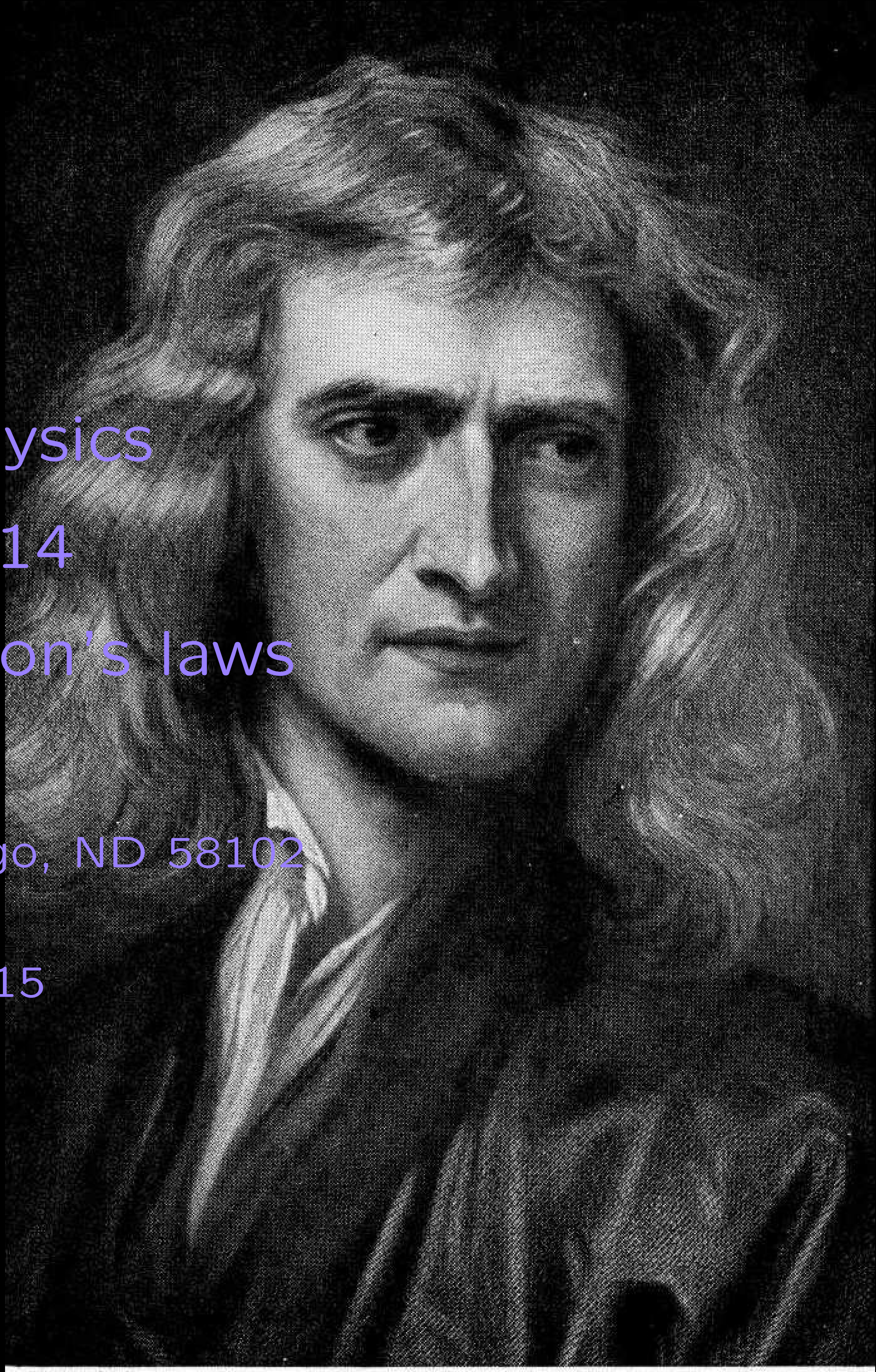

Lecture 4

Fundamentals of Physics

Phys 120, Fall 2014

Why things move: Newton's laws

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Overview

- Galileo
- Newton
- Force and acceleration
- Weight
- Forces come in pairs
- Momentum
- Review

A changing society

The medival society collapsed when the black death spread over Europe from 1346 to 1353, killing 75 to 200 million people, or 30-60% of Europe's total population. As a result, labor was scarce and field workers could demand higher wages. Movable wealth was spread more evenly, and as a side-effect paper made from rags became affordable, since there were more cloth and bed linen than could be used. So there was an overabundance of rags.

