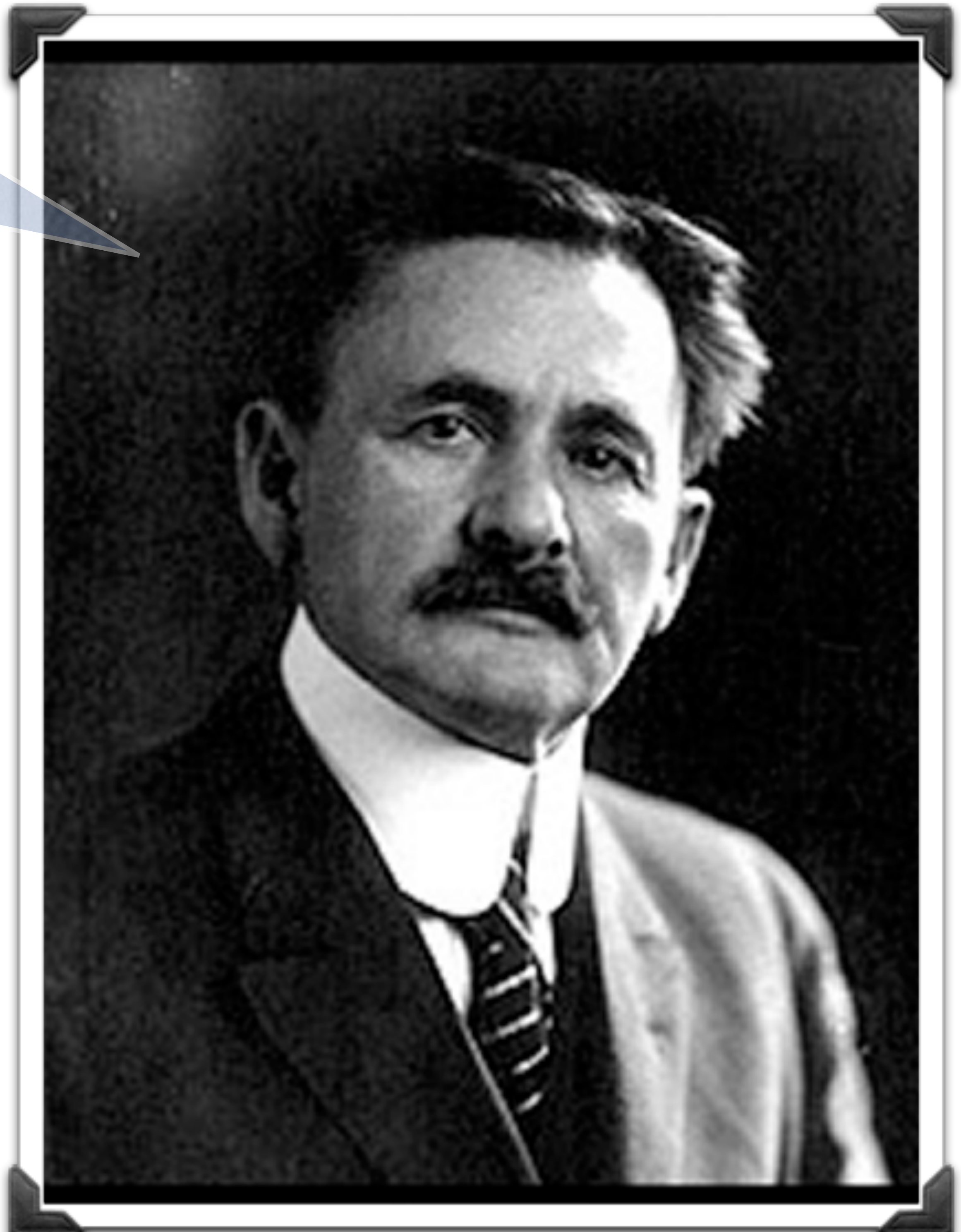
Welcome back to PHY 3305

Today's Lecture:

Michelson-Morley Experiment

Simultaneity



Albert A. Michelson
1852-1931

What is simultaneity?

occurring or done at the same time

Will two observers always agree that two events are simultaneous?

No. More on this later in the lecture.

What is relativity?

The dependence of various physical phenomena on relative motion of the observer and the observed objects

- Properties:
  - An observer in motion and an observer at rest may disagree on the sequence of events, However, **they do agree on the results**. (example: ball thrown in air)
  - The laws that govern the motion are the same.
  - We can transform from one frame to another using a **Galilean Transformation**.

What is a frame of reference?

A system of coordinates defined for an observer.

