Final Exam: April 16, 9:00 a.m. -12:00 noon

1. The formula sheet has been posted.
2. You are responsible for material in Chapters 2-11, and 37. The following sections are excluded: 6.2, 9.9, 11.9, 37.3, 37.4 (Lorentz transformation part), 37.5-37.6.
3. There are 25 questions on the final, covering all aspects of the course.
4. Answers for chapter 11 homework problems will be posted on Monday; chapter 37 on Friday.
5. The SEEQ evaluations will be done on Wednesday in the last 15 minutes of class.
6. There is a review lecture next Friday. If time permits, I will take questions (*e.g.* clarifications, or old exam questions) and do examples.

Chapter 37

Relativity

Relativity

Relativity:

- Measurements of events, where and when they happen, and by how much any two events are separated in space and in time.
- Examines transforming such measurements (and also measurements of energy and momentum) between reference frames that move relative to each other.

Special Relativity (as formulated by Einstein, 1905)

- Deals with **inertial reference frames**, which are frames in which Newton's laws are valid.
- His **General Theory of Relativity** treats the more challenging situation in which reference frames can undergo gravitational acceleration.

Observational Facts

1. Light has a finite speed: $c = 3.00 \times 10^8$ m/s
   - "Light" includes all electromagnetic waves: radio, microwave, visible light, infrared, x-rays

Example

Earth-Moon: $d = 3.82 \times 10^5$ km

$$t = \frac{d}{c} = 1.27 \text{ s} \quad \text{time for light signal}$$

Earth-Sun: $d = 150 \times 10^6$ km

$$t = \frac{d}{c} = 500 \text{ s} = 8'20'' \quad \text{time for light signal}$$

Observational Facts

2. All observers measure the same value of c, no matter what inertial reference frame they are in (*i.e.* no matter how "fast" they are moving with respect to any other inertial reference frame).
   How can that be? This is a violation of the velocity addition law of Galilean relativity.

Examples

- Observer A emits a pulse of light at speed c
- Observer B is moving away from A at a speed $c/4$
- According to A, we expect B to measure a speed of $3c/4$ for the speed of the pulse
- Observer C is moving toward A at a speed $c/4$
- According to A, we expect C to measure a speed of $5c/4$ for the speed of the pulse

37.2: The postulates:

These observational facts require a fundamental change in our notions of both space **and** time.

Einstein's postulates:

1. The laws of physics are the same for all observers in all inertial reference frames. No one frame is preferred over any other.
2. The speed of light in vacuum (c) is the **same** for all observers in all directions. It does not depend on the relative speeds of the source or detector.

Cosmic speed limit

$c = 299\,792\,458$ m/s (by definition)

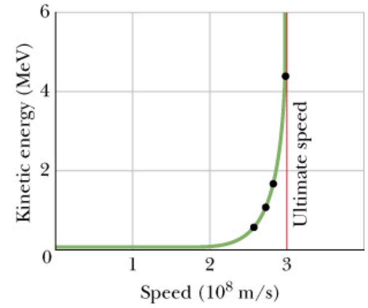
- Nothing travels faster than the speed of light.
- Verified by many experiments.
- Particles with mass never reach the speed of light.
- For example, in the most powerful electron accelerators:

$$v_e = 0.999\,999\,999\,950\,c$$

The Ultimate Speed

Experiment by Bertozzi in 1964 accelerated electrons and measured their speed and kinetic energy independently.

Kinetic energy → ∞ as speed → c



Ultimate Speed→Speed of Light: $c = 299\ 792\ 458$ m/s

Testing the Speed of Light Postulate

If speed of light is same for all inertial reference frames, then speed of light emitted by a source (pion, π^0) moving relative to a given frame (*e.g.* a laboratory) should be the same as the speed light that is emitted by a source that is at rest in the laboratory).

1964 experiment at CERN (European particle physics lab):

Pions moving at 0.9975 c with respect to the laboratory decay, emitting two photons (γ).

$$\pi^0 \rightarrow \gamma + \gamma$$

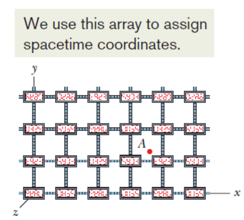
The speed of the light waves (γ-rays) emitted by the pions was measured always to be c in the lab frame (not up to 2 c!)

→ same as if pions were at rest in the lab frame!