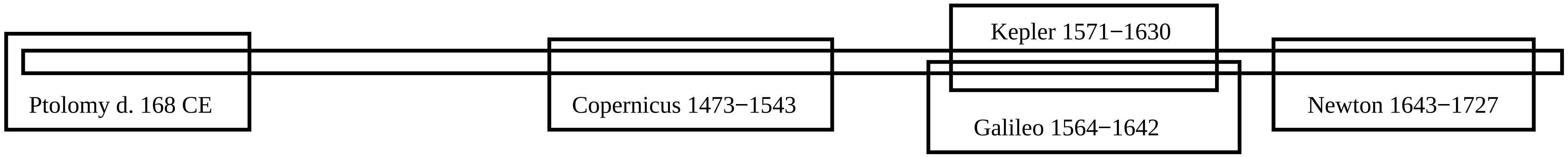
This allowed for the invention of the printing press with movable types by Gutenberg in 1439, and books once priceless treasures became more widespread. This enhanced the transfer of knowledge enormously.
Furthermore the previously tightly regulated medieval communities were shaken to their core, allowing for much more freedom among the remaining population.

Galileo

Last lecture we learned that Galileo discoverd that objects will remain in their state of motion unless they are acted upon by a force.

This was restated by Newton and is now (somewhat unfairly) known as Newtons first law.

Space Station movie (More on the Space Station)



Why do things move?

Galileo found out that objects stay in their state of motion (i.e. move in a straight line with constant velocity) unless they are acted on by a force.

That begs the question: what happens when there is a net force acting on the body? It state of motion will change, but just how is a difficult question. There were a lot of attempts to explain how forces will change the state of motion. An interesting reference for this may be found in Leibniz's (1646-1716) Philosophy, especially section 3 on Leibniz's dynamics.

But in this lecture we will focus on what we now (up to corrections in extreme cases of very high velocities or very small objects) believe to be the correct description of motion. But the apparently simple derivation of Newton's law belies the difficulty of actually thinking about motion in an effective way. Look up the reference above to get a little insight into that.

Newton

Isaac Newton was an exceptional English Physicist who happened to live just at the right time. He said: *If I have seen further it is by standing on the shoulders of giants.*

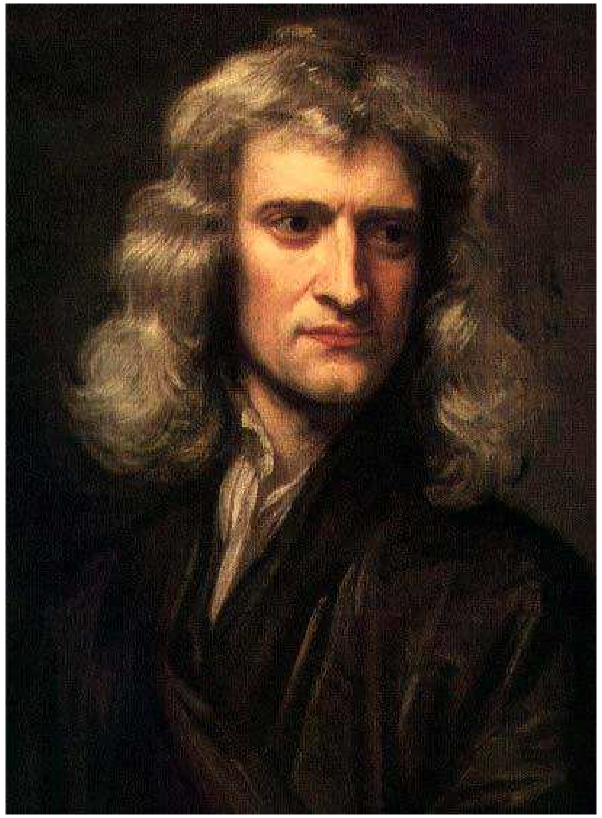
He made significant progress in a number of areas:

His most important work is *PhilosophiæNaturalis Principia Mathematica* ("Mathematical Principles of Natural Philosophy"), first published in 1687 develops Classical Mechanics and the universal laws of gravitation. He *derived* the Kepler orbits from his theory (which ended the geocentric worldview).

