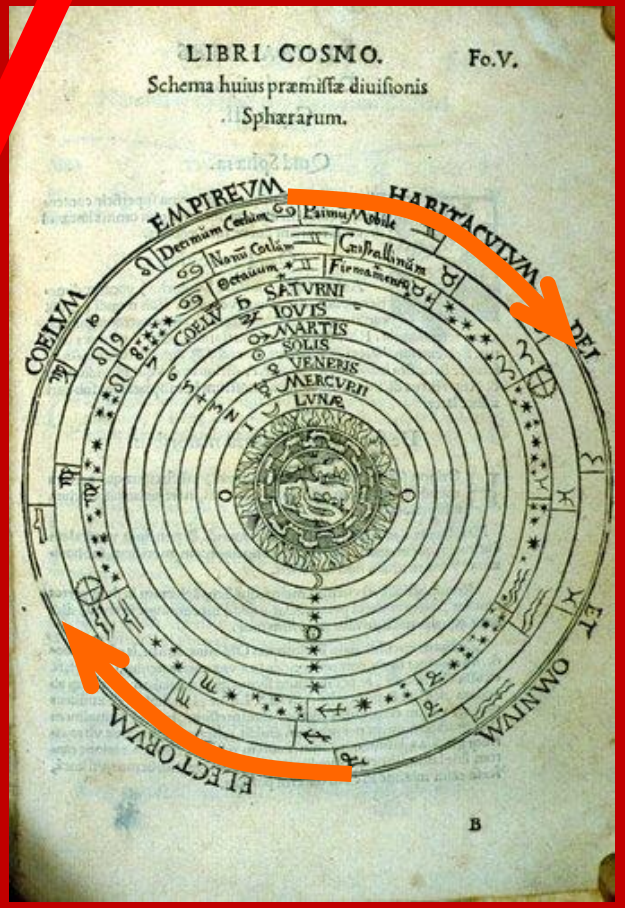


Consistent with casual observations; empirical.

Dynamics

Photo courtesy of nickwheeleroz on Flickr.

Photo courtesy of n0rthw1nd on Flickr.

Built around *proportions*:
"A given weight moves a given distance in a given time. A weight which is greater moves the same distance in less time, the times being inversely proportional to the weights."
Aristotle, *De Caelo*, I 6

According to Aristotle, the rock should fall much more quickly than the feather.

Trajectories

The javelin thrower's hand sets some of the surrounding air in motion. That air, in turn, acts on the neighboring air, keeping the javelin moving forward.

Photo courtesy of tableatny on Flickr.

The pushes from the air diminish over time. Eventually the javelin falls to the ground: its *natural motion* (straight down) overcomes the impressed motion.

"Nature abhors a vacuum":
Aristotle assumed a *plenum universe*.

Thresholds

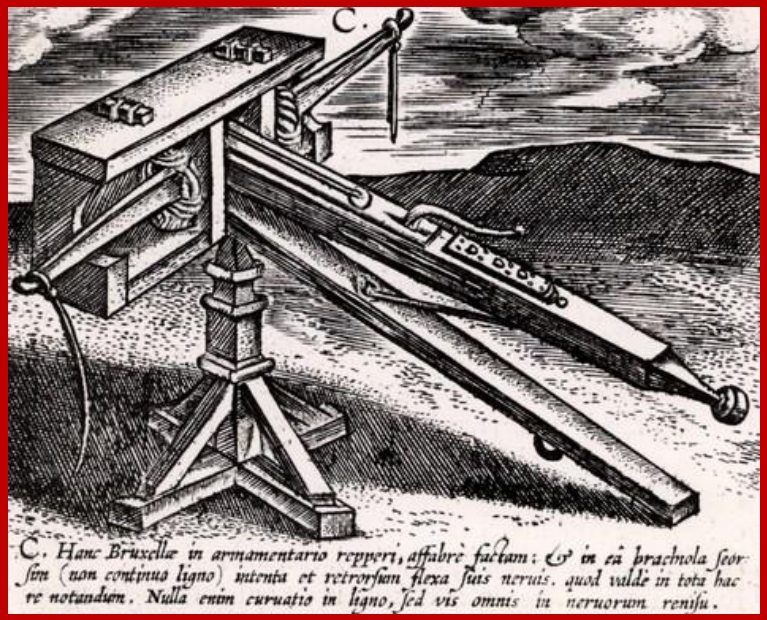
Even though 50 men can haul a ship over land at a given speed, it is *not* the case that 1 man can haul the ship at 1/50th the speed.

