

ASTR 340: Origin of the Universe

Prof. Benedikt Diemer

Lecture 6 • Principles of space and time II

09/16/2021

Homework #1

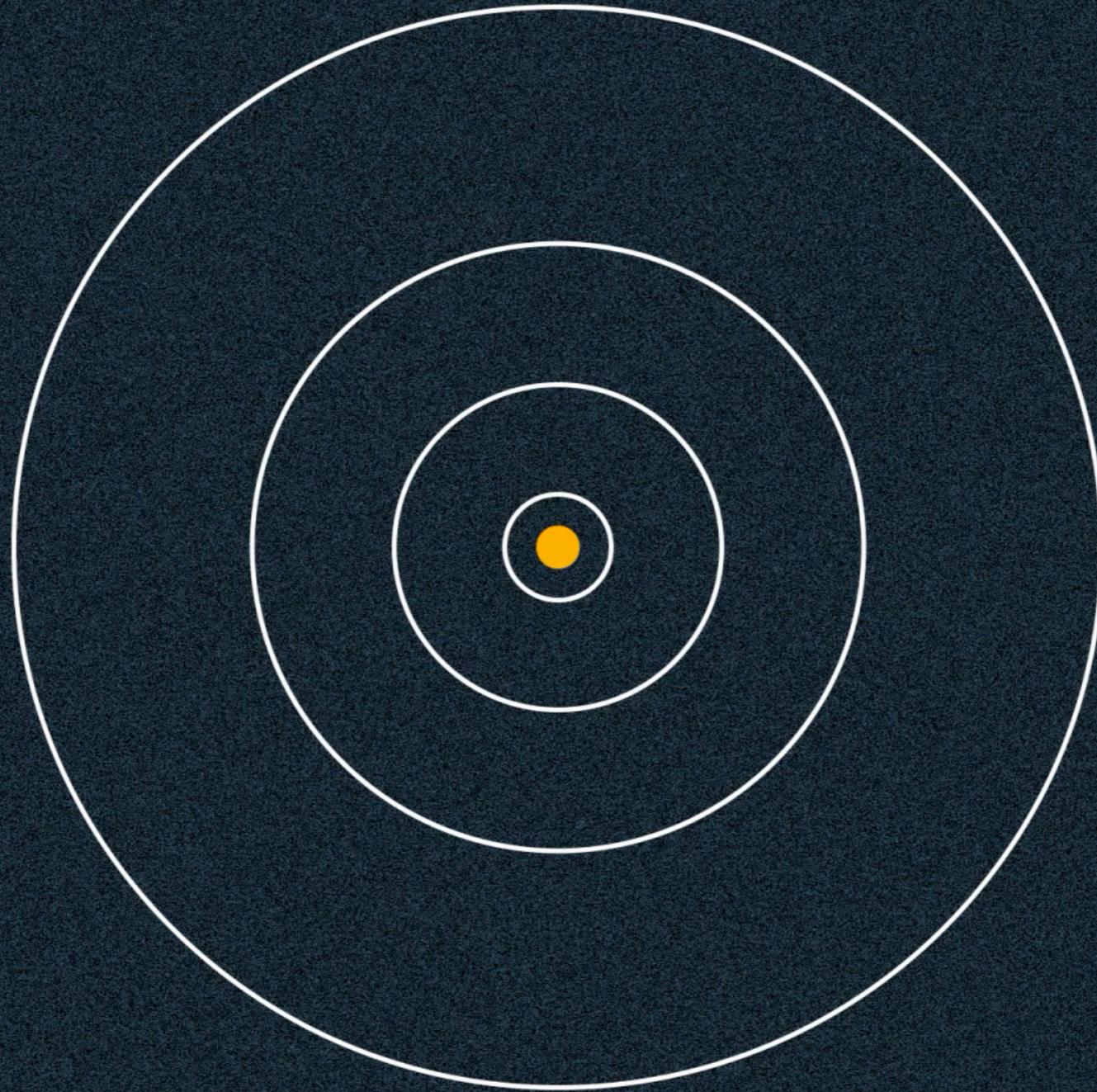
- Forgot to mention distance to Betelgeuse: you can use **220pc**

Today

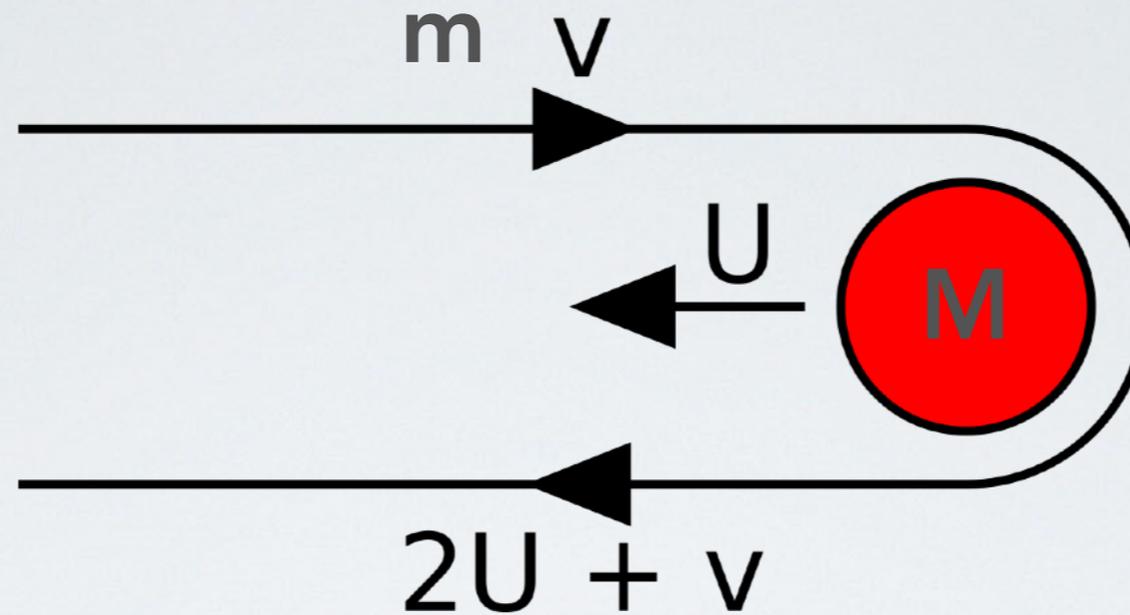
- **Gravitational slingshot**
- **Coordinate systems**
- **The time domain**
- **Light, ether, and the breakdown of Newtonian physics**
- **Einstein's postulates**

