PHYS 3313 – Section 001
Lecture #5

Wednesday, Feb. 1, 2017
Dr. Jaehoon Yu

- Galilean Transformation
- Do we need Ether?
- Michelson-Morley Experiment
- Einstein's postulates
- Lorentz Transformations

Announcements

- Reading assignments: CH 2.10 (special topic), 2.13 and 2.14
  - Please go through eq. 2.45 through eq. 2.49 and example 2.9
- Reminder: Homework #1
  - chapter 2 end of the chapter problems
  - 17, 21, 23, 24, 32, 59, 61, 66, 68, 81 and 96
  - Due is by the beginning of the class, Wednesday, Feb. 8
  - Work in study groups together with other students but PLEASE do write your answer in your own way!
- Colloquium today
  - Dr. C.K.Shih of UT Austin

From: Cody, Stacey Nicole scody@exchange.uta.edu
Subject: Colloquium/ C.K. Shih/ February 1st in room 103 SH at 4:00
Date: January 31, 2017 at 12:01 PM
To: PHYS-INFO@LISTSERV.UTA.EDU

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Physics Department
The University of Texas at Arlington
COLLOQUIUM

Atomic and electronic structures of 2D electronic materials and their heterostructures

C.K. Shih
Department of Physics,
The University of Texas at Austin

Wednesday February 1, 2017
4:00 Room 103 Science Hall

The emerging atomic layer materials offer a remarkably wide range of building blocks of nanostructures ranging from metals (e.g. graphene), large gap insulators (BN), to semiconductors (transition metal dichalcogenides and black phosphorous). Key advantages of these van der Waals materials include a broad span of energy gaps, flexibility of stacking different types of materials to form heterostructures, tunability in material properties by doping and strain, and the relative ease of integration with other electronic and photonic devices. This talk will be focused on the usage of scanning tunneling microscopy and spectroscopy to probe the atomic and electronic structure of transition metal dichalcogenides (TMDs) and their heterostructures.

I will first introduce a comprehensive form of scanning tunneling spectroscopy (STS) which allows us to probe not only the quasi-particle band gaps but also the critical point energy locations and their origins in the Brillouin Zone (BZ) can be revealed using this comprehensive form of STS. By using this new method, we unravel the systematic trend of the critical point energies for TMDs due to atomic orbital couplings, spin-orbital coupling and the interlayer coupling [1]. I will then present STM/S investigations of the vertically stacked MoS2/WSe2. I will show how interlayer coupling can be used as a new designing parameter to create a lateral 2D electronic superlattices [2]. Finally I will address the current topic of band gap renormalization by using MBE grown MoSe2 on several different substrates, including MoSe2/graphite, MoSe2/graphene and MoSe2/hBN/Ru(0001) [3]. 1] “Probing Critical Point Energies of Transition Metal Dichalcogenides: Surprising Indirect Gap of Single Layer WSe2” Chendong Zhang et al., NANO LETTERS Volume: 15 Pages: 6494-6500 (2015).