Sir Ernest Shackleton's 1914 Antarctic expedition

To Aristotle, empirical observation should rein in deductive reasoning.

Hellenistic Engineering

When designing military weapons, it was "necessary to determine [parameters of the weapons] not accidentally or haphazardly but by some definite method. [...] This could not be done except by increasing or decreasing the diameter of the bore and testing the results."



Crossbow attributed to Philo of Byzantium (ca. 250 BCE)

Weight in minas	Diameter of opening in digits*
10	11
15	12¾
20	14
30	15¾
50	18¾
60 (= 1 talent)	21
150 (= 2½ talents)	25
180 (= 3 talents)	27

Philo of Byzantium, *Belopoeica*, ca. 250 BCE

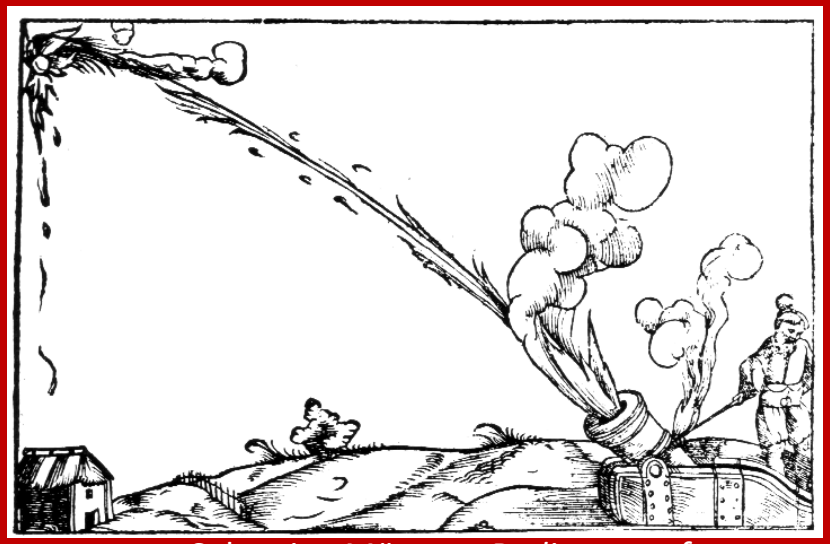
"For it is not possible to arrive at a complete solution of the problems involved merely by reason and by the methods of mechanics. Many discoveries can, in fact, be made only as a result of trial."

Philo of Byzantium, *Belopoeica*

Ballistics and Artillery

Gunpowder (invented by Chinese) entered Europe in the early 14th century.

Renewed importance of the study of motion: where will cannon balls land?



Sebastian Münster, *Rudiments of Mathematics*, 1551

"Mons Meg" cannon, Edinburgh, 1457

Photo courtesy of buhny on Flickr.

By the early 17th century, firearms and artillery had become the *dominant* weapons in European warfare, surpassing swords and pikes.

Galileo's Mechanics

Galileo Galilei (1564 – 1642) was born into court culture: his father was a court musician at the Tuscan court in Florence.

Ottavio Leoni, *Galileo*, 1624

Galileo taught mathematics at the University of Pisa and the University of Padua during the 1580s and 1590s. He also served as a consultant to the Venetian Senate.

Photo of Galileo's telescope from 1609 removed due to copyright restrictions.

Galileo's telescope, 1609

What Goes Up... Must Come Down

Galileo became court philosopher under Cosimo II de Medici in Florence, 1610...