Part 1: Gravitational slingshot

Gravitational slingshot



Gravitational slingshot

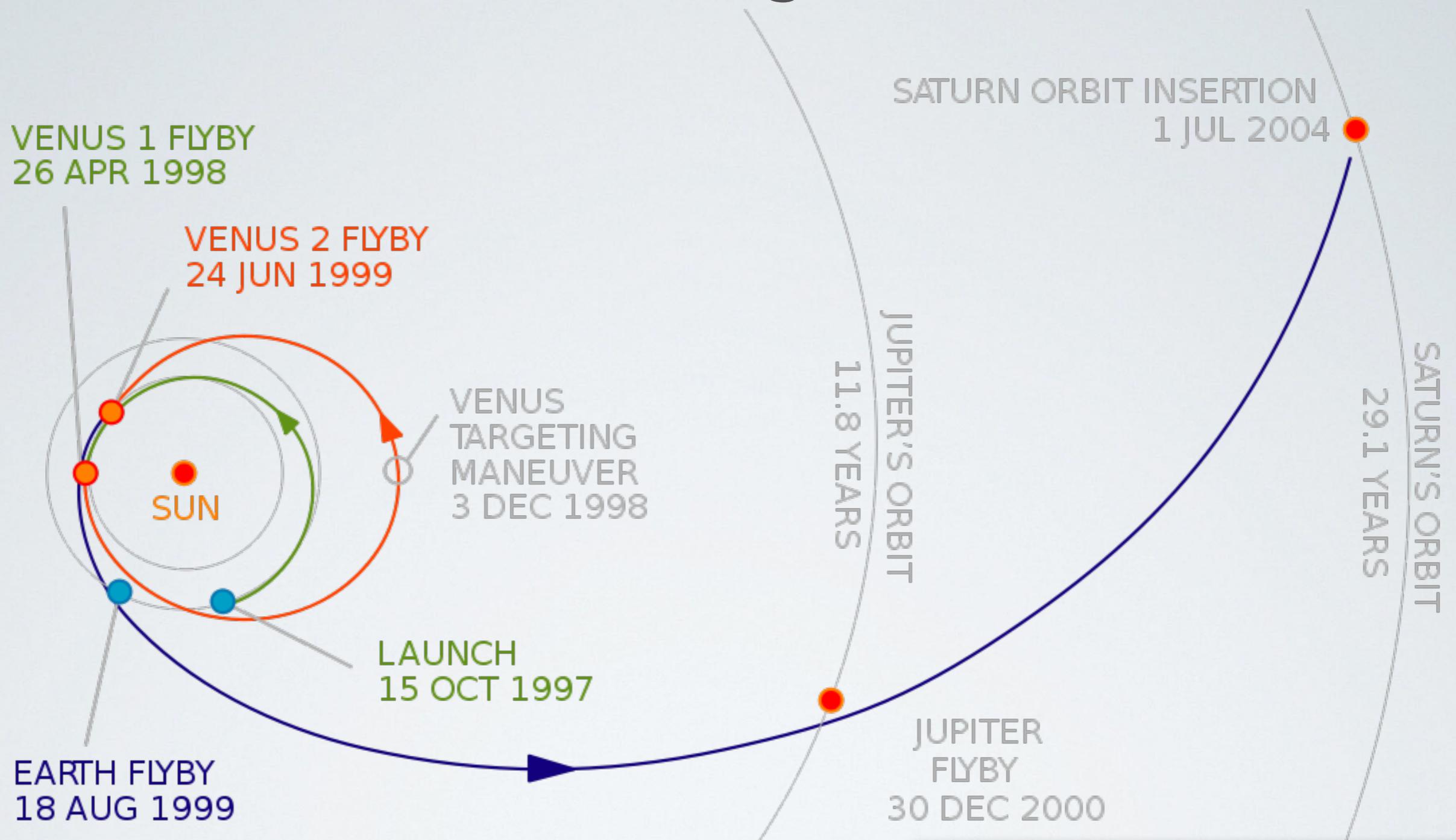


Momentum conservation: $mv_1 + MU_1 = mv_2 + MU_2$

Energy conservation: $mv_1^2 + MU_1^2 = mv_2^2 + MU_2^2$

$$\Rightarrow v_2 = \frac{\left(1 - \frac{m}{M}\right)v_1 + 2U_1}{1 + \frac{m}{M}} \approx v_1 + 2U_1$$

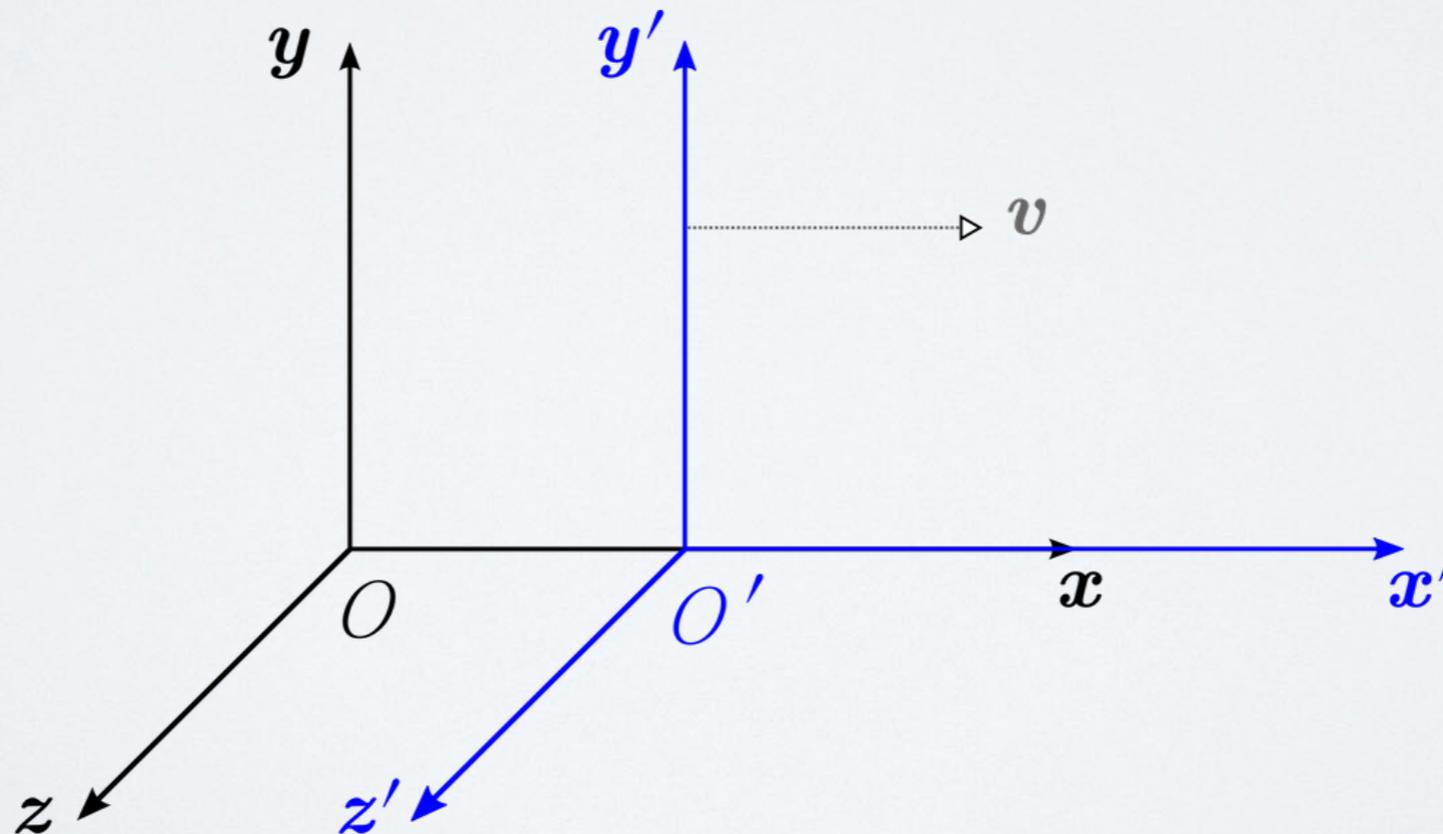
Gravitational slingshot (Cassini)



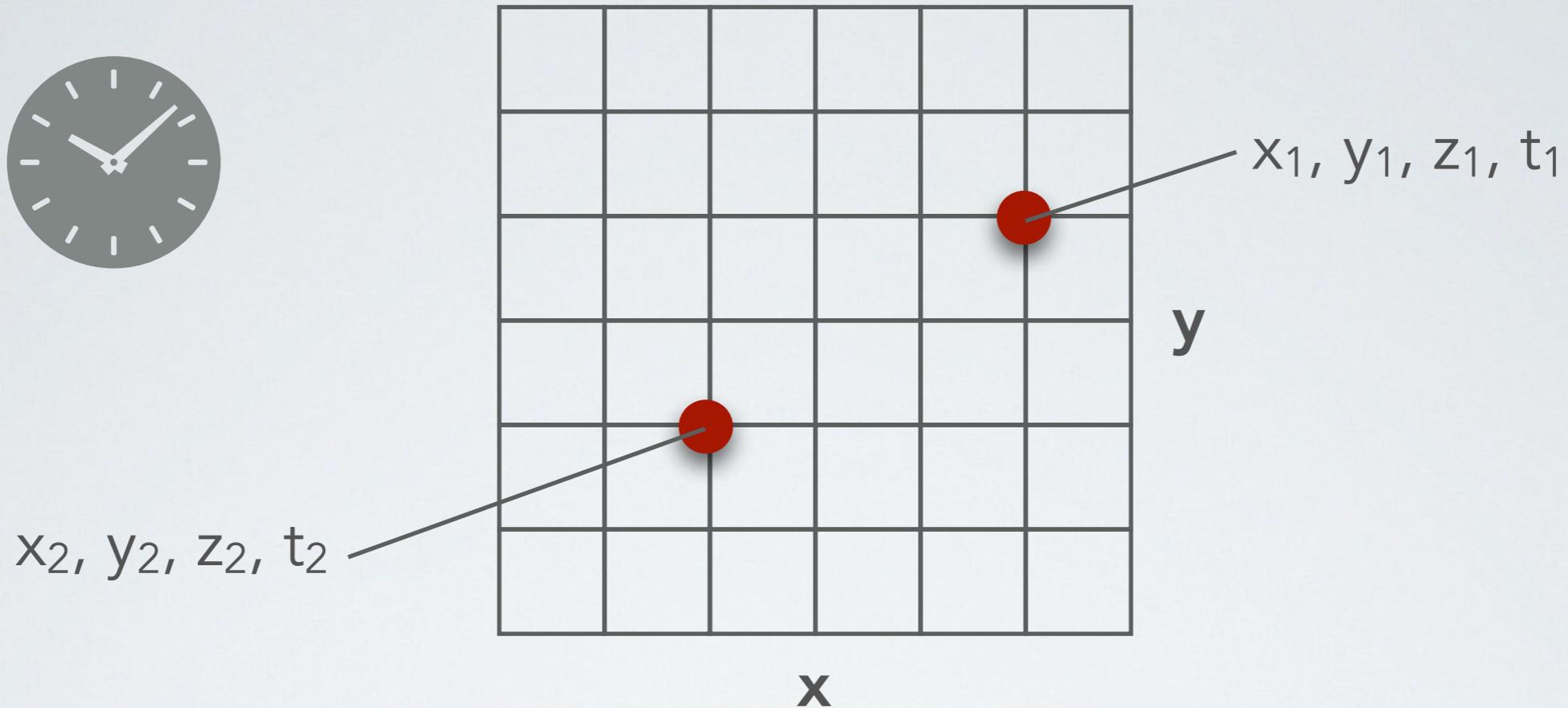
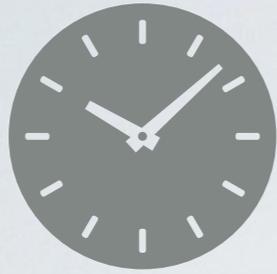
Part 2: Coordinate systems