He developed differential calculus (in competition with Leibnitz)

He built the first functional reflecting telescope, developed a theory of color (based on the spectrum) and much more.

He was brilliant, but difficult as a person. He had a feud with Leibnitz about who should get the credit for the discovery of differential calculus. He is now believed to have suffered from Asbergers.



* 25 Dec. 1642
† 20 March 1727

Forces: why things accelerate

Galileo found out that objects will continue to move with a constant speed in a straight line if no net forces act upon them.

So how to you get objects to change their velocity?

You need to act upon them (i.e. apply a force).

Connecting Force and change in velocity (acceleration)*

Doubling the force (F) means doubling the acceleration (a):

$$a \propto F$$

(The funny symbol $\propto$ means *proportional to*)
Applying force to an object with twice the mass (inertia) will only give you half the acceleration:

$$a \propto \frac{1}{m}$$

Mass and weight: mass determines how easy or difficult it is to accelerate an object. Weight tells you how much the object is pulled towards the earth. Mass is a property of the object, weight depends on where you are (i.e. on the moon or in space the weight will be very different). It is defined through a standard lump of metal that is defined to have the mass of 1kg.

*This is a modern description, developed with 20/20 hindsight and full knowledge of Newton's theory. The historical development of this theory included many missteps, because the researchers were still steeped in Aristotelian thinking.

Force and acceleration, cont.

From this we can conclude

Acceleration is proportional to the applied force divided by the mass of the object.

$$a \propto \frac{F}{m}$$

But we need to find a measure (or a unit) for the force. We define the unit of force to be a Newton, which is to be the force it takes to accelerate a mass of $1kg$ in $1s$ to the speed of $1m/s$ (i.e. it gives it an acceleration of $1m/s^2$).

Then we have

$$\text{acceleration} = \frac{\text{force}}{\text{mass}} : \qquad a = \frac{F}{m}$$

when we measure acceleration in m/s^2, the mass in kg and the force in Newtons.

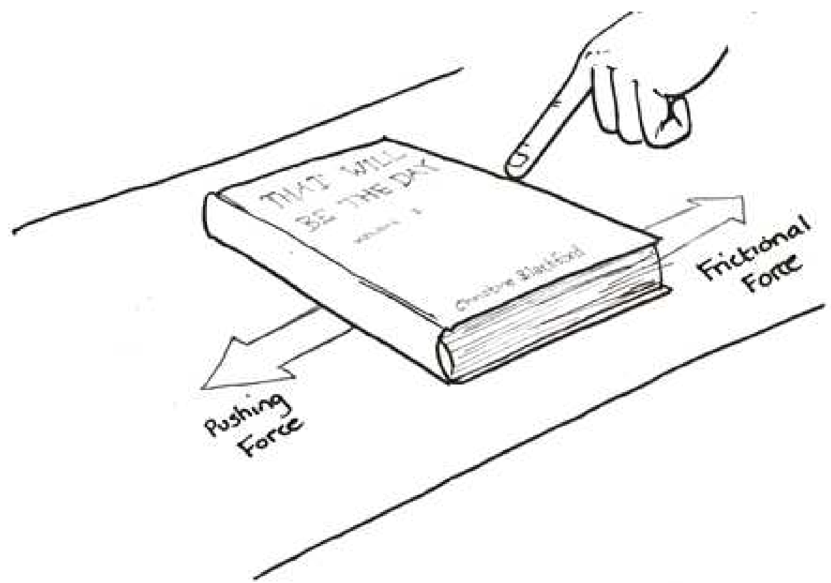
This is also known as Newton's second law, and it is the basis of much of our understanding of the world. Most of Engineering and much of Physics consists of solving this one equation for various systems.

Newton's law of motion: centerpiece of Newtonian Physics

What if more than one force is acting?