Michele Castrucci, *Cosimo II de Medici*, ca. 1610

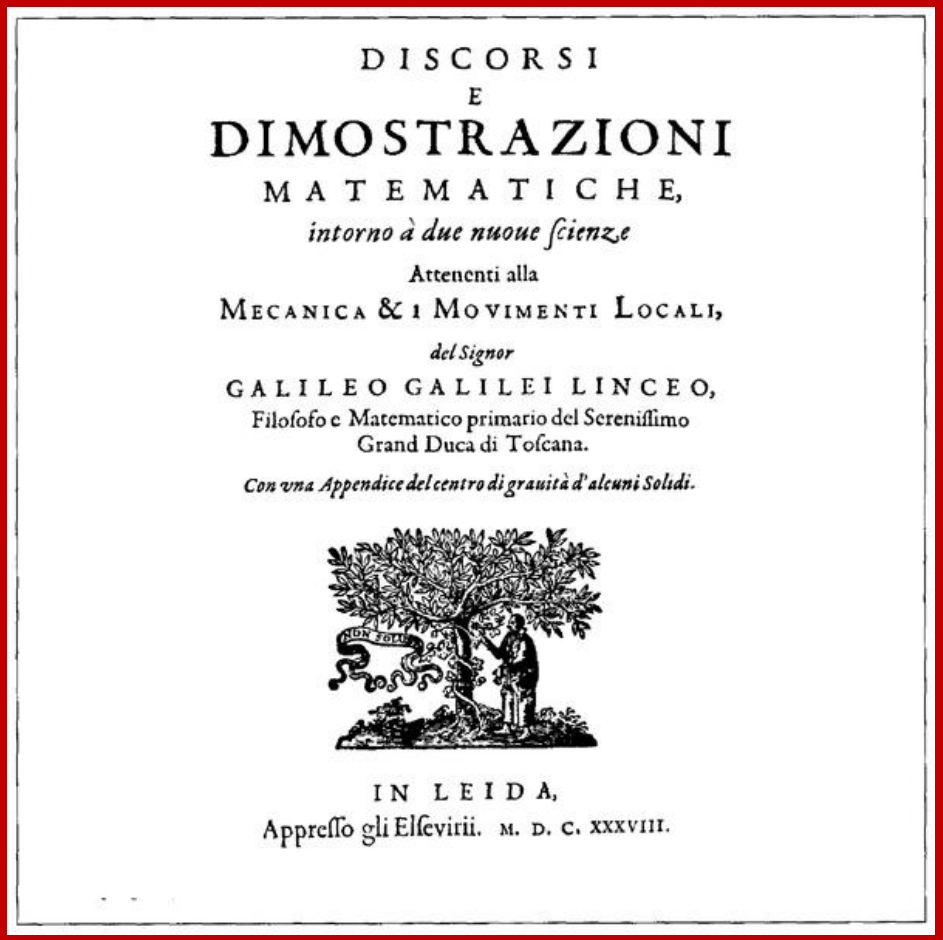
Cristiano Banti, *Galileo Facing the Roman Inquisition*, 1857

... and faced the Roman Inquisition in 1632.

Image of "Galileo, Courtier: The Practice of Science in the Culture of Absolutism," Mario Biagioli, removed due to copyright restrictions.

"Two New Sciences"

While living under house arrest, Galileo completed a major work on motion: *Discourses and Mathematical Demonstrations Concerning Two New Sciences.*



DISCORSI
E
DIMOSTRAZIONI
MATEMATICHE,
intorno à due nuoue ſcienze
Attenenti alla
MECANICA & I MOVIMENTI LOCALI,
del Signor
GALILEO GALILEI LINCEO,
Filoſofo e Matematico primario del Sereniſſimo
Grand Duca di Toſcana.
Con vna Appendice del centro di grauità d'alcuni Soldi.

IN LEIDA,
Appreſſo gli Elſevirii. M. D. C. XXXVIII.

A follower smuggled the manuscript out of Italy to Leiden, in Protestant Netherlands, where the book would not be subject to the Catholic Inquisition. Elsevier published it in 1638.