Coordinate systems (or reference frames)

- Scientific observations involve making measurements: events with **coordinates in space and time**
- Space-time coordinates are often written as **(x, y, z, t)**
 - Coordinates are convenient **labels**, not fundamental attributes of space and time
 - We are free to choose units (e.g. cm, m, km, foot), and coordinate origin



Intervals



What matters is the **intervals in time and space**, not absolute numbers!

$$\left. \begin{aligned} \Delta x &= x_2 - x_1 \\ \Delta t &= t_2 - t_1 \end{aligned} \right\} v = \frac{\Delta x}{\Delta t} \quad a = \frac{\Delta v}{\Delta t}$$

$$\Delta s = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}$$

Part 3: The time domain

Participation: Age of the Earth



Respond to the poll on TurningPoint

Session ID: diemer



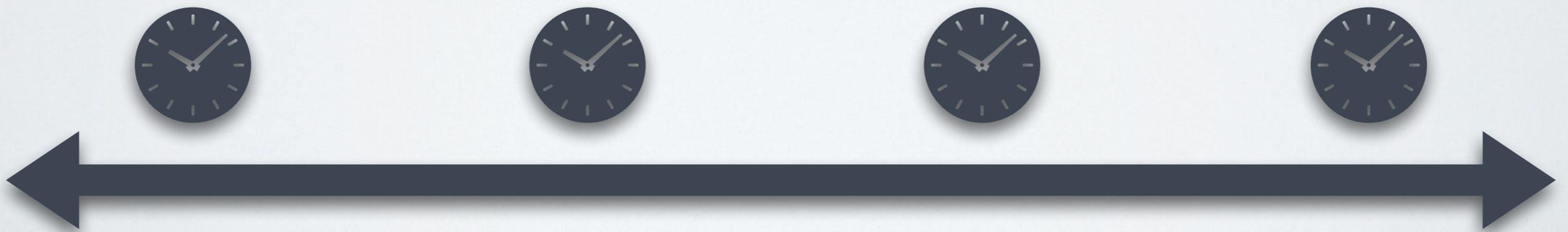
30 seconds

Cosmic timescale: The age of the solar system

- From ~1700-1860, the idea took hold that **Earth is very old**
 - Slow processes such as weathering, volcanism, etc.
 - Fossils of (often extinct) creatures in successive layers of rock
 - Physical progression in fossil features (invertebrates, fish, mammals) implied a biological transformation
 - Charles Darwin in *The Origin of Species* (1859) argues that evolution proceeds via natural selection (slow change, Darwin estimated at least 300 Myr)
- Kelvin and Helmholtz argue that **Sun** is powered by **gravitational contraction**
 - Gives **10s of Myr**
 - Astronomy and geology/biology in conflict until early 20th century
 - Nuclear physics: **Sun's energy source is fusion**
- Ages of meteorites etc. establishes that formation of the Solar system occurred about **4.6 billion years ago**
 - Dinosaurs 100 Myr, humans 250,000 years (0.25 Myr)

Is time symmetric?

- The laws of physics do not seem to change with time
- But what about **cosmic time**? As in, billions of years?
- Is there a **beginning** to the Universe?
 - Would it conserve energy?



Participation: Metacognition (Discussion #6)

Free-writing metacognition exercise

From what we have learned so far, **how has your view of the Universe and its physics changed?**

Select three ways in which your thinking has changed, starting with the ones that feel the most fundamental or surprising to you. They don't have to correspond exactly to one of our main topics! But to jog your memory, here are some of the topics we have covered so far:

- Creation myths & Ancient cosmology
- The scientific method
- The solar system (geocentrism, heliocentrism, planetary orbits)
- Newton's laws & Galilean relativity
- Weak equivalence principle, the nature of gravity and acceleration
- Our general idea of space and time (Copernican principle, isotropy/homogeneity/symmetry)

You can write bullet points or sentences, but they should include how you used to imagine the relevant aspects of the Universe and how your mental image has evolved.