You need to add up the forces. (In this lecture forces all point along a line)

Example: Book on table



If the forces act in the same direction, add them, if they point in the opposite direction, subtract them.

Weight: gravity's force on a body

Earth exerts a gravitational force on objects that are falling to the ground. It still exerts a force, even when the object is not falling. All other massive objects also exert a gravitational force (see next lecture).

Weight refers to the net gravitational force exerted on it by all other objects. Since weight is a force it can be measured in Newtons.

Galileo found that all objects fall with the same acceleration. If two objects have the same mass, then the forces acting on them also have to be the same. But the force acting is just the force of gravity, or their weight!
Two objects of equal mass also have equal weight (as long as they are at the same place)*.

This is how scales can measure weight (i.e. a force) and represent them as mass (i.e. kg).

*Why the resistance to acceleration and the gravitational attraction should be linked is not clear. But this observation led Einstein to develop the general theory of relativity, as we shall see later.

Concept check

Consider a book lying on a table, what are the forces on it?

The law of force pairs

All forces come in pairs!

If you want to move an object you apply a force to it. But in the process the object pushes back on you!

Touch your neighbor's arm. Your hand is touched by your neighbor's arm. You cannot touch without being touched.

The law of Force Pairs
Every force is an interaction between two objects. Thus, forces must come in pairs; Whenever one body exerts a force on a second body, the second exerts a force on the first. Furthermore, the two forces are equal in strength but opposite in direction.

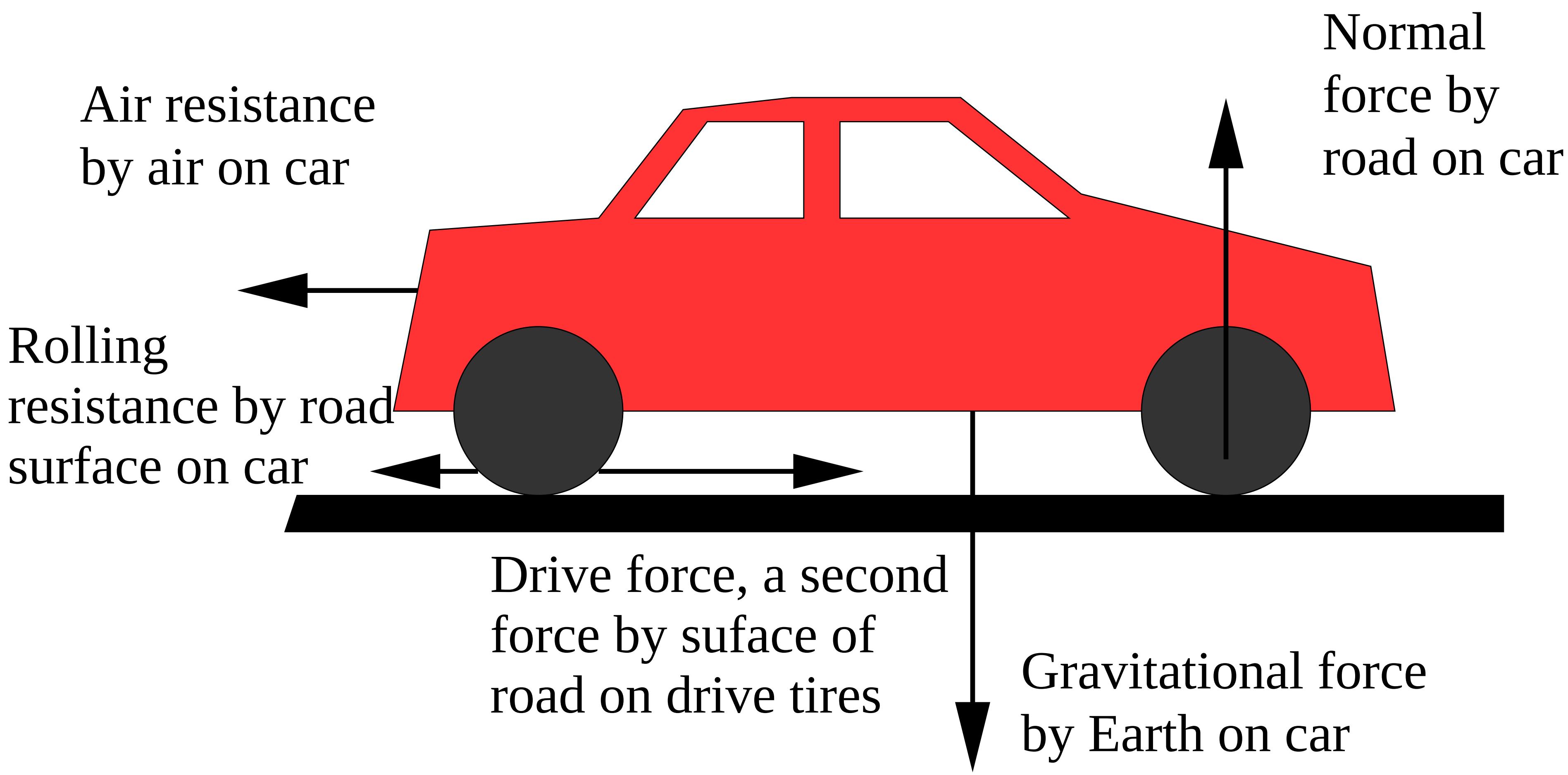
(This is also known as Newton's third law.)

