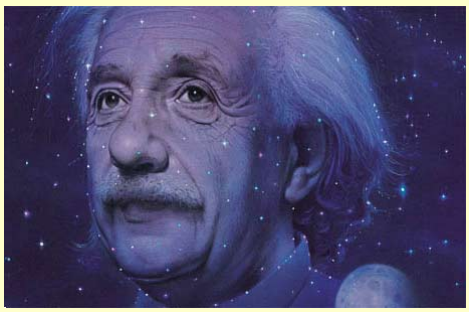
Lecture 13 Birth of Relativity

The Birth of Relativity
Albert Einstein



Person of the Century
Time Magazine, Dec. 1999

Announcements

- Today: Einstein and the Birth of Relativity
  - Lightman Ch 3, March, Ch 9
- Next Time: Wedding of Space and Time
  Space-Time
  Twin Paradox, . . .
  - Lightman Ch 3, March Ch 10
- Homework 5 due Today

Introduction - I

- Last time: Michelson-Morley experiment
- Either the earth does not move or the behavior of light is not described by the laws of classical physics -- Either way, a fundamental breakdown of classical physics
- How to understand? How can one think about a wave whose speed is always the same? No matter how fast you run to catch up with it it always moves at the same speed ahead of you!

Introduction - II

- Today: The Birth of Relativity
- Einstein Realized the deeper consequence. This was not merely about light, but about time and space and what we mean by measurements.
- Einstein made two postulates for special relativity ("special" in the sense that it is restricted to observers moving at constant velocity).
- Explored consequences of the postulates by thought (gedanken) experiments.
- No demos! Just thought !

Introduction - III

- What is time and space?
- Concepts defined only within our minds that do not exist in any other sense? (Kant)
- Absolute quantities in which all objects exist observed by humans? (Newton and other scientists of classical physics)
  (See Lightman, Ch. 3)
- Einstein introduced an approach different from either of these views.

Introduction - IV

- Example of Revolution in Physics (Science in general) described by Thomas Kuhn, "The Structure of Scientific Revolutions"
- Classical physics defined the framework of to think about nature – a paradigm
- A crisis occurred -- observations that could not be reconciled with the paradigm
- A new paradigm emerged -- in which these observations became part of the new paradigm

Lecture 13 Birth of Relativity

Albert Einstein (1879-1955)

- Born German, went to university in Switzerland, became naturalized Swiss citizen.
- 1902: Job at patent office in Bern
  Does physics on the side.
- 1905: 5 Five seminal papers
  - molecular dimensions
  - Brownian motion
  - Photoelectric effect (Nobel prize)
  - Relativity
  - $E = mc^2$
- 1909: Zurich prof.
  1913: Berlin chair in Physics
  1916: General relativity

Information on Einstein

- "Mr Tomkins in Paperback" by George Gamow,
  - Imaginative Description of Relativity (and other areas of physics)
  - Told through tales of an English bank clerk who dreams when he is put to sleep by physics lectures.
- "Einstein for Beginners" by Joseph Schwartz and Michael McGuinness
  - Creative, instructive comic-book style description of Einstein's life and ideas
  - Also the political situations and events that shaped his life
- "Physics for the Rest of Us" by Roger Jones
  - Essays on modern physics and metaphors on the meaning
  - Also the relation to religion and society
- Resource on Einstein: American Institute of Physics
  - http://www.aip.org/history/einstein/einstein.htm

Einstein's Two Postulates

- Principle of Relativity:

  "The phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest. They suggest rather that .. the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good."
  - *That is,* the results of experiments are independent of the translational motion of the frame of reference in which they are performed.
- Speed of Light:

  "Light is always propagated in empty space with a definite velocity c which is independent of the state of motion of the emitting body"
  - *That is,* the speed of light is the same (= c) for all observers regardless of motion of the observer or the source.

What Are These Postulates?

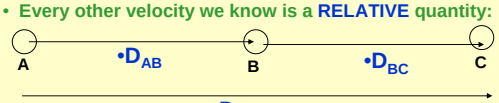
- The first is the same as Galileo proposed! That uniform motion could no be detected by any experiment.
  - Galileo used this to argue that one could not detect the motion of the earth - that it did not matter if the earth moved
  - Einstein added that the laws describing electromagnetism (including light) must also obey this principle
- The second is the statement that if the speed of light is c for one observer (determined by the laws of E&M) then it must be the same for all observers.

What Do These Postulates Do?