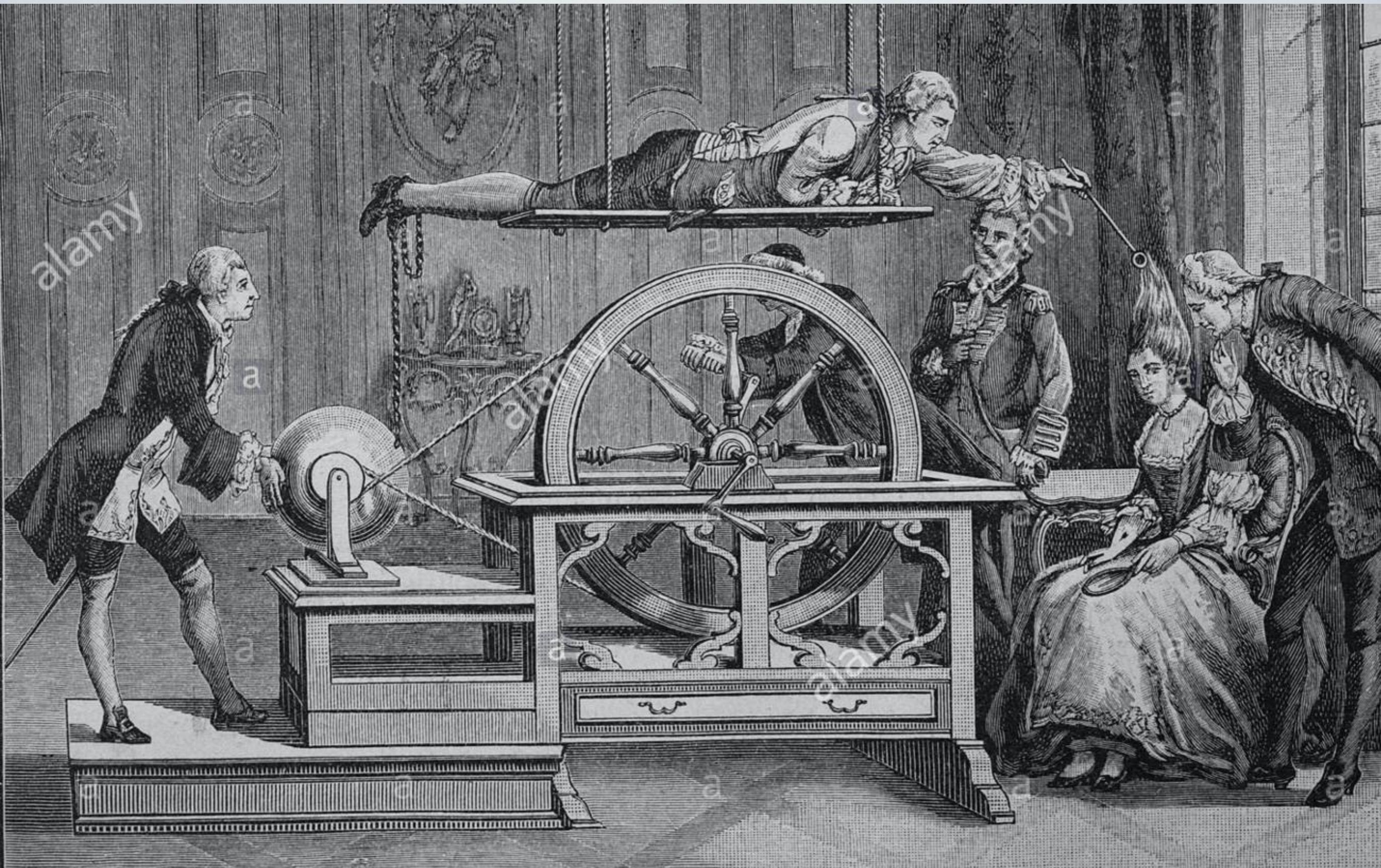
10 minutes

Part 4: The breakdown of Newtonian physics

Issues with Newtonian physics

- Newton himself had concerns about his theory
- Gravity is **action at a distance**
 - Gravitational force mysteriously reaches across large distances
 - How is information **communicated** from one body to another?
- Problems with a **static universe**
 - Newton imagined an infinite Universe full of stationary stars, each exerting a gravitational force on the others
 - This configuration is **unstable**: the smallest disturbance and it will collapse in on itself! What prevents this collapse?

Electricity



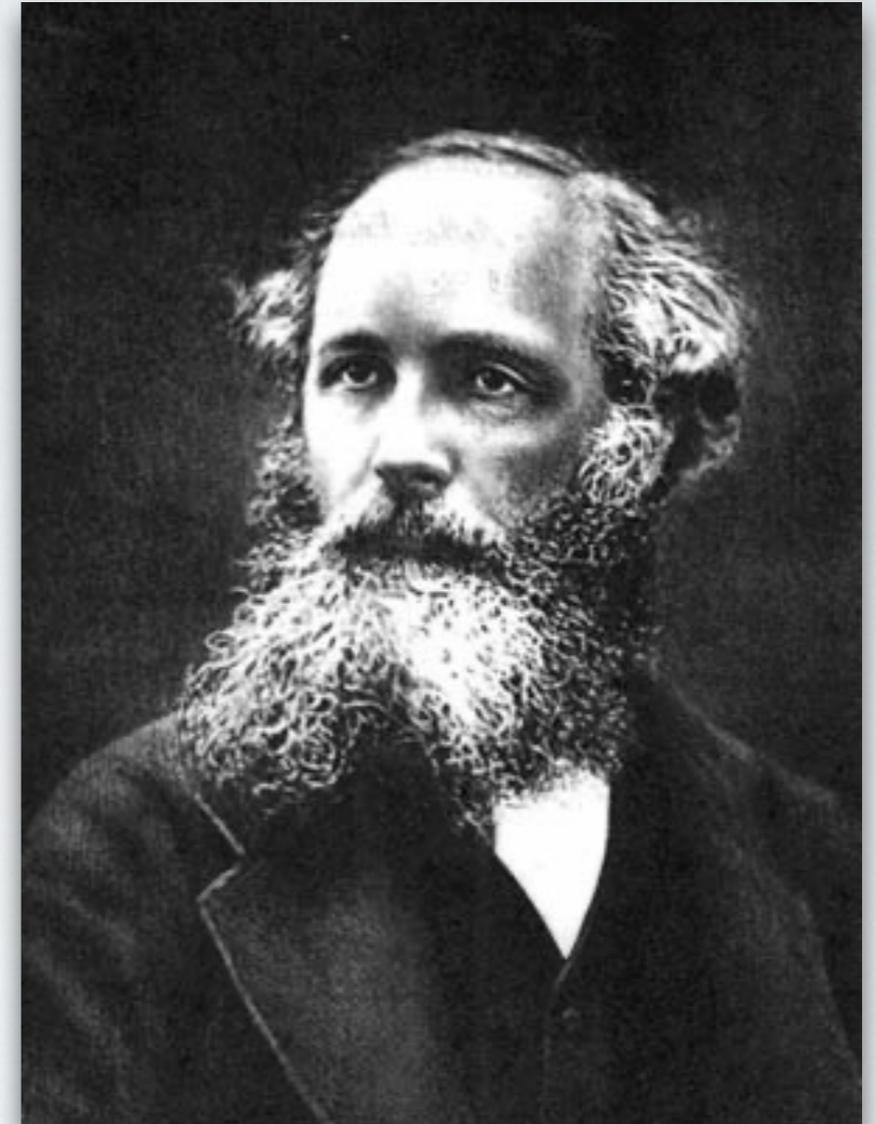
Maxwell Equations

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \epsilon_0 \mu_0 \frac{\partial \vec{E}}{\partial t}$$



Maxwell's equations

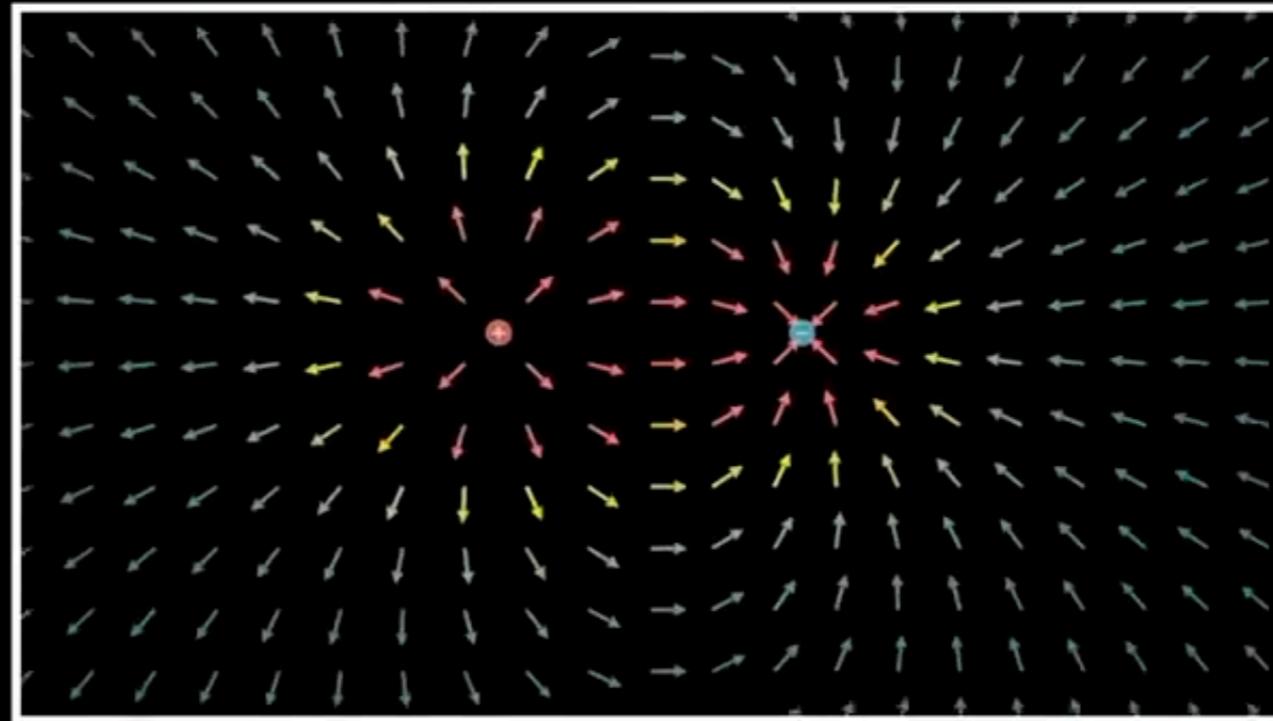
Electric field: **E** Magnetic field: **B**