Automobiles and Rockets

You cannot pull yourself up by your nose! So how can a car (or a person) be self-propelled?

Try to imagine all the forces on a automobile.

Forces on a car



Concept check

A car weighing 10,000 N moves along a straight, level, road at a steady 80 km/h. Air resistance is 300 N, and rolling resistance is 400 N. The net force on the car is

1. 10,000 N forward
2. 9,300 N
3. 10,700 N
4. 700 N
5. cannot be determined without knowledge of the strength of the drive force
6. is zero.

Momentum

Forces always come in pairs. So the sum of all forces has to be zero. This has an important consequence: the forces accelerate bodies, but if I accelerate one body in one direction, the second body will be accelerated in the opposite direction. The acceleration changes the velocities of the bodies, so there needs to be another quantity related to the velocity that is also balanced.

This quantity is the momentum (p):

$$\text{momentum} = \text{mass} \times \text{velocity} \quad p = mv$$

The sum of all the momenta will be conserved in any physical process. (Examples: collision of balls)

Proof: consider an impact time Δt between two objects. Then

$$\begin{aligned}
&m_1 \Delta v_1 + m_2 \Delta v_2 \\
=&m_1 a_1 \Delta t + m_2 a_2 \Delta t \\
=&m_1 \frac{F_1}{m_1} \Delta t + m_2 \frac{F_2}{m_2} \Delta t \\
=&(F_1 + F_2) \Delta t \\
=&0
\end{aligned}$$

Momentum example

Consider the collision of two balls, each of mass m.

If the first one is at rest, and the second one is moving with +3m/s, then after the collision we have the same total momentum:

$$p_1 + p_2 = m \times v_1 + m \times v_2$$

is the same before and after the collision.

Space collision

Catching a ball in space example on paper.

How does this compare to Aristotle's laws?

Natural motion: Objects move towards the center of the earth because of gravity (more about that in the next lecture).

Violent motion: Forces cause objects to move and motion stops when the forces stop. This becomes true if there is a strong frictional force. As long as your driving force is balancing the friction force you can keep an object moving, once you stop driving it will come to rest quickly.

Celestial motion: There is no (or at least very little) friction in celestial motion, which it why it appears different.

Concept check: How does Newtonian dynamics resolve the problem of throwing a spear, that could not be understood with the help of Aristotle's laws?