- Explains the negative results of Michelson-Morley!
  - Postulate 1 ⇒ there is no special frame, which the ether certainly would be.
  - Postulate 2 ⇒ speed of light the same in all directions, so of course the "race" will always be a tie!
  - Note how the anomalous (in terms of the classical wave paradigm) result has become the expected (in terms of Einstein's postulates)!
- At what price have we explained the Michelson-Morley results?
- Are these ideas reasonable???

If Einstein is right, something is wrong with our ideas of space and time!

- The 2nd Postulate implies that a special velocity (that of light) is an ABSOLUTE quantity
- Every other velocity we know is a RELATIVE quantity:



$V_{AC} = D_{AC}/t = (D_{AB}+D_{BC})/t = V_{AB}+V_{BC}$

- This is our experience in everyday life.
  - The velocity of an object (e.g. a car) or a wave (e.g. sound) is relative to the observer. It is different as seen by different observers!
- Example: Ambulance and sound wave in Java demo from the course links
  http://home.a-city.de/walter.fendt/phe/phe.htm

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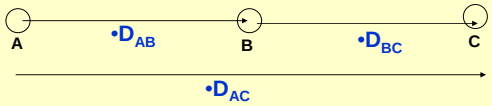
What could be wrong with our ideas of space and time??

- Our usual (Galilean) picture of relative velocities:



$V_{AC} = D_{AC}/t = (D_{AB}+D_{BC})/t = V_{AB}+V_{BC}$

- Question: What assumptions are hidden above?
- Einstein: We must define concepts strictly using operational definitions:
  - Space is what you measure with meter sticks
  - Time is what you measure with clocks

The Key Concept concerning Time: Simultaneity

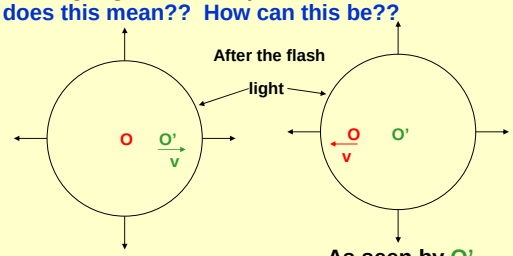
- Two things either happen at the same time or they don't? Right??
- If time is the same everywhere for all observers, then it is a simple matter to determine whether two things happen at the same time - each observer just looks at his watch.
- Einstein's response: maybe, maybe not.. I don't know it means until we define what we mean by things (we'll call them events from now on) happening at the same time.

Simultaneity: Definition

- Einstein's analysis of "happening at the same time"
- Must distinguish between the simultaneity of local events (events happening at the same place) and simultaneity of spatially separated events.
- Local events
  - We don't need to define simultaneity for these events
  - We take it to be a primitive concept.
  - Time for all events at the same place is defined by one single clock at that place.
- Spatially separated events:
  - We CANNOT claim this to be a primitive concept.
  - We cannot be present at both these events so we cannot make the same judgment we can make for local events.
  - We need an operational definition!

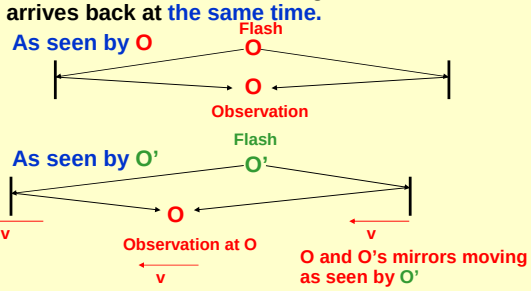
Einstein's "Gedanken Experiments"

- Example: Two observers O and O' are moving relative to each other. Just as they pass, a flash bulb fires. According to the postulate each observer sees light go out as a sphere around himself. What does this mean?? How can this be??



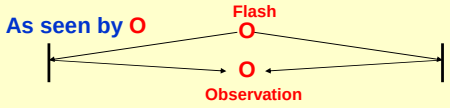
An Operational Test

- What does it mean to say, "Light goes out in a sphere around me." One must make a test.
- Example: Observer O puts mirrors at the same distance to reflect back the light reflect back. It arrives back at the same time.



Simultaneity: Operational Test

- Both Observers agree: the light arrives back at O at the same time.
- They do NOT agree that the light hit the mirrors at the same time!
- Observer O says the light hits the mirrors simultaneously.



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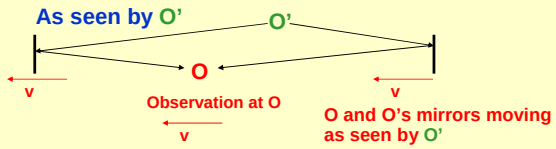
Simultaneity: Operational Test

- Observer O' says light hits the right mirror before hitting the left mirror -- since light always travels at speed c to observer O'



- Conclusion: We must give up the idea that the phrase "happened at the same time" has an unambiguous meaning for two events that happen in different places.