Special Project #3

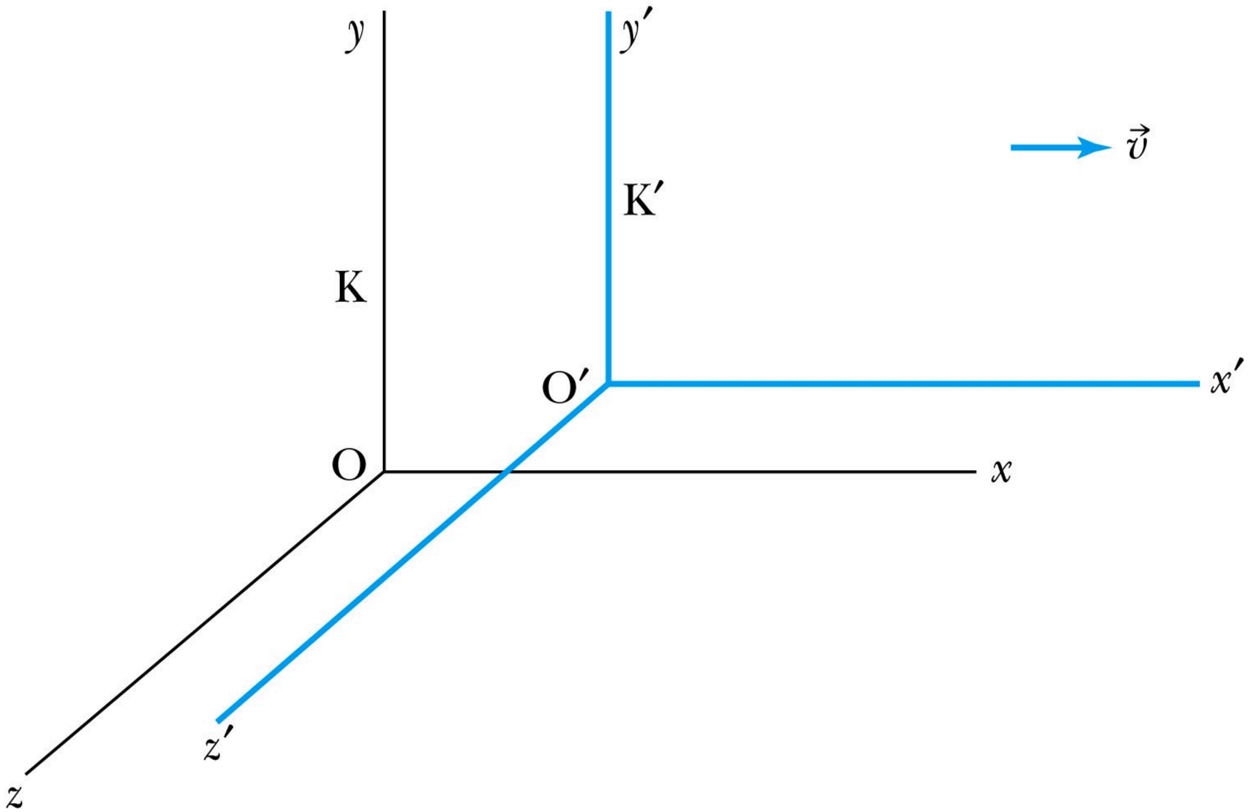
1. Derive the three Lorentz velocity transformation equations, starting from Lorentz coordinate transformation equations. (10 points)
2. Derive the three reverse Lorentz velocity transformation equations, starting from Lorentz coordinate transformation equations. (10 points)
3. Prove that the space-time invariant quantity $s^2=x^2-(ct)^2$ is indeed invariant, i.e. $s^2=s'^2$, in Lorentz Transformation. (5 points)
4. You must derive each one separately starting from the Lorentz spatial coordinate transformation equations to obtain any credit.
   - Just simply switching the signs and primes will NOT be sufficient!
   - Must take the simplest form of the equations, using β and γ.
5. You MUST have your own, independent handwritten answers to the above three questions even if you worked together with others. All those who share the answers will get 0 credit if copied.

- Due for the submission is this Monday, Feb. 13!

Newtonian (Classical) Relativity

- It is assumed that Newton's laws of motion must be measured with respect to (relative to) some reference frame.
- A reference frame is called an **inertial frame** if Newton's laws are valid in that frame.
- Such a frame is established when a body, not subjected to a net external force, is observed to move in rectilinear motion at constant velocity
- → Newtonian Principle of Relativity (Galilean Invariance): If Newton's laws are valid in one reference frame, then they are also valid in another reference frame moving at a uniform velocity relative to the first system.

Inertial Frames K and K'

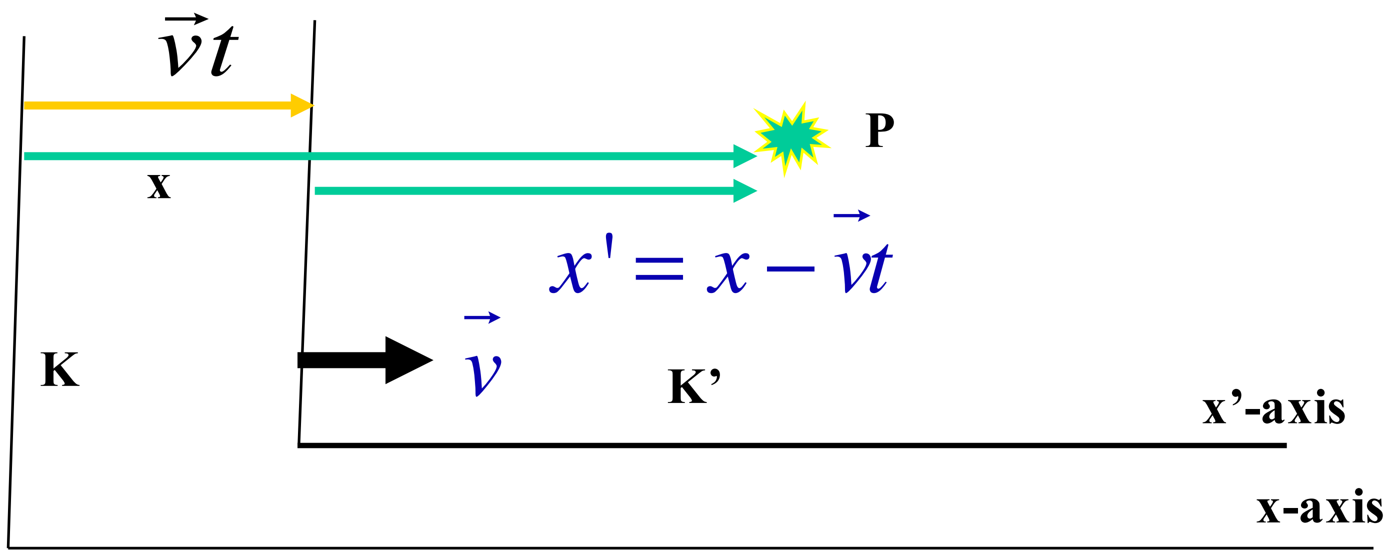


- K is at rest and K' is moving with a constant velocity $\vec{v}$
- Axes are parallel
- K and K' are said to be *INERTIAL COORDINATE SYSTEMS*