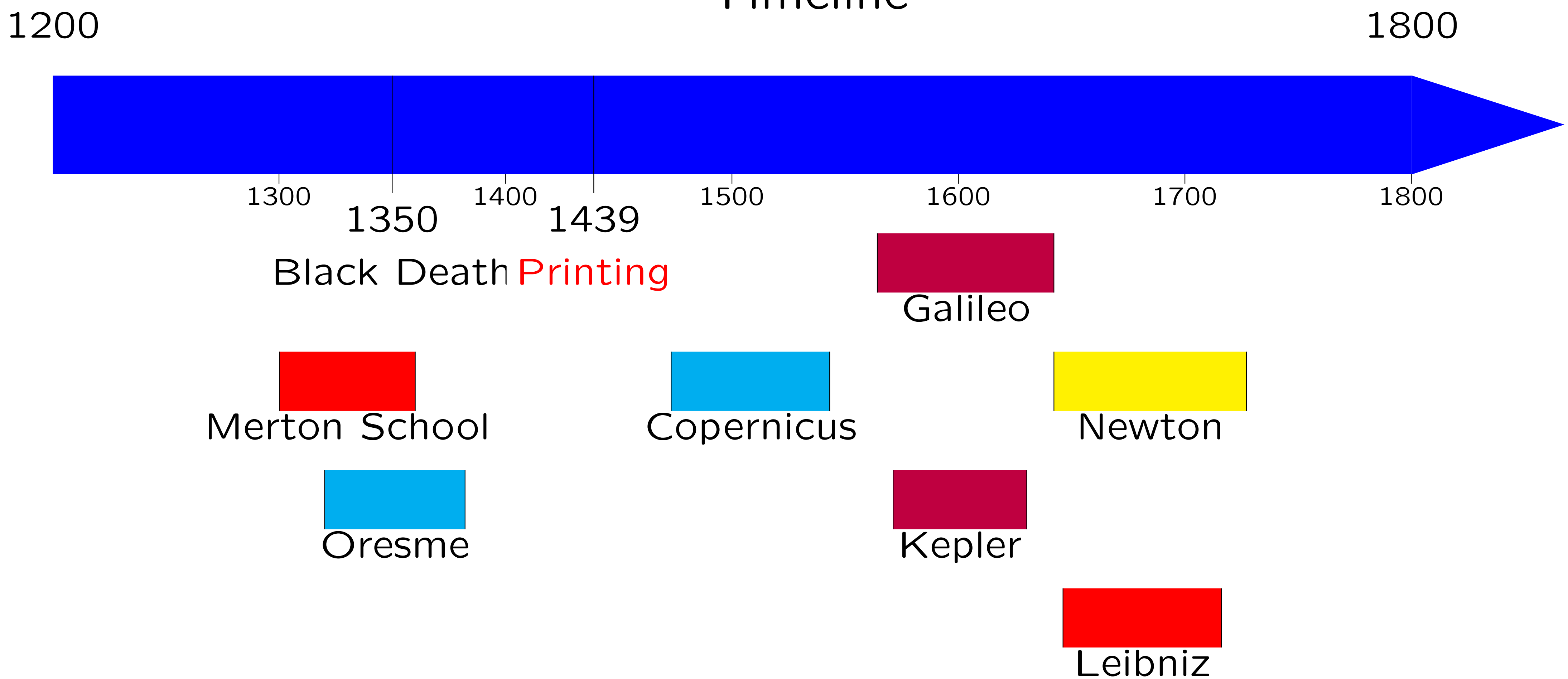
How “wrong” was Aristotle

Aristotle’s model of motion describes a large number of phenomena, but even at their time there were counter examples (i.e. throwing a spear). This is why we would not call Aristotle’s model a scientific “law” today. However the scientific method was not invented in Aristotle’s times, so we should not be too harsh on him.

Scientific method: You observe, you develop a hypothesis of how things work. You test your hypothesis and if you can verify it you have developed a theory. This theory will then undergo rigorous testing and if, despite everyones worst efforts, no counter examples can be found it will achieve the status of a scientific law. However, later experiments may turn up a counter example, so there is no guarantee that a scientific law is always true.

In the case of Aristotle’s “law” we see a typical pattern of a **scientific revolution**: the new law (Newton’s in this case) will recover the results of the overturned law in certain cases, but it will be much more generally valid.

Timeline



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1800
1300
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1600
1700
1800
1350
1439
Black Death
Printing
Galileo
Merton School
Copernicus
Newton
Oresme
Kepler
Leibniz

Summary

- Newton
- Newton's law (2) F=ma
- Forces come in pairs Newton (3)
- Weight
- Momentum
- scientific revolutions and scientific laws