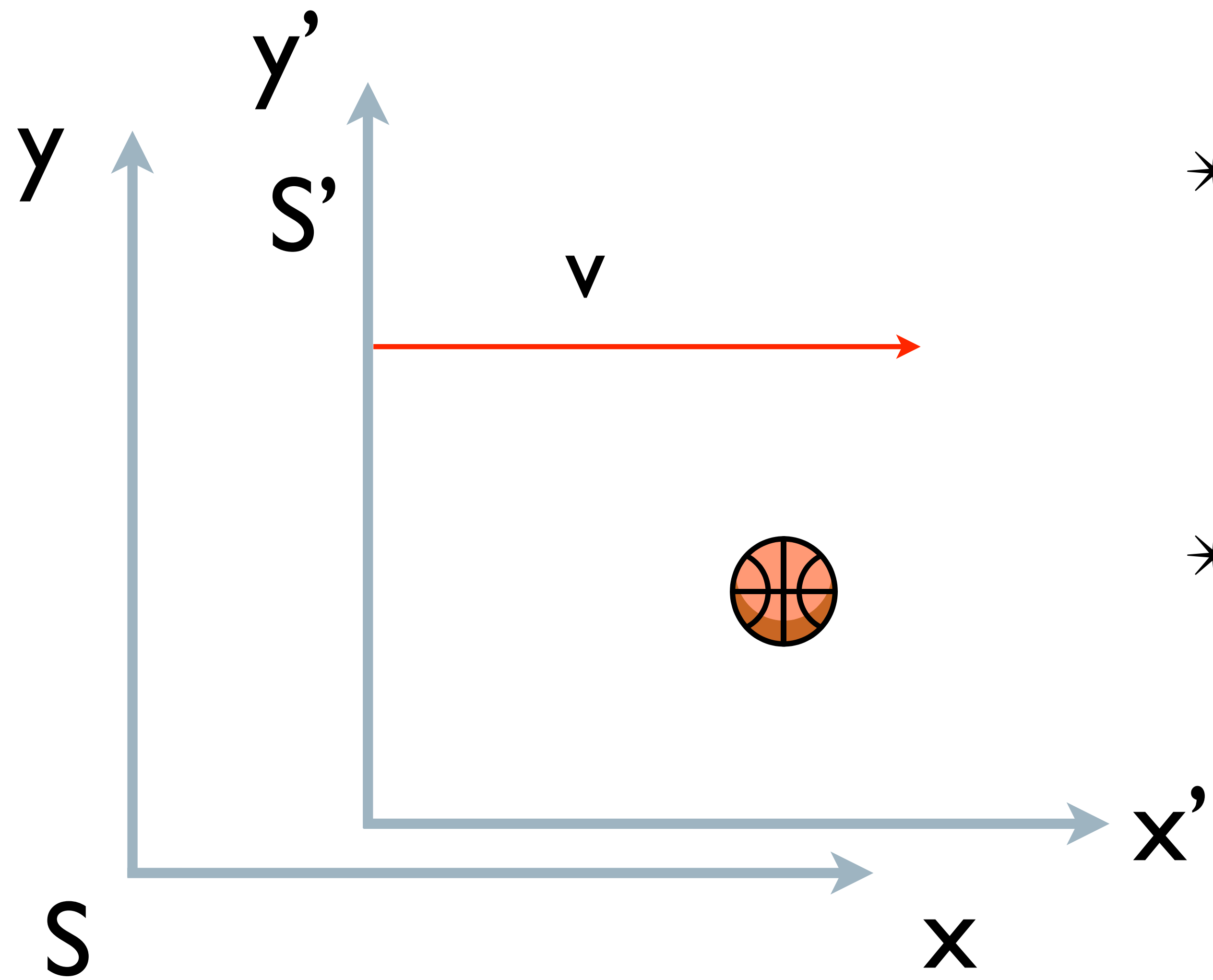
- Convention is to have the observer at the origin of the system and to define all distances relative to that point.
- Each reference frame can have it's own origin.

What is an inertial reference frame?

A frame of reference in which an object experiencing zero net force moves at constant velocity.

- A frame which is not accelerating.
- No absolute reference frame (can't tell one apart from another).
- Galilean Transformation holds

REVIEW: GALILEAN TRANSFORMATIONS



- Reference frame S' is moving at constant velocity v wrt to S. (Restrict motion to x-axis)
- Transform from S' to S:

$$\boxed{\begin{aligned} t &= t' \\ x' &= x - vt \end{aligned}}$$

Note: we will use u' and u to designate the velocity of the ball in respective coordinate systems.

$$u' = \frac{dx'}{dt} = \frac{d}{dt}(x - vt) = \frac{dx}{dt} - \frac{d}{dt}(vt) \quad = u - v$$

$$\boxed{u' = u - v}$$

Consequences: Galilean Transformations

What does it mean for a quantity or law to be INVARIANT?

The quantity or law remains unchanged when after undergoing a transformation to a different coordinate system.

Non-invariant Quantities

- $x' \neq x$
- $v' \neq v$

Invariant Quantities

- $a' = a$
- $F' = ma' = ma = F$

☑ The Laws of Mechanics are unchanged under a Galilean transformation

Consequences: Galilean Transformations

Examine the Wave Equation

$$\frac{\partial^2 E}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = 0$$

Transform using x' = x - vt, t' = t and the chain rule for derivatives.

$$\frac{\partial}{\partial x} = \frac{\partial x'}{\partial x}\frac{\partial}{\partial x'} + \frac{\partial t'}{\partial x}\frac{\partial}{\partial t'}$$

$$\frac{\partial}{\partial t} = \frac{\partial x'}{\partial t}\frac{\partial}{\partial x'} + \frac{\partial t'}{\partial t}\frac{\partial}{\partial t'}$$

We obtain:

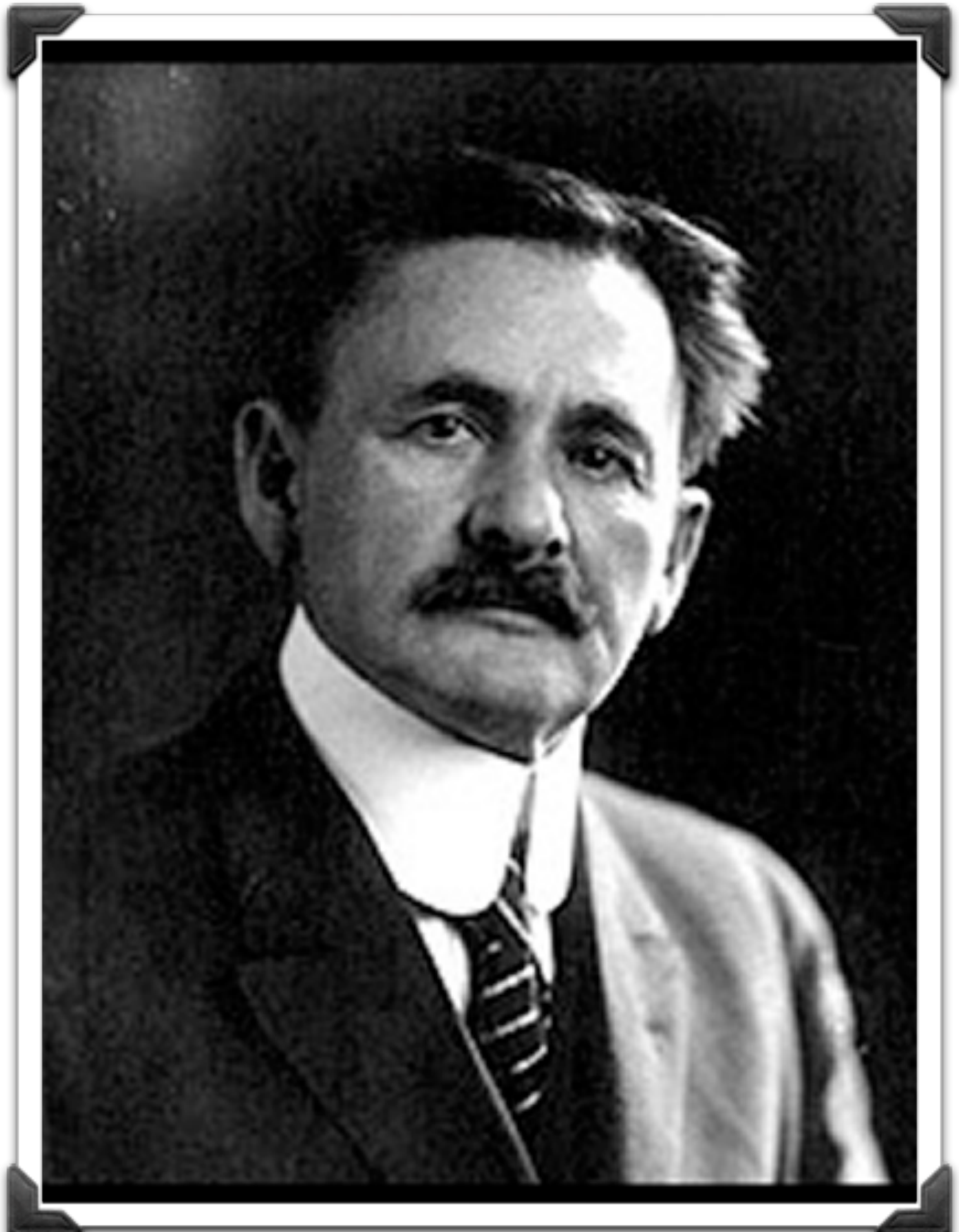
$$(1 - \frac{v^2}{c^2})\frac{\partial^2 E}{\partial x'^2} - \frac{1}{c^2}\frac{\partial^2 E}{dt'^2} - 2\frac{v}{c^2}\frac{\partial^2 E}{\partial x'\partial t'} = 0$$

☑ The Laws of E&M are changed under a Galilean transformation (unless v<<c)

THE ETHER

- Proposed solution: Light waves travel in a medium called ether (or aether). (Like sound waves in air or water waves in water)
    - The ether becomes the absolute and unique frame of reference where Maxwell's equations hold.
    - Mechanical waves propagate in a medium. So, it is a reasonable assumption that light would as well.