Practical Matters

FIRST DAY

INTERLOCUTORS: SALVIATI, SAGREDO AND SIMPLICIO

SALV. The constant activity which you Venetians display in your famous arsenal suggests to the studious mind a large field for investigation, especially that part of the work which involves mechanics; for in this department all types of instruments and machines are constantly being constructed by many artisans, among whom there must be some who, partly by inherited experience and partly by their own observations, have become highly expert and clever in explanation.

Mean Speeds

Galileo explained that uniformly accelerated motion could be reduced to an equivalent uniform-speed motion — even simpler. Work in terms of *mean* or *average speeds*.

Graph of the Mean Speed Theorem removed due to copyright restrictions.

Area of the triangle: $(1/2)\ (v_f - v_i)\ T$

Area of the rectangle: $v_{avg}\ T$

Typical of Galileo's arguments: relied upon simple geometrical relationships and ratios, rather than algebra (no calculus yet!).

Times Square Law

$$\frac{L_{\text{full}}}{L_{1/4}} = 4, \quad \frac{t_{\text{full}}}{t_{1/4}} = 2,$$

t	L	
0	0	
		1
1	1	
		3
2	4	
		5
3	9	
		7
4	16	

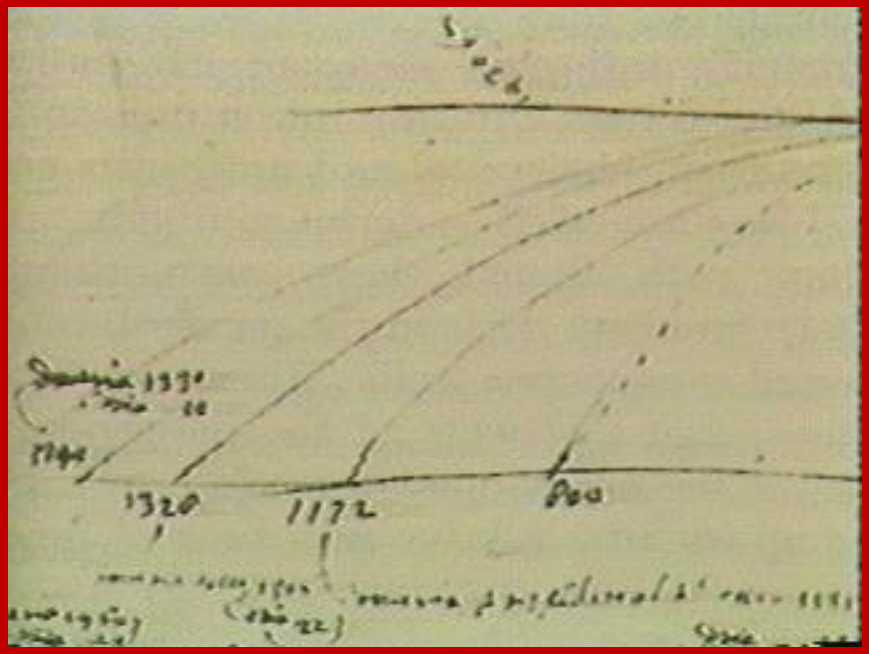
"The differences in distances covered should be like the odd numbers."

We'd say: $L = kt^2$

Bernard Poyet, *Chinese water clock*, ca. 1800

Compound Motion

Projectiles often combined uniform-speed motion (horizontal) with uniform-acceleration motion (vertical).



Galileo's notebook

Once again Galileo used geometrical arguments and ratios. We would say:

$$\left.\begin{aligned} x &= vt \\ y &= kt^2 \end{aligned}\right\} \quad t^2 = x^2 / v^2 = y / k$$

$y \sim x^2$, parabola

Which Falls Faster?

Legend has it that Galileo challenged the Aristotelians by dropping balls of different weights off the Leaning Tower of Pisa, to demonstrate that they would fall at the *same* rate, contra Aristotle's teachings.

