Einstein for Everyone
Lecture 1: Introduction

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Einstein for Everyone

Everything should be made as simple as possible, but not simpler.

Albert Einstein (1907)

Objectives

Appreciate Einstein's contributions to science

- Basic physical concepts in his theories
- Historical context

Creative achievement in science

- How did Einstein do it? Philosophical aspects of his approach to physics
- Example of conceptual change

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Readings

Required Texts:

- Robert Geroch, *General Relativity from A to B*, University of Chicago Press.
- D. Mermin, *It's About Time: Understanding Einstein's Relativity*
- John Norton, *Einstein for Everyone*. (Online text.)
- *Online Articles*. Articles and handouts posted on `http://strangebeautiful.com/lmu/2014-summer-einstein-everyone.html`, including forthcoming articles and Einstein's original papers.

Suggested Reading:

- Einstein, *Relativity: The Special and General Theory*

Evaluation

1. Paper (100%): one 12–15 page paper, due some time in September (the exact date to be determined later).

2. Homework (0%): 10 assignments over the term; though not counted towards final grade, I strongly urge you to do them.

Implications of Einstein's theories

- Do astronauts age more slowly?
- Is space "curved" near the sun?
- Can a finite universe have no edge?
- Can time have a beginning?
- Is time travel possible?
- Does the moon change because someone looks at it?

Answer to all these questions:

.... YES!

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Answer to all these questions:

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Aging Astronauts

Bizarre Consequence of Special Relativity

All processes appear to slow down for a system moving at high speed relative to you. *Including metabolism of an astronaut!*

- Contradicted by everyday experience?
- Effect *very small* at ordinary speeds

  Car at 160 km / h $\rightarrow$ lose .35 s in $1,000,000$ years

  Rocket at escape velocity $(40,320$ km / h$)$ $\rightarrow$ lose .022 s in 1 year

  Rocket at 99 % the speed of light $(1,070,000,000$ km / h$)$ $\rightarrow$ lose 30136864 s in 1 year (95.5 %; age 16 days in 1 year!)

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- Why is this true?

  Thought experiment: shouldn't observer "chasing a light beam" measure smaller speed? (Based on usual way of thinking about speed.)

  Einstein's answer (1905): *No!*

  Instead, *All observers measure the same speed of light.*

  Speed: distance (measuring rods) / time (clocks). Everyday assumptions about *both* are incorrect.

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Gravity as Curvature

- Newtonian Gravity
  - Objects such as the planets would move along *straight lines*, but
  - *Deflected* by gravitational force of sun → curved orbits
- Einstein's New Theory, General Relativity (1915)
  - No "gravitational force" – deep change from Newton's theory
  - Objects move along *straight lines* in a curved geometry, curvature due to the sun.

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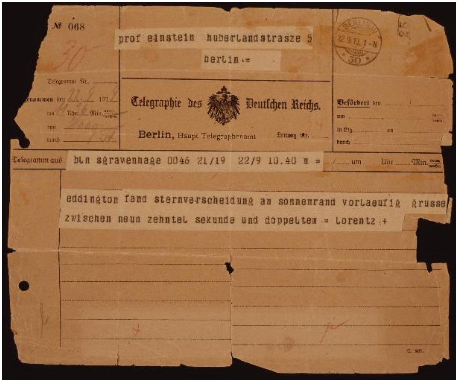
1919 Eclipse Expedition: Light Bends around the Sun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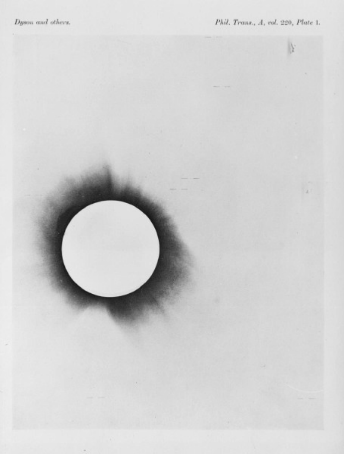
Lorentz's telegram to Einstein



Images from Eddington's observations in Principe

Closed Universe?

- Einstein 1917: cosmological model, physical model of the "whole universe" based on new gravitational theory
- Describes universe that is spatially *finite* but with no edge...