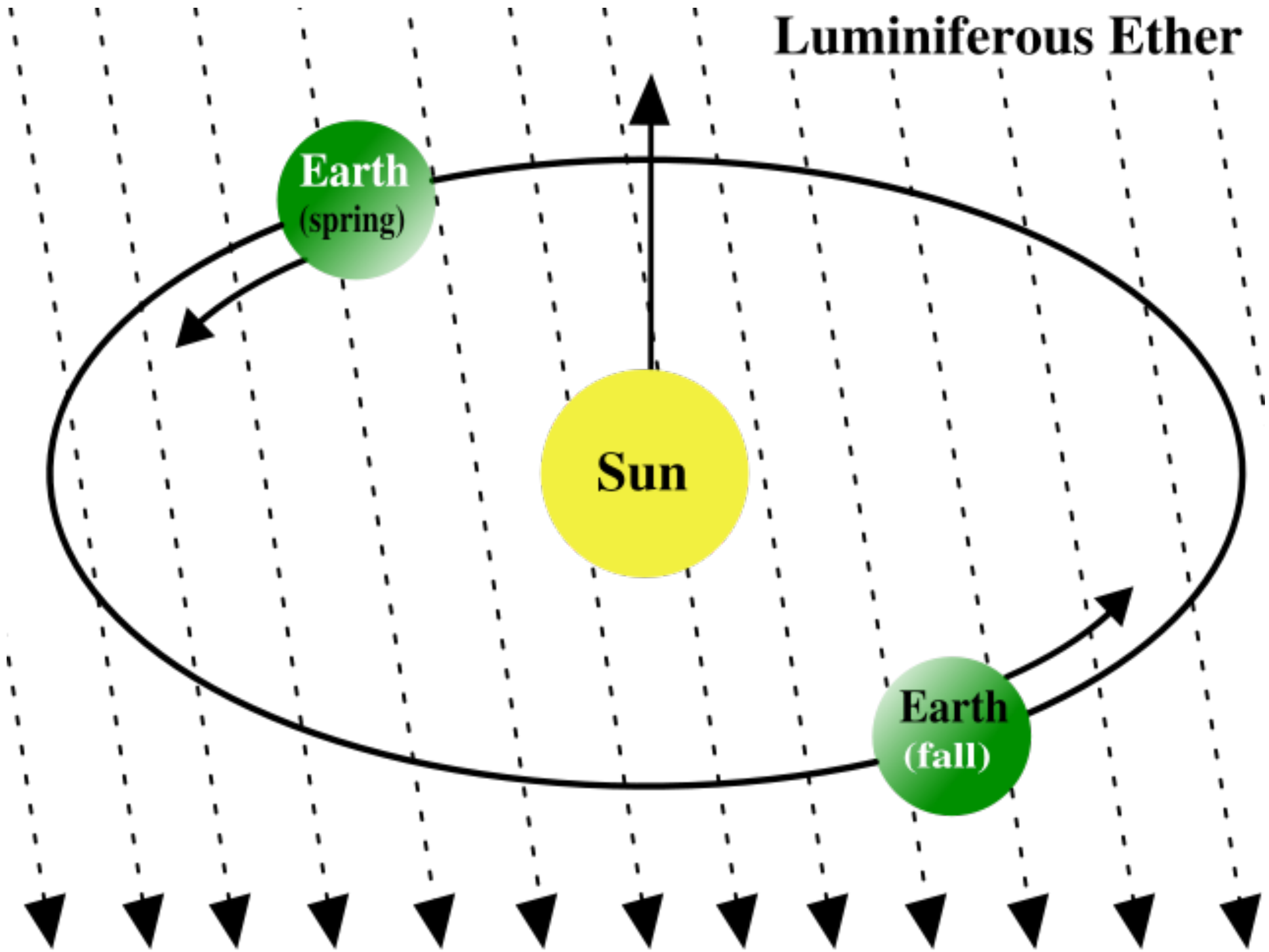
WAVE PROPAGATION



- Michelson-Morley experiment tried to determine the speed at which Earth propagated through the ether.