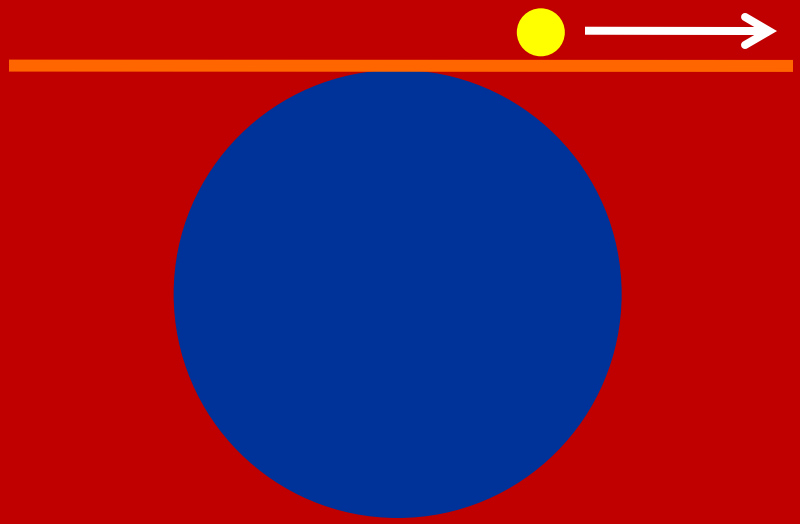
Leaning Tower of Pisa

Photo courtesy of otzberg on Flickr.

First told by Galileo's friend and biographer after Galileo's death. Most likely the story was apocryphal, though Galileo may well have performed less dramatic tests while living in Pisa.

"Natural Motions" Revisited

Galileo broke with Aristotle in *specifics*, but not really in *framework*: he concluded that Nature prefered uniform circular motion for *all* natural motions.

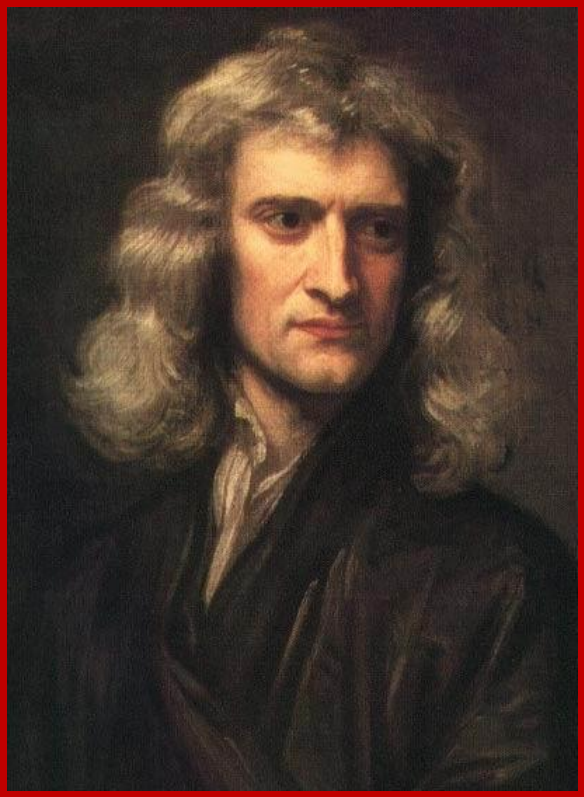


If the object kept moving horizontally, it would go uphill; but then its "innate heaviness" would change its path. Only a circular path would allow the ball to remain in uniform-speed motion.

His reason was also quasi-Aristotelian: only uniform circular motion was perfect enough to exist eternally; it's indefinitely sustainable.

Newton's Early Life

Isaac Newton (1642 – 1727): his father died before he was born; his mother sent him off to be raised by his grandmother. He inherited a small farm, but failed at the task. So instead it was off to Cambridge University in 1661.