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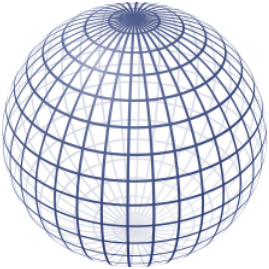

Beginning of Time

- Astronomical observations (1920s - today): universe not *static*, but changing with time
- Hubble (1929): *expansion* of the universe, measured by motion of galaxies
- Extrapolate backwards to ... BIG BANG!

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Closed Loops

- In what sense is time travel possible?
  - *Contrast* between “possible” and “actual”
  - Possibility *according to* a particular theory
- Gödelian time travel
  - Temporally closed (rather than spatially closed) universe is possible according to Einstein’s theory
  - Observer would return to the beginning of their journey

A Glimpse of Quantum Theory

- sometimes, quantum systems behave as though they were particles, sometimes as though they were waves: "wave-particle duality"
- which is manifested depends on experimental arrangement
- the act of observation seems to change a system under study in non-deterministic ways

Einstein's Worry

Power of Observation?

"...during one walk, Einstein suddenly stopped, turned to me, and asked whether I really believed that the moon exists only when I look at it." (Abraham Pais, physicist, friend and biographer of Einstein)

"...No one can forget how he expressed his discomfort about the role of the observer, 'When a mouse observes, does that change the state of the universe?' " (John Wheeler, physicist, friend of Einstein)

Einstein's Two Postulates

1. *Principle of relativity*: "...the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good."
2. *Light postulate*: "... light is always propagated in empty space with a definite velocity independent of the state of motion of the emitting body."

Presentation of Theory

- Einstein admired theories presented in terms of small number of basic postulates (Euclid, Newton, thermodynamics)
- Postulates capture core ideas of the theory

Einstein's Two Postulates

1. *Principle of relativity*
2. *Light postulate*

One striking consequence: "... the introduction of a 'luminiferous ether' will prove to be superfluous."

Questions

- What do these postulates mean? Are they even compatible?
- Relation to earlier ideas in physics? What is the "ether", and why is it unnecessary in Einstein's theory?

Plan of Attack

1. Principle of Relativity
   - Version 1.0: Galileo
   - Einstein's Problem: version 2.0?
2. Light Postulate
   - Light as an Electromagnetic Wave
   - Light and Principle of Relativity

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Inertial Motion

Definition (Inertial Motion)

Motion in a straight line with uniform velocity (that is, covering equal distances in equal times).

Accelerated Motion

Change in *velocity* (speed up or slow down) or *direction* (*e.g.*, rotation)

Based on...

- *Spatial Geometry*: straight line; distances measured by measuring rods
- *Time*: time elapsed, measured by a clock
- *Location over time*: distance traveled over time

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Inertia and Relativity

Principle of Relativity

All observers in inertial motion (inertial observers) see the same laws of physics.

Shut yourself up with some friend in the main cabin below decks on some large ship, and have with you there some flies, butterflies, and other small flying animals. Have a large bowl of water with some fish in it; hang up a bottle that empties drop by drop into a wide vessel beneath it. With the ship standing still, observe carefully how the little animals fly with equal speed to all sides of the cabin. The fish swim indifferently in all directions; the drops fall into the vessel beneath; and, in throwing something to your friend, you need throw it no more strongly in one direction than another, the distances being equal; jumping with your feet together, you pass equal spaces in every direction. When you have observed all these things carefully (though doubtless when the ship is standing still everything must happen in this way), have the ship proceed with any speed you like, so long as the motion is uniform and not fluctuating this way and that. You will discover not the least change in all the effects named, nor could you tell from any of them whether the ship was moving or standing still. (Galileo, *Dialogue* [1632])

Inertia and Relativity

Principle of Relativity

All observers in inertial motion (inertial observers) see the same laws of physics.

Consequences:

- No experiment can detect inertial motion
- Contrasts: *accelerated* motion; *relative* motion with respect to other objects

Galilean Relativity

- Context: Debate regarding Copernican Hypothesis (1543)

  Objection: we're obviously not moving!
- Galileo's Response
  - Earth moves (*approximately*) inertially; so it will look (*approximately*) as though it were at rest
  - Newton: cannot detect *inertial* motion, formulates principle of relativity as a consequence of his laws

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Shut yourself up with some friend in the main cabin below decks on some large ship, and have with you there some flies, butterflies, and other small flying animals. ... And have with you there an instrument that allows you to measure the speed of light very precisely ...