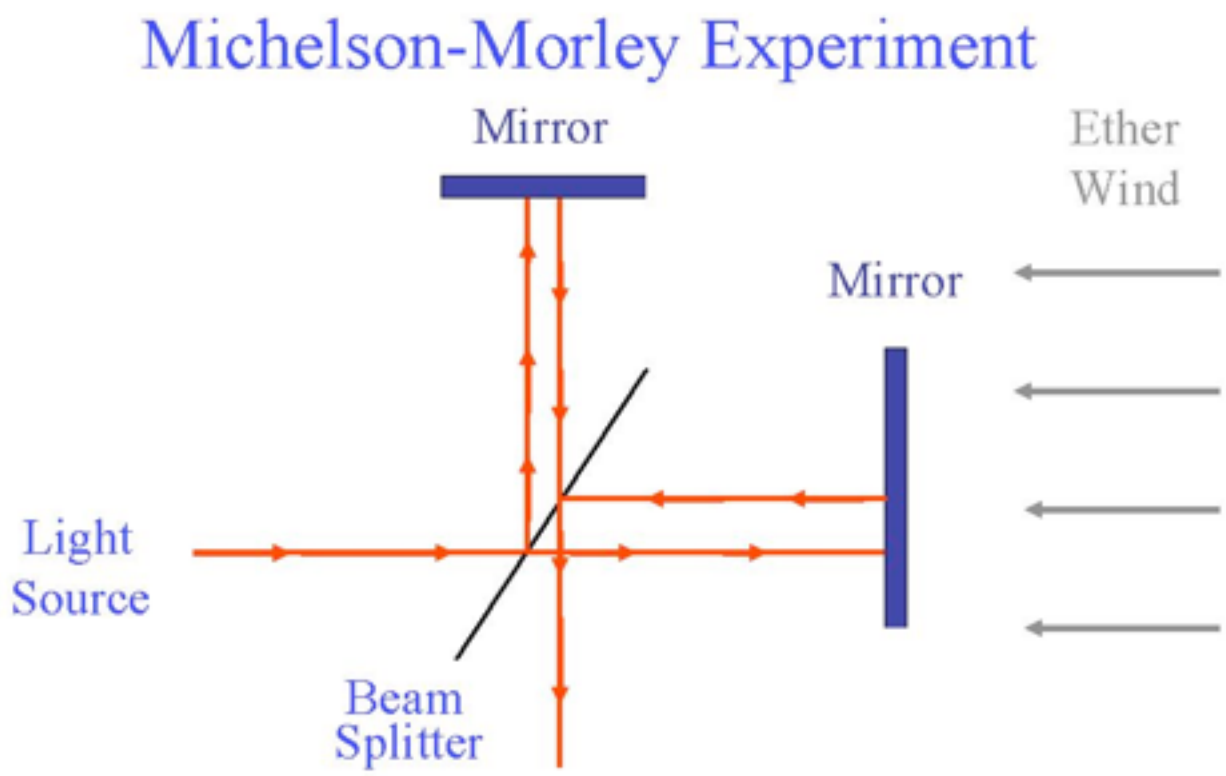
Albert A. Michelson
1852-1931

MICHELSON - MORLEY



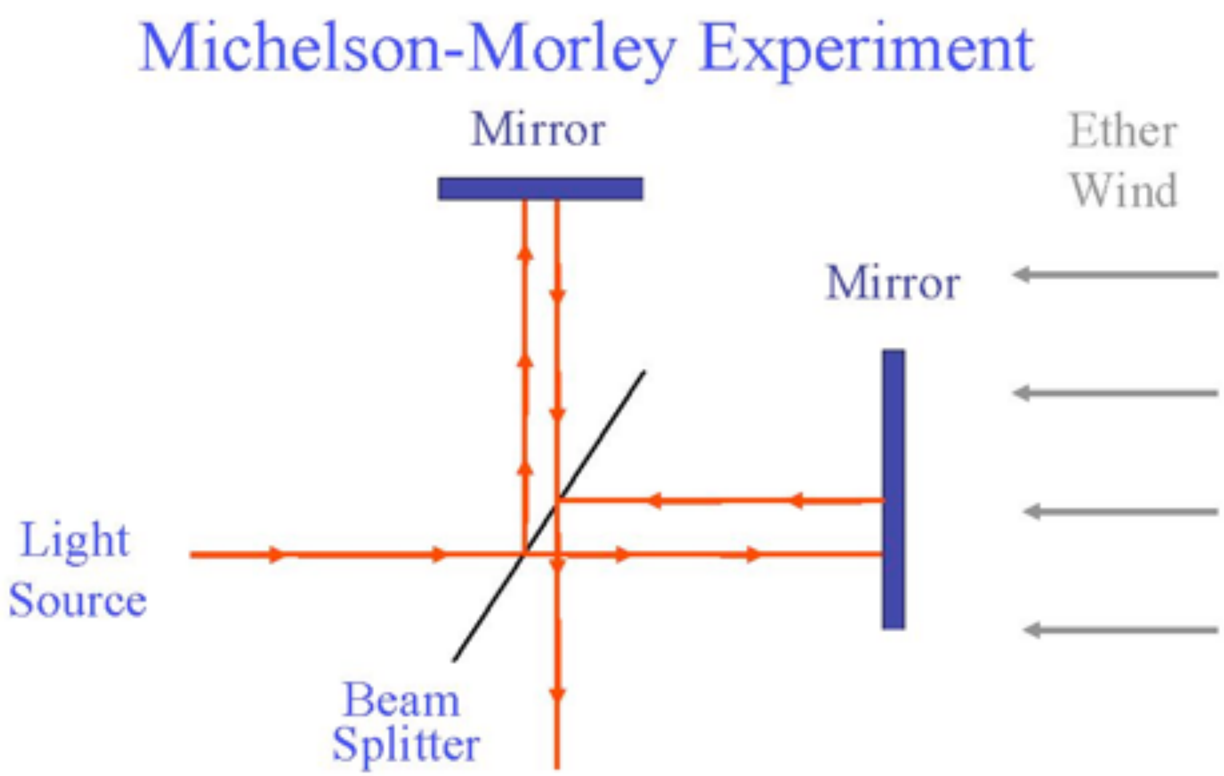
Earth moves through the ether.

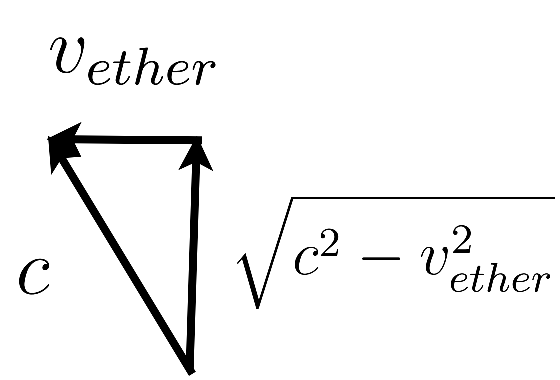
MICHELSON - MORLEY



- Start two light beams at the same point & time, then send them on two paths
  - one path parallel to the motion of the earth through the ether
  - one perpendicular
  - Measure the time difference it takes for them to arrive at the same point

MICHELSON - MORLEY





Parallel to Ether:

$$v_{away,1} = c - v_{ether}$$

$$v_{back,1} = c + v_{ether}$$

Perpendicular to Ether:

$$v_{away,2} = \sqrt{c^2 - v_{ether}^2}$$

$$v_{back,2} = \sqrt{c^2 - v_{ether}^2}$$

MICHELSON - MORLEY

Time for each trip is given by

$$t_{||} = \frac{L}{c - v_{ether}} + \frac{L}{c + v_{ether}}$$

$$t_{||} = \frac{L(c + v_{ether}) + L(c - v_{ether})}{c^2 - v_{ether}^2}$$

$$\boxed{t_{||} = \frac{2Lc}{c^2 - v_{ether}^2}}$$

$$t_{\perp} = \frac{L}{\sqrt{c^2 - v_{ether}^2}} + \frac{L}{\sqrt{c^2 - v_{ether}^2}}$$