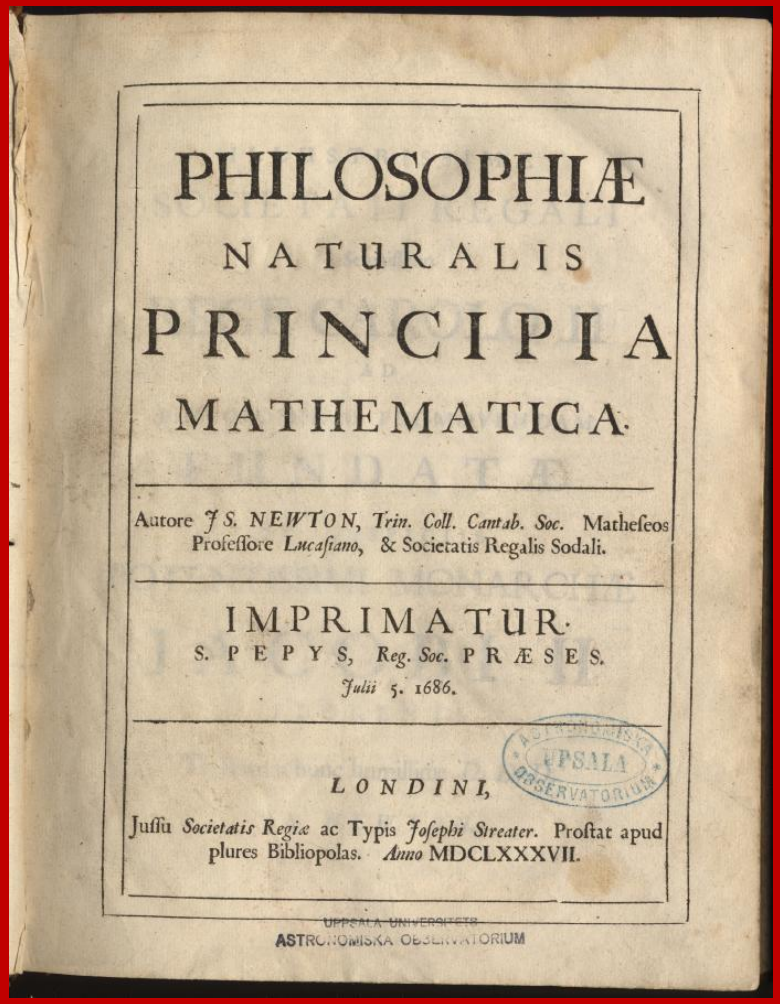
Godfrey Kneller, portrait of Isaac Newton, 1689

A lackluster student, his breakthrough came when Cambridge closed because of the plague (1665–1666). Back in Woolsthorpe, on his own, Newton invented the calculus and most of the laws of motion...

"Mathematical Principles of Natural Philosophy"

- Lucasian Chair of Mathematics, 1669 (at age 27);
- Elected to the Royal Society, 1672.

Meanwhile, Newton kept nearly all of his results to himself. He wrote a brief unpublished pamphlet, *De Motu* (On motion), to answer Edmund Halley's questions.


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.

UPSALA
ASTRONOMISKA OBSERVATORIUM

Finally, due mostly to Halley's urging, Newton published his *Principia* in 1687.

Form of the Argument

suggested by recoil in gunnery

Images of excerpts from "Principia Mathematica," I. Newton, removed due to copyright restrictions. See: Newton's Principia.

Looks like Euclid. Why no use of calculus?

Organization of the *Principia*

Book 1: "Motion of Bodies" [in vacuum]

universal laws, yet they don't always match experience

"which I conceive may be of use in the building of ships"

Book 2: "Motion of Bodies" [in resistant media]

of more practical concern, and more directly tied to experiments.

Halley: "This rule may be of good use to all Bombadiers and Gunners, so that they may shoot with more certainty."

Book 3: "System of the World"

celestial applications

Beyond Newton

Hooke's law:
ceiiinosssttuu (1676)
ut tensio sic vis (1678)
["as extension, so is force"]

$$F = -kx$$

Frontispiece of Thomas Sprat, *History of the Royal Society*, 1667

Hooke arrived at this result from his experiments at the Royal Society on the strengths of twisted vs. untwisted cords: "research for hire" for the Navy.

Thursday, June 23, 2011, STS.003

Pendulum's Period is Independent of its Mass

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