How would this change Galileo's conclusion?

1. Principle of relativity fails: can now detect motion
2. Principle of relativity holds: still cannot detect motion

To answer this need to consider theory describing light...

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Outline

1. Detecting Ether Drift
   - Fresnel's Coefficient
   - Michelson-Morley Experiment

   Others: Fizeau, Trouton-Noble,...
2. Lorentz's Response
   - Length Contraction
   - Generalized Contraction Hypothesis
3. Einstein's Response
   - Emission theories?
   - Revise concepts of space and time
   - Simultaneity

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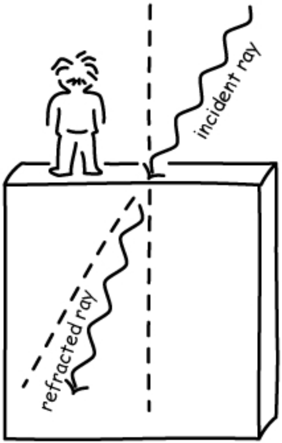
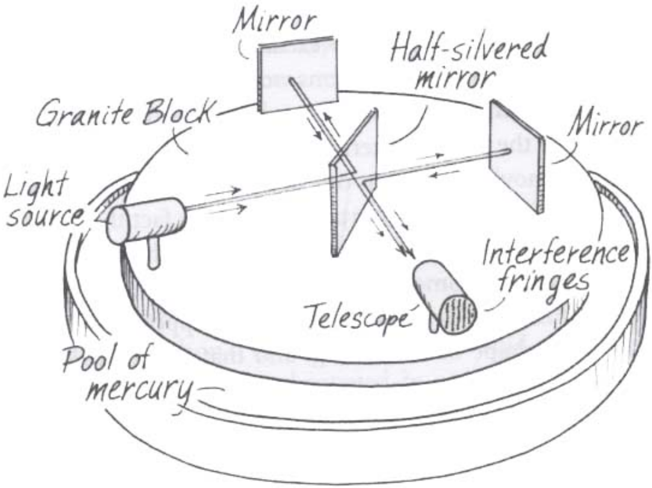
Fresnel's Coefficient



- Light passing through optical medium (e.g., glass block)
  - Ether dragged by medium
  - Depends on refractive index, exactly mimics ordinary refraction
- Guarantees that block's motion is undetectable!

The Apparatus (Michelson and Morley 1887)



Testing for Ether Drift

Travel time for arm 1 (parallel to ether flow):

$$\frac{l}{c+v} + \frac{l}{c-v} = \frac{2lc}{c^2 - v^2} \qquad (7.1)$$

Travel time for arm 2 (perpendicular to ether flow):

$$\frac{2l}{\sqrt{c^2 - v^2}} \qquad (7.2)$$

Conclusion

Travel time differs along the two arms, depends on velocity with respect to ether (by an amount $\frac{l}{c}\frac{v^2}{c^2}$).
Measurement difference in travel time $\rightarrow$ measure velocity!

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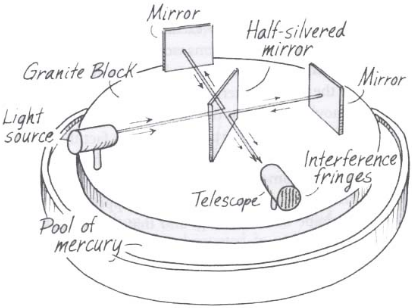

- Interferometer
  - Interference pattern between light rays
  - Change in travel time $\rightarrow$ shift in interference fringes
- Rotation
  - Rotate entire apparatus by 90°
  - Prediction: shift in interference fringes (depends on v)

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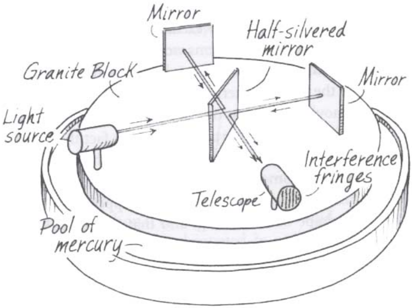

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Null Result

- Result: *no shift in interference fringes*!
  - Travel times along interferometer arms *unaffected* by rotation
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