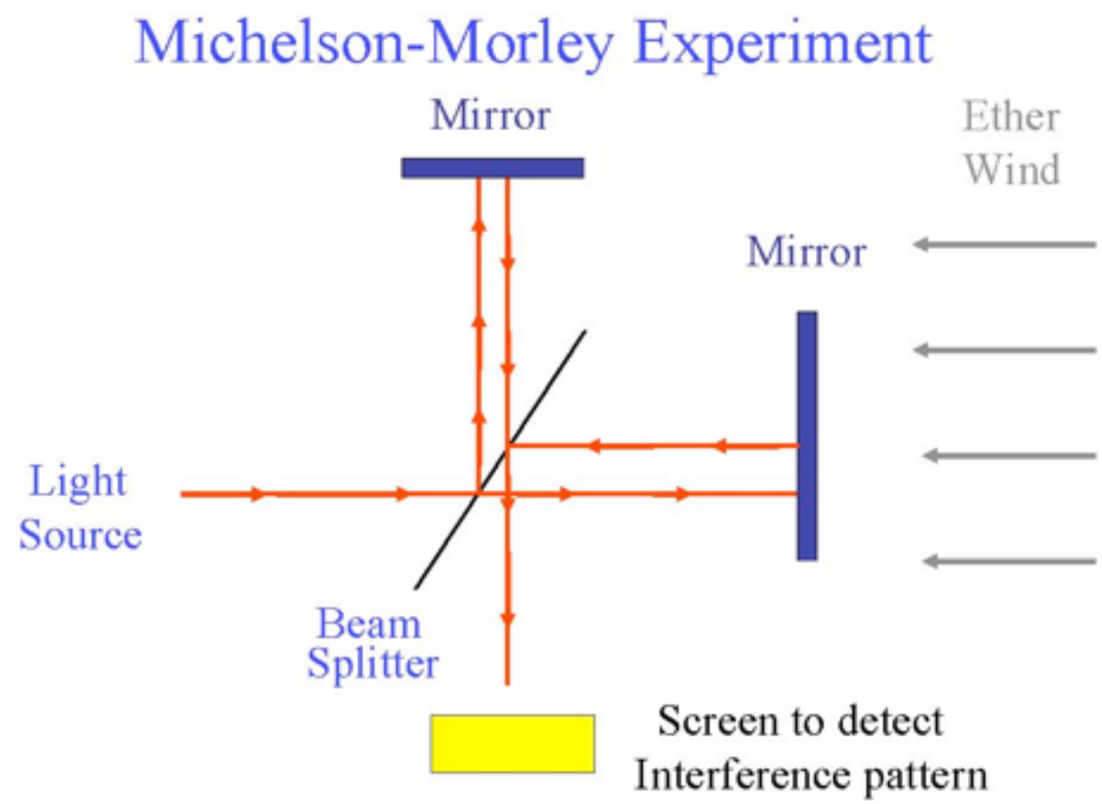
$$\boxed{t_{\perp} = \frac{2L\sqrt{c^2 - v_{ether}^2}}{c^2 - v_{ether}^2}}$$

$$\boxed{\Delta t = \frac{2Lc}{c^2 - v_{ether}^2} - \frac{2L\sqrt{c^2 - v_{ether}^2}}{c^2 - v_{ether}^2}}$$

MICHELSON - MORLEY

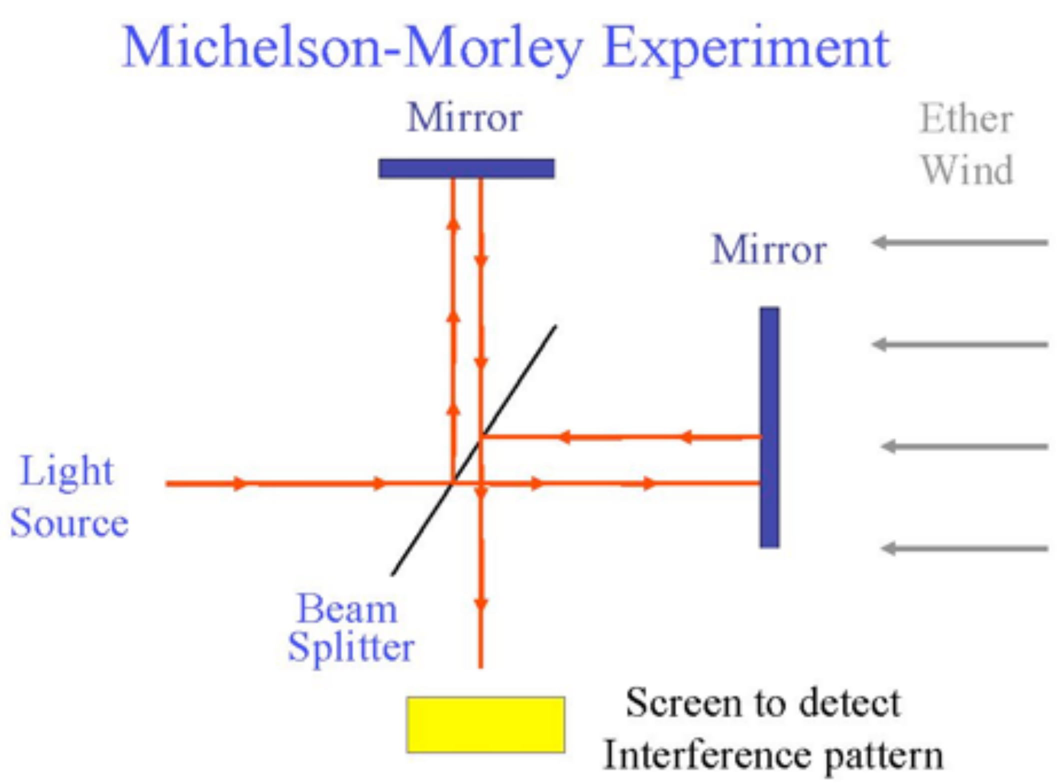
Problem: The speed of Earth moving through the ether is ~10,000 times smaller than the speed of light. Instrumentation of the period was not sensitive enough to measure such small timing differences.

Solution: Observe the interference between the two beams.



MICHELSON - MORLEY

If the two beams are moving at different speeds, there will be a fast arm and a slow arm. Deduce Δt from observed # fringes.



$$N_{fringes} = \frac{\Delta t}{T}$$

T = period of light wave.

$$N_{fringes} = \frac{2L(c - \sqrt{c^2 - v_{ether}^2})}{T(c^2 - v_{ether}^2)}$$

Observation: No fringe.

Outcomes of Michelson-Morley Experiment

a) The speed of light was shown to be independent of the motion of the observer.

b) Helped cast away the ether hypothesis

c) E&M explained the origin of light, but did not require a medium for its wave propagation

d) 1907 Nobel Prize awarded to Michelson (1st American Physicist)

WHERE ARE WE LEFT?

a) Many experiments (culminating with Michelson & Morley) showed that E&M was incompatible with a Newtonian relativity, Galilean Transformations, and the concept of ether.

b) So, what gives?