$$\operatorname{div} \mathbf{E} = \frac{\rho}{\epsilon_0}$$

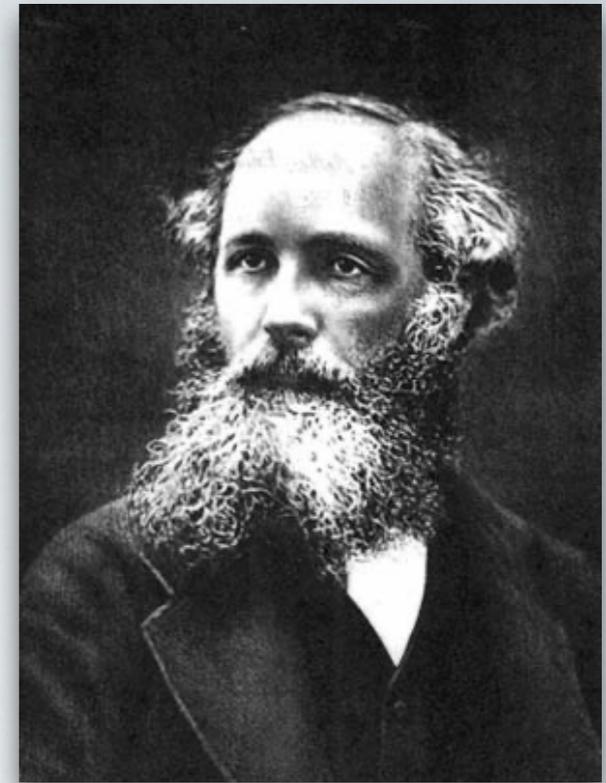
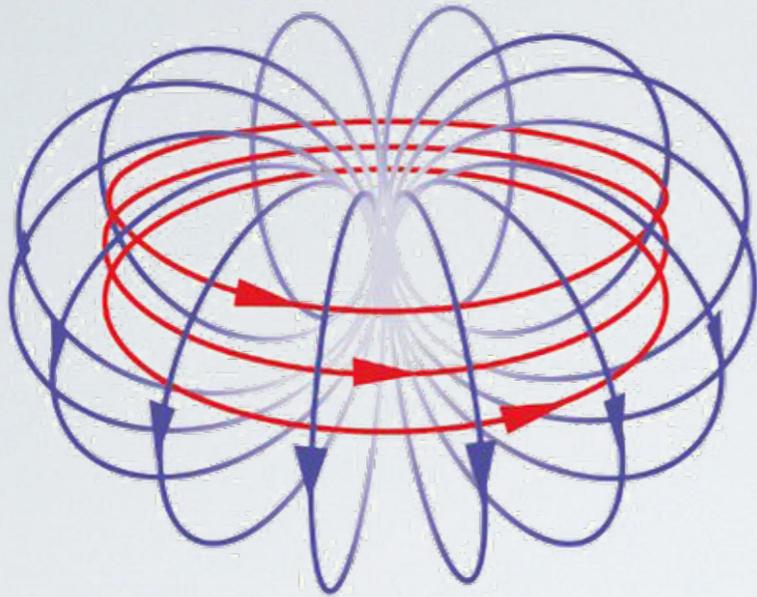
$$\operatorname{div} \mathbf{B} = 0$$

$$\operatorname{curl} \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\operatorname{curl} \mathbf{B} = \mu_0 \left(\mathbf{J} + \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$$



Maxwell Equations



$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

"electric E-field lines end on charges"

$$\nabla \cdot \vec{B} = 0$$

"magnetic B-field lines close on themselves"

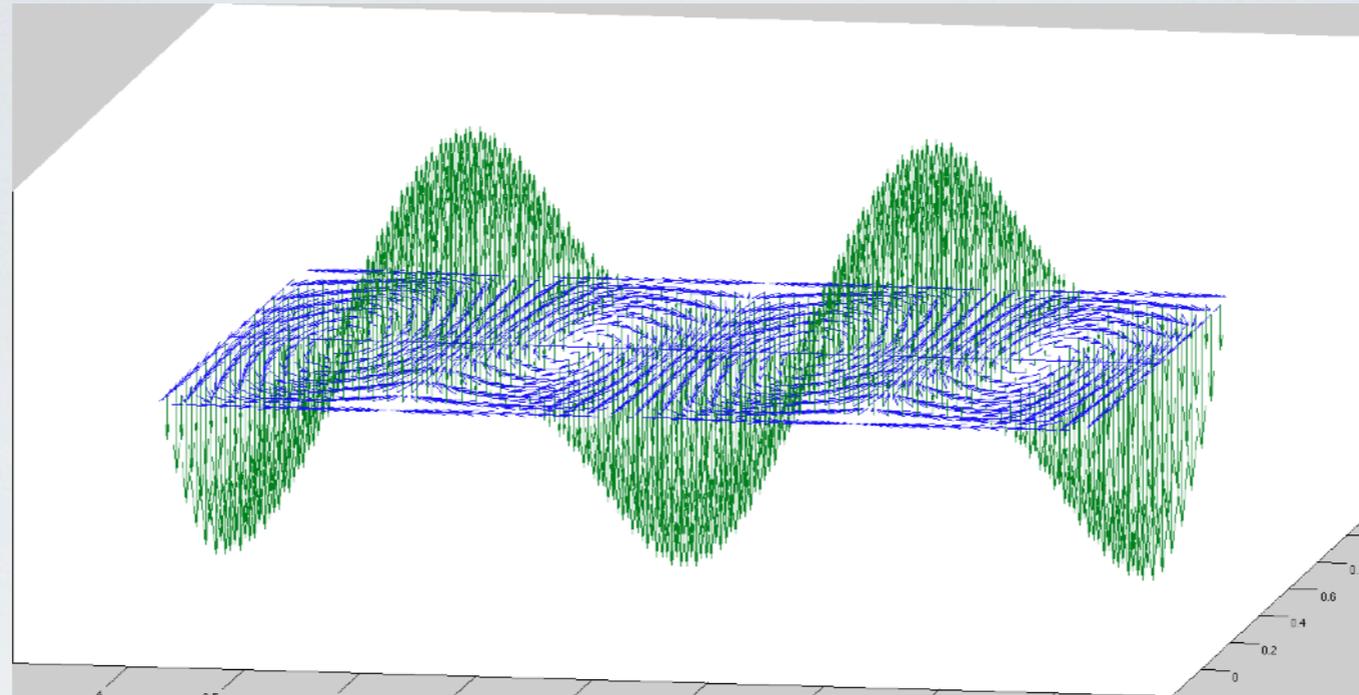
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

"changes in B cause curling E-fields"

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \epsilon_0 \mu_0 \frac{\partial \vec{E}}{\partial t}$$

"changes in E and currents cause curling B-fields"

Maxwell Equations



$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \epsilon_0 \mu_0 \frac{\partial \vec{E}}{\partial t}$$

"wave equation"

$$\frac{\partial^2 E}{\partial x^2} = \frac{1}{c^2} \frac{\partial^2 E}{\partial t^2}$$

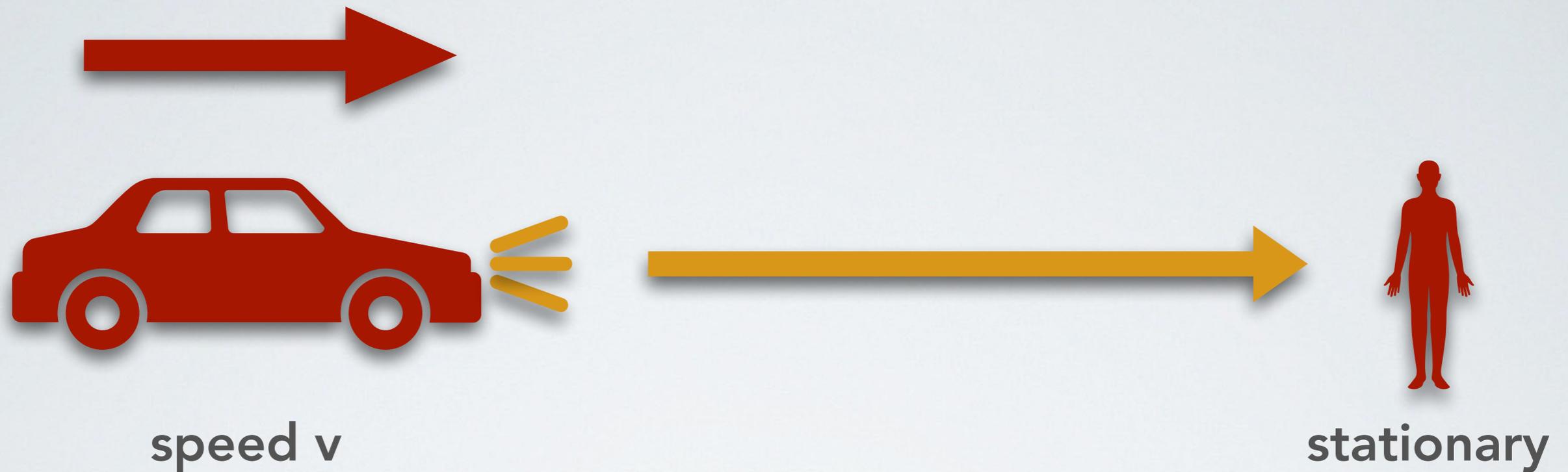
speed of wave:

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}}$$

natural constants!