Measuring an Event:

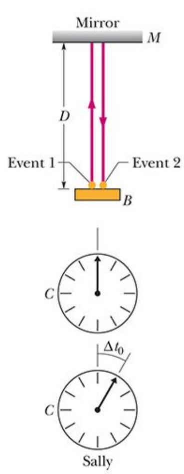
- **Event**: something that happens (*e.g.* a flash of light, a particle passing some point in space, a measurement of some parameter)
- Each **event** characterized by its **location** in **space** (three spatial coordinates x, y, and z) and in **time** (one coordinate t).

  These four parameters are the **space-time** coordinates of the event.



37.1: The Relativity of Time:

- Measure time between events with a light clock.
- Light is emitted, reflected by mirror and detected. Time between emission and detection is one tick of light clock.
- Event 1 and event 2 take place at the same location
- Now put light clock on moving train.



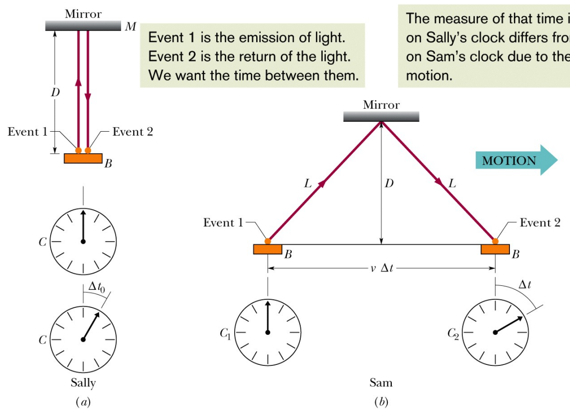
Light clock on moving train

- Sally on train. Clock is at rest with respect to (wrt) Sally.
- Sam on ground. Clock is moving wrt Sam at speed v.

The Relativity of Time

Event 1 is the emission of light.
Event 2 is the return of the light.
We want the time between them.

The measure of that time interval on Sally's clock differs from that on Sam's clock due to the relative motion.



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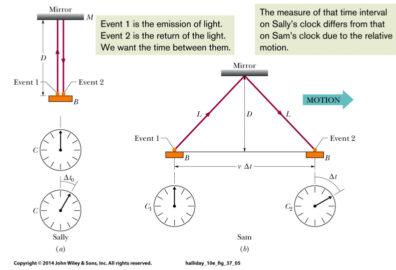
The Relativity of Time



$$\Delta t_0 = \frac{2D}{c} \quad (\text{Sally})$$

$$\Delta t = \frac{2L}{c} \quad (\text{Sam})$$

$$L = \sqrt{\left(\tfrac{1}{2}v\Delta t\right)^2 + D^2}$$

$$L = \sqrt{\left(\tfrac{1}{2}v\Delta t\right)^2 + \left(\tfrac{1}{2}c\Delta t_0\right)^2}$$

How can we distinguish these 2 observations?

$$\therefore \Delta t = \frac{\Delta t_0}{\sqrt{1-(v/c)^2}}$$

Sally: Event 1 and event 2 take place at **the same** location.
Sam: Event 1 and event 2 take place at **different** locations.

When two events occur at the same location in an inertial reference frame, the time interval between them, measured in that frame, is called the **proper time interval** or the **proper time**. Measurements of the same time interval from any other inertial reference frame are always greater.

In the previous example, who measures the proper time?
Sally uses **one** clock. Sam uses **two** clocks.
Therefore Sally measures proper time.

Speed parameter: $\beta = v/c, \quad 0 \le \beta \le 1$ (β is dimensionless)

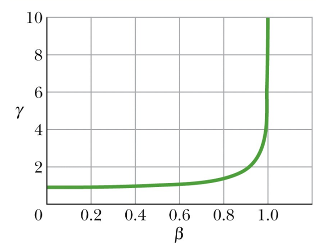
Lorentz factor: $\gamma = \frac{1}{\sqrt{1-\beta^2}} = \frac{1}{\sqrt{1-(v/c)^2}}, \quad \gamma \ge 1$ $\quad \Delta t = \gamma \Delta t_0$

Time dilation: Moving clocks run **slow** (compared to proper time interval Δt_0)

The Relativity of Time

Lorentz factor γ as a function of the speed parameter $\beta = v/c$

As the speed parameter goes to 1.0 (as the speed approaches c), the Lorentz factor approaches infinity.



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$$\gamma = \frac{1}{\sqrt{1-\beta^2}} = \frac{1}{\sqrt{1-(v/c)^2}}, \quad \gamma \ge 1$$

Example

On a highway there is a flashing light to mark the start of a section of the road where work is being done. Who measures the proper time between two flashes of light?

A. A worker standing still on the road
B. A driver in a car approaching at a constant velocity
C. Both the worker and the driver
D. Neither the worker nor the driver