- The idea that all inertial frames are equivalent?
- The theory of mechanics?
- The theory of electromagnetism?

An experimental question: Is physics the same ("invariant") in all inertial frames?

Experiments suggest YES, for BOTH mechanics and electromagnetism

A theoretical question: How to describe this invariance mathematically. What is the transformation law that leaves physics invariant?

Galilean transformation works for Mechanics, but not E&M.
Lorentz transformation works for E&M and for Mechanics. -- More later in the lecture.

Special Relativity

The theory that governs physical phenomena when one object or reference frame moves relative to another at speeds comparable to that of light: $c = 3 \times 10^8$ m/s.

Einstein's Postulates:

1. The laws of physics are invariant to observers in different inertial reference frames.

2. The speed of light is the same to all observers, regardless of their motion relative to the light source.

What is an event?

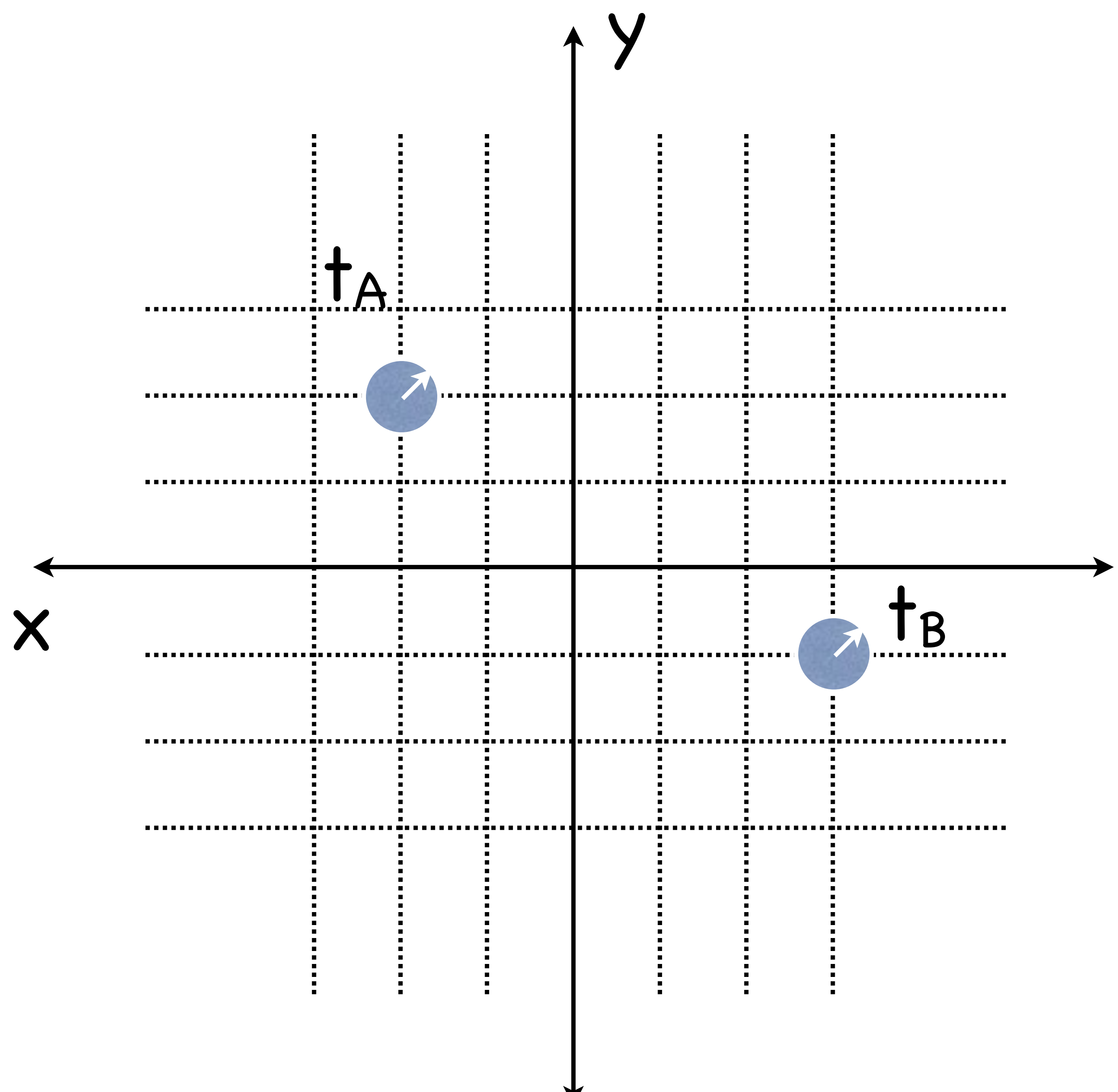
- An “event” is a physical occurrence, independent of any reference frame
  - i.e. a chalk breaks
  - two particles collide
  - a photon reaches a sensor
- The properties of the event, e.g. position, time, can be described in any reference frame.

CONSEQUENCE 1: RELATIVE SIMULTANEITY

What does it mean for two events to occur simultaneously?

Two events are defined as simultaneous if they occur at the same time as measured by each local clock.