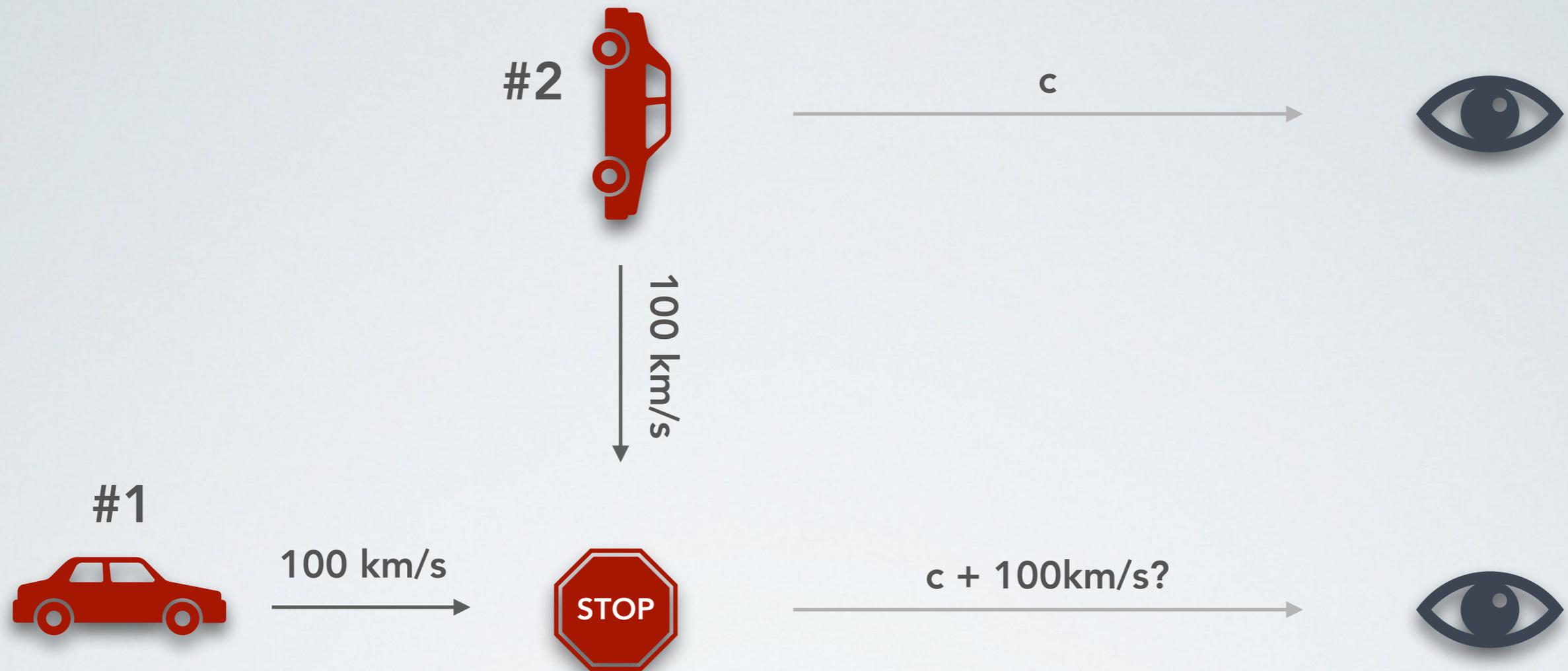
c = speed of light in vacuum
= 3x10¹⁰ cm/s

Speed of light and Galilean relativity



- What speed of light do we see? **Galileo says $v+c$?**

Thought experiment: Collision or not?



- Major mystery ("crisis") in 19th century physics: two highly successful theories seemed incompatible!
 - **Mechanics** (Galilean Relativity and Newton's laws)
 - **Electromagnetism** (Maxwell's equations)

Participation: What is ether?



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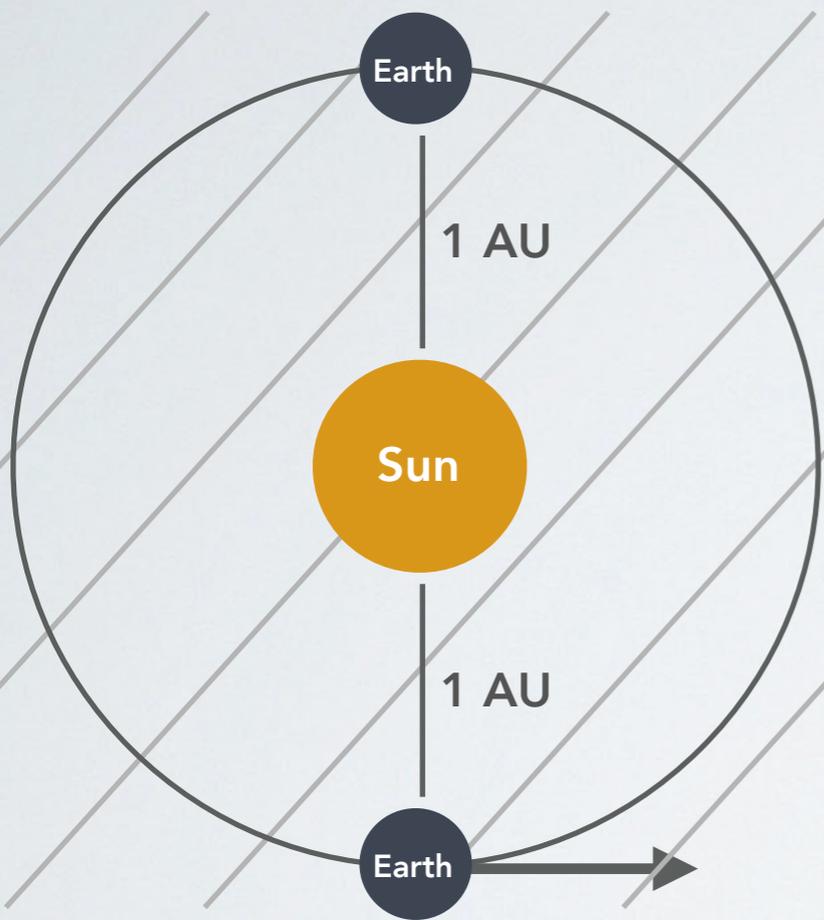
30 seconds