The universal speed limit

- Two first conclusions:
- The preceding example shows that it is impossible to satisfy Einstein's postulates if the speed of either observer exceeds the speed of light.
  - An observer moving faster than light could not even see the light from the flash!
- There can be only one such speed that is a universal limit! Otherwise a logical inconsistency.

Time and Space

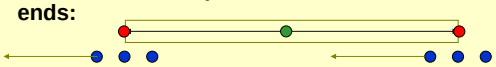
- Einstein's postulates lead to the conclusion that all previous ideas of time and space must change
- Time and space must be defined by operational definitions
- Notice how far reaching are the consequences of this simple, direct logic:
  - If the speed of light is constant for all observers:
  - Then we must give up the concept of "simultaneity" at different points in space -- the order in which things happen can be different for different for different observers!
  - Nothing can travel faster than light
  - There be one one such maximum speed
- What about space??? (We will return to time later.)

Apparent length of a moving object

- For an object at rest, one simply measures the length with a ruler also at rest.
- Example of a moving train.
  - To a person on board the train its length can be measured by laying down meter sticks.
  - (Nothing changes! No experiment on the train can detect its uniform motion!)
- How can a person on the ground measure the length of the train while it is moving?
  - For an object moving wrt the ruler, then one measures the length by the position of the front and the back at the same time.
- Thus "simultaneity" in time is part of the measurements of lengths in space!

Measuring a moving train - I

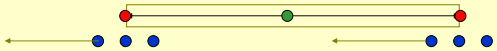
- As seen by 2 conductors at ends of the train. A flash of light at the middle of the train (measured by rulers on the train) defines "same time" at the two ends:



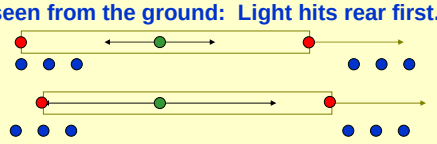
- Each conductor observes that he is at the position of the telegraph poles at the instant the light arrives.
- Each conductor sets off another flash that illuminates each pole exactly when the first light flash arrives
- Two observers on the ground at the positions of the poles agree:
  - Each conductor set off a flash as he passed the respective pole.
  - But do they agree that the two flashes were at the same time???

Measuring a moving train - II

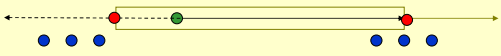
- As seen by 2 conductors at the ends of the train:



- As seen from the ground: Light hits rear first.



- As seen from the ground: Light hits front later.



- Thus, as seen from ground, moving train must be shorter than distance between poles!

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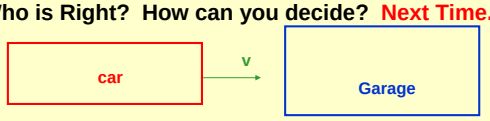
Moving objects appear shorter than when at rest!

- All observers agree:
  - Each of the two conductors at the ends of the train each sees a pole next to his end of the train at the moment he sees a flash
- But they do not agree that this was at the same time.
- Since we define the length by measurement of positions at the same time, the length must change for different observers
- To a person on the ground:
  - Everything about the train appears to contracted in the direction of motion - the people on board, the atoms, . . .
- The "gedanken experiment" can also be reversed!
  - The a person on the train, everything on the ground appears contracted to them!

Garage Paradox

- Question: If a long car goes fast enough, will it fit into a short garage?
  - Assume: Length of car in rest frame of car = L_0 = 20 ft
  - Length of garage in rest frame of garage = G_0 = 20 ft
  - Speed of car wrt garage = v = 0.6 c = 0.6 ft/ns (γ = 1.25 c = 1 ft/ns)
- Answer from Garage Attendant: You bet !!
  - L = 20/γ = 20/(1.25) = 16 ft. Your 16 ft car should fit easily into my 20 ft garage!
- Answer from Car Driver: No way!!
  - G = 20/γ = 20/(1.25) = 16 ft. My 20 ft car can't fit into your 16 ft garage!
- Who is Right? How can you decide? Next Time.



Summary

- Einstein produced 5 original papers in 1905 – each truly exceptional.
- One was the theory of special relativity
  - The speed of light is the same in all directions to all observers
- This led to fundamental changes in our notions of space and time
  - Require that theory must agree with direct observations
  - Give up idea that time is the same at different places (not a direct observation, as was assumed in classical physics)
  - Time is neither absolute, nor is it invented by human minds
  - Additional Conclusions:
  - Length of moving objects shrink along direction of motion
  - Nothing can travel faster than the speed of light -- the one and only " Universal speed limit"