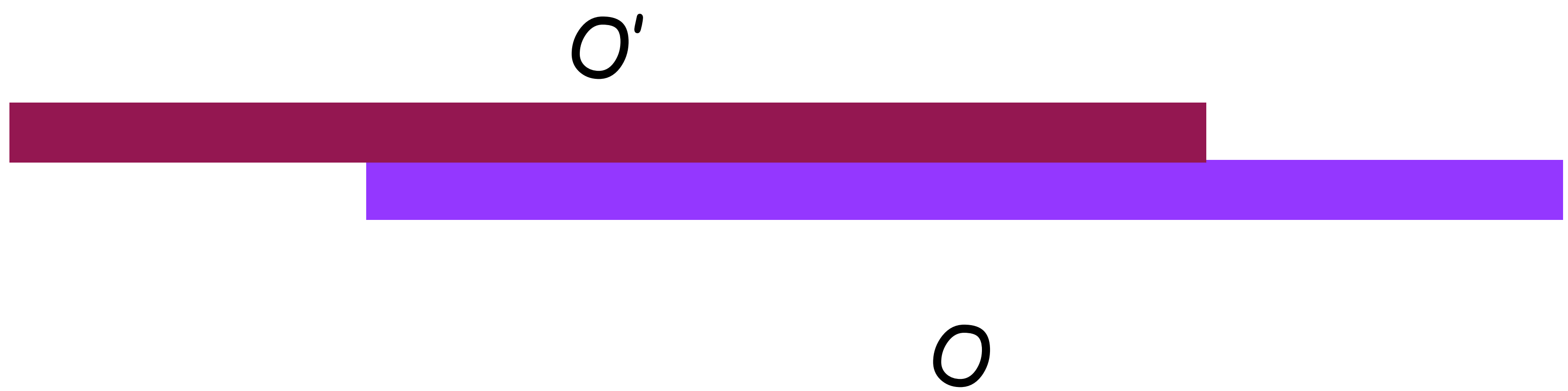
- i.e. only if $t_A = t_B$
- For another inertial frame $t'_A \neq t'_B$
- Events simultaneous in one frame will not be simultaneous in another



Professor Jodi Cooley

EVENTS IN DIFFERENT FRAMES

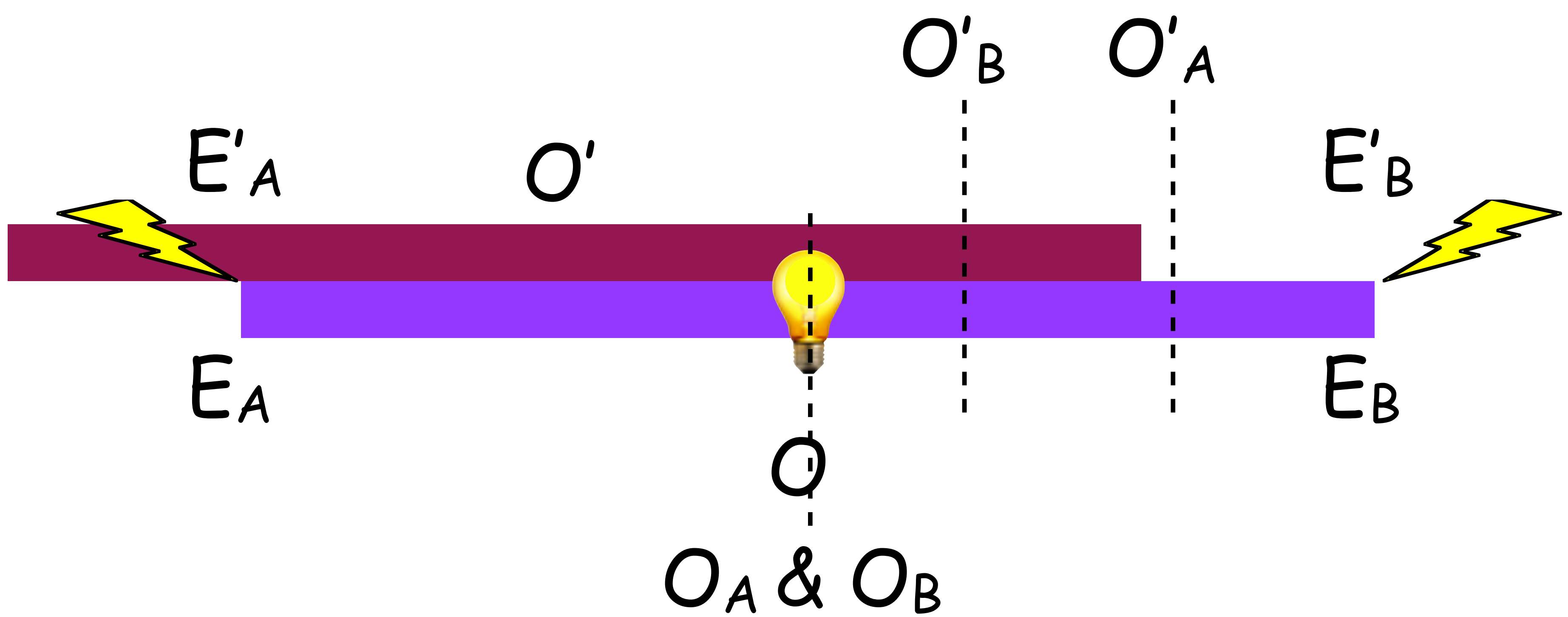
- Anna is an observer in the S' reference frame.
- She is on a high speed train traveling westward at the speed of light.
- O' is her origin.



Anna = S'
Bob = S

EVENTS IN DIFFERENT FRAMES

At the instant Anna and Bob pass each other, lightening strikes both ends of the train. Do Anna and Bob agree on the ordering of the lightening strikes?



(Anna) O' sees E'B
(Bob) O sees EB and EA
(Anna) O' sees E'A

Anna = S'
Bob = S

What is the conclusion?

- Anna argues that the lightening strikes did not occur at the same time.

Does Anna agree that the light hit Bob at the same time?

- Yes. She sees the western strike (E_b') before the eastern strike (E_a'). In her frame of reference Bob appears to be moving toward one light wave and away from the other light wave.

This is not an optical illusion. Space and time are different for all observers in relative motion.

THE END
(FOR TODAY)