Possible solution: Luminiferous ether

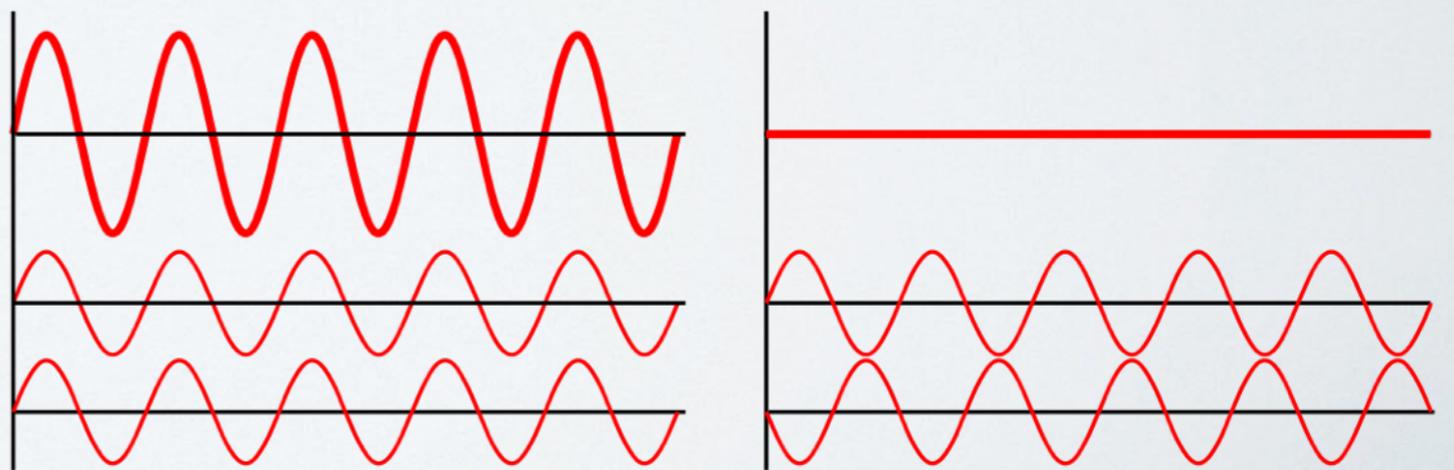
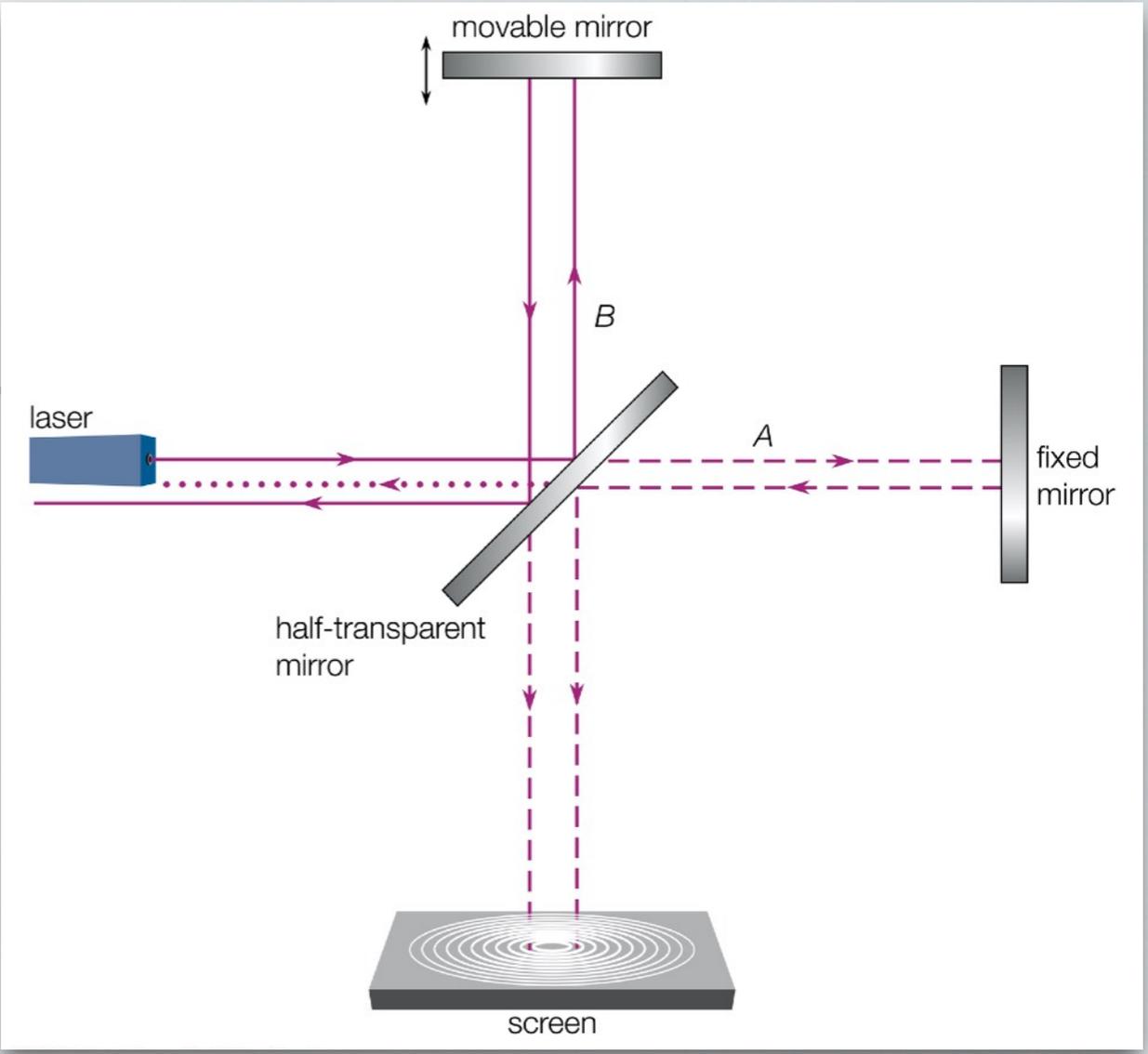
- Luminiferous Ether
 - **A medium through which light can travel**
 - Hypothetical substance that fills all space
 - Maxwell's equations, as written, would **apply only in frame of ether**
 - Speed of light measured in non-ether frames would be different
 - Would explain why the speed of wave propagation c is a constant in the equations
 - Popular solution in the late 19th century
- Albert Michelson & Edward Morley attempted (1887) to measure motion of Earth through ether

Michelson-Morley experiment

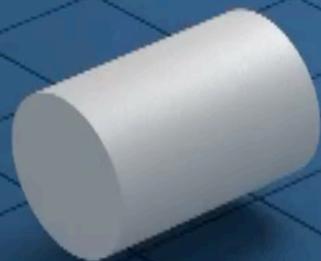
motion with respect to ether frame



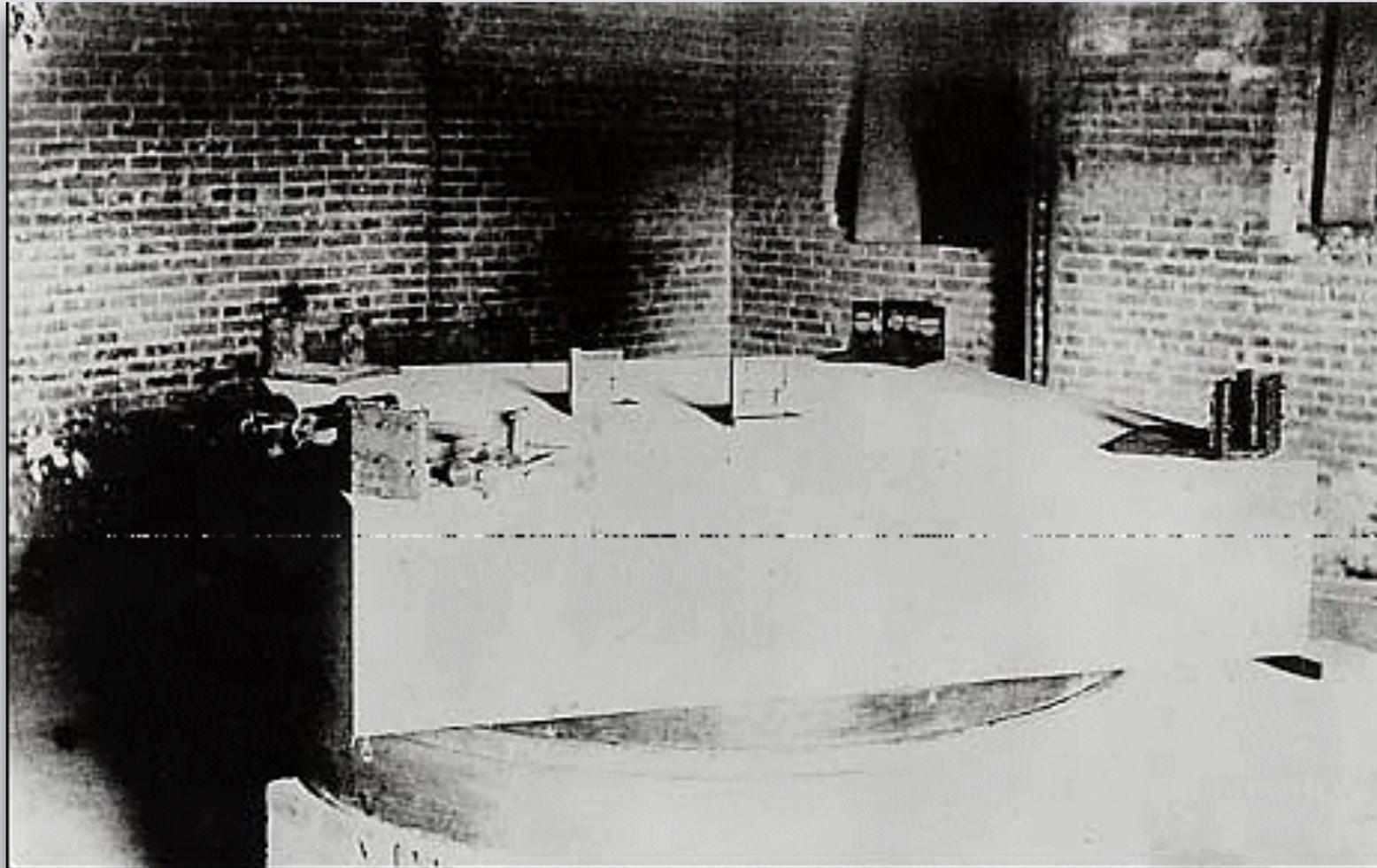
$v_{\text{earth}} \sim 30 \text{ km/s}$



Interferometers



Michelson-Morley experiment



- Result: differences in $c < 5 \text{ km/s}$
- Modern experiments are much more accurate (10^{-17})
- Speed of light seems to be **constant**
- **No ether!**