The Galilean Transformation

For a point P

- In system K: P = (x, y, z, t)
- In system K' : P = (x' , y' , z' , t')



Conditions of the Galilean Transformation

- Parallel axes between the two inertial reference frames
- K' has a constant relative velocity in the *x*-direction with respect to K

$$x' = x - \vec{v}t$$

$$y' = y$$

$$z' = z$$

$$t' = t$$

- **Time** (*t*) for all observers is a *Fundamental invariant*, i.e., the same for all inertial observers
  - Space and time are separate!!

The Inverse Relations

Step 1. Replace $\vec{v}$ with $-\vec{v}$

Step 2. Replace "primed" quantities with "unprimed" and "unprimed" with "primed"

$$x = x' + \vec{v}t$$

$$y = y'$$

$$z = z'$$

$$t = t'$$

The Transition to Modern Relativity

- Although Newton's laws of motion had the same form under the Galilean transformation, Maxwell's equations did not.
- In 1905, Albert Einstein proposed a fundamental connection between space and time and that Newton's laws are only an approximation.

They Needed Ether!!

- The wave nature of light suggested that there existed a propagation medium called the *luminiferous ether* or just **ether**.
  - Provides an inertial reference frame
- The properties of ether
  - Very low density for planets to move through it without the loss of energy
  - Sufficiently high elasticity to support the high velocity of light waves (c=?)

Ether as the Absolute Reference System

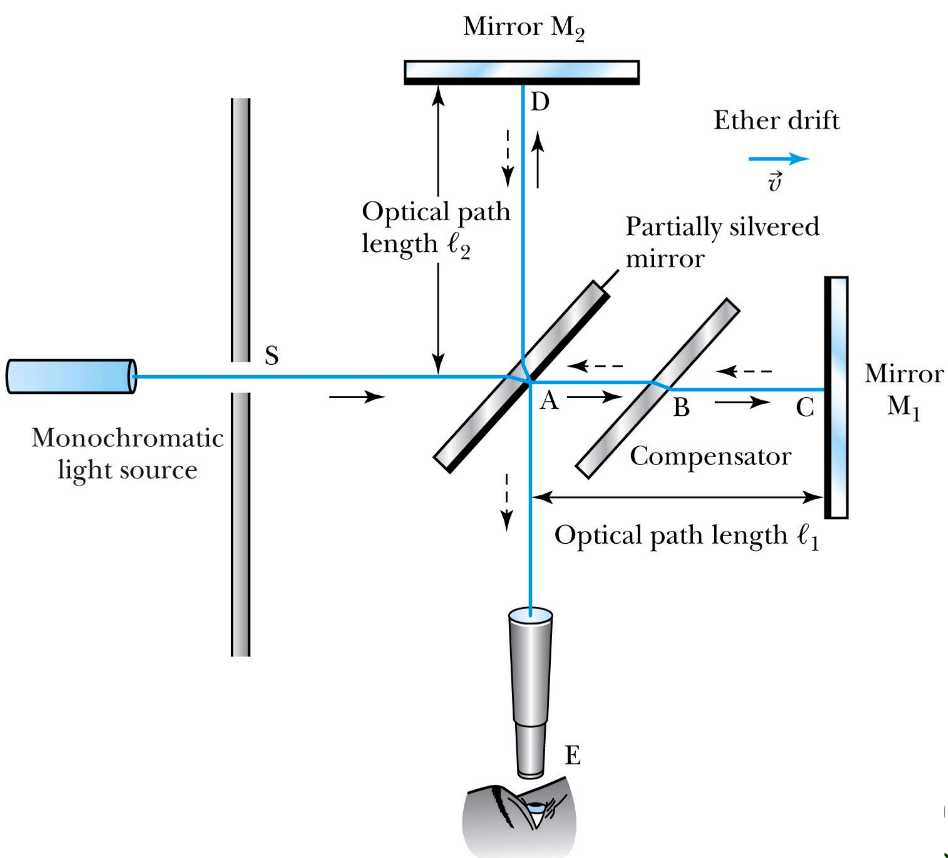
- In Maxwell's theory, the speed of light is given by