Crisis in physics

- Major mystery (or crisis) in 19th century physics: two highly successful theories seemed incompatible!
 - **Mechanics** (Galilean Relativity and Newton's laws)
 - **Electromagnetism** (Maxwell's equations)
- **Ether** solution does not work: speed of light does seem to be constant

Part 5: Einstein's postulates

Einstein's solution

Newtonian Mechanics: The **laws of nature** are the same in all inertial frames of reference



Electromagnetism: The **speed of light** in a vacuum is the same in all inertial frames of reference



Galilean relativity: Relative **motions of frames add**, but there is an absolute time



Participation: What would be your solution?



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30 seconds

Einstein's solution

Newtonian Mechanics: The **laws of nature** are the same in all inertial frames of reference



Electromagnetism: The **speed of light** in a vacuum is the same in all inertial frames of reference



Galilean relativity: Relative **motions of frames add**, but there is an absolute time



Einstein's solution

Postulate 1: The **laws of nature** are the same in all inertial frames of reference

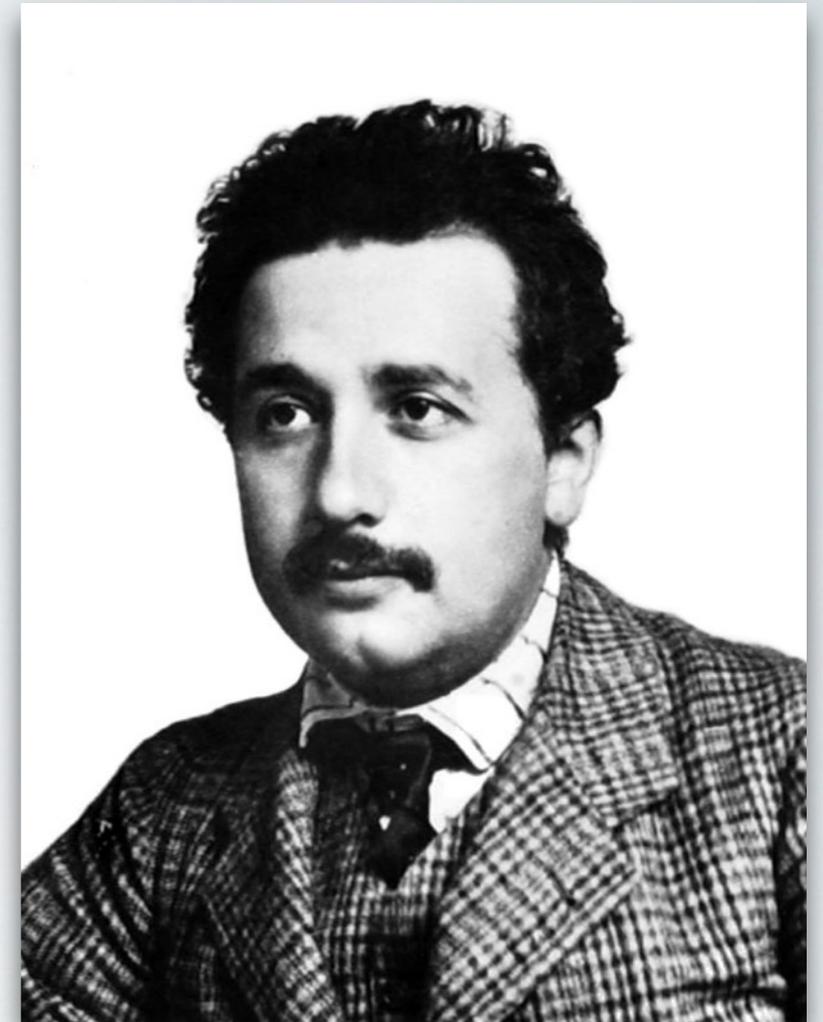
Postulate 2: The **speed of light** in a vacuum is the same in all inertial frames of reference

Galilean relativity: Relative velocities of frames add, but there is an absolute time



Albert Einstein (1879-1955)

- Three papers in 1905 ("annus mirabilis")
 - **Photoelectric Effect**
(light is quantized in energy)
 - **Brownian Motion**
(motion of molecules is thermal)
 - **Special Relativity**



Relativity Paper (1905)

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3. Zur Elektrodynamik bewegter Körper; von A. Einstein.

Daß die Elektrodynamik Maxwells — wie dieselbe gegenwärtig aufgefaßt zu werden pflegt — in ihrer Anwendung auf bewegte Körper zu Asymmetrien führt, welche den Phänomenen nicht anzuhafte scheinen, ist bekannt. Man denke z. B. an die elektrodynamische Wechselwirkung zwischen einem Magneten und einem Leiter. Das beobachtbare Phänomen hängt hier nur ab von der Relativbewegung von Leiter und Magnet, während nach der üblichen Auffassung die beiden Fälle, daß der eine oder der andere dieser Körper der bewegte sei, streng voneinander zu trennen sind. Bewegt sich nämlich der Magnet und ruht der Leiter, so entsteht in der Umgebung des Magneten ein elektrisches Feld von gewissem Energiewerte, welches an den Orten, wo sich Teile des Leiters befinden, einen Strom erzeugt. Ruht aber der Magnet und bewegt sich der Leiter, so entsteht in der Umgebung des Magneten kein elektrisches Feld, dagegen im Leiter eine elektromotorische Kraft, welcher an sich keine Energie entspricht, die aber — Gleichheit der Relativbewegung bei den beiden ins Auge gefaßten Fällen vorausgesetzt — zu elektrischen Strömen von derselben Größe und demselben Verlaufe Veranlassung gibt, wie im ersten Falle die elektrischen Kräfte.

Beispiele ähnlicher Art, sowie die mißlungenen Versuche, eine Bewegung der Erde relativ zum „Lichtmedium“ zu konstatieren, führen zu der Vermutung, daß dem Begriffe der absoluten Ruhe nicht nur in der Mechanik, sondern auch in der Elektrodynamik keine Eigenschaften der Erscheinungen entsprechen, sondern daß vielmehr für alle Koordinatensysteme, für welche die mechanischen Gleichungen gelten, auch die gleichen elektrodynamischen und optischen Gesetze gelten, wie dies für die Größen erster Ordnung bereits erwiesen ist. Wir wollen diese Vermutung (deren Inhalt im folgenden „Prinzip der Relativität“ genannt werden wird) zur Voraussetzung erheben und außerdem die mit ihm nur scheinbar unverträgliche

...failed attempts to find a motion of the Earth relative to the light medium...

...lead to the conjecture...

...that the laws of electrodynamics and optics are also valid in all coordinate systems where the equations of mechanics are valid

“Principle of Relativity”

Take-aways

- Galilean relativity and a constant speed of light are incompatible, causing a **crisis** in 19th century physics
- **Ether** was a theoretical attempt to construct an absolute frame of reference for light
- Einstein decided to **discard Galilean relativity**, starting Special Relativity instead

Next time...

We'll talk about:

- Special Relativity, time dilation, length contraction

Assignments

- Post-lecture quiz (by tomorrow night)
- Homework #1 (by Tuesday 9/21)

Reading:

- H&H Chapter 7 (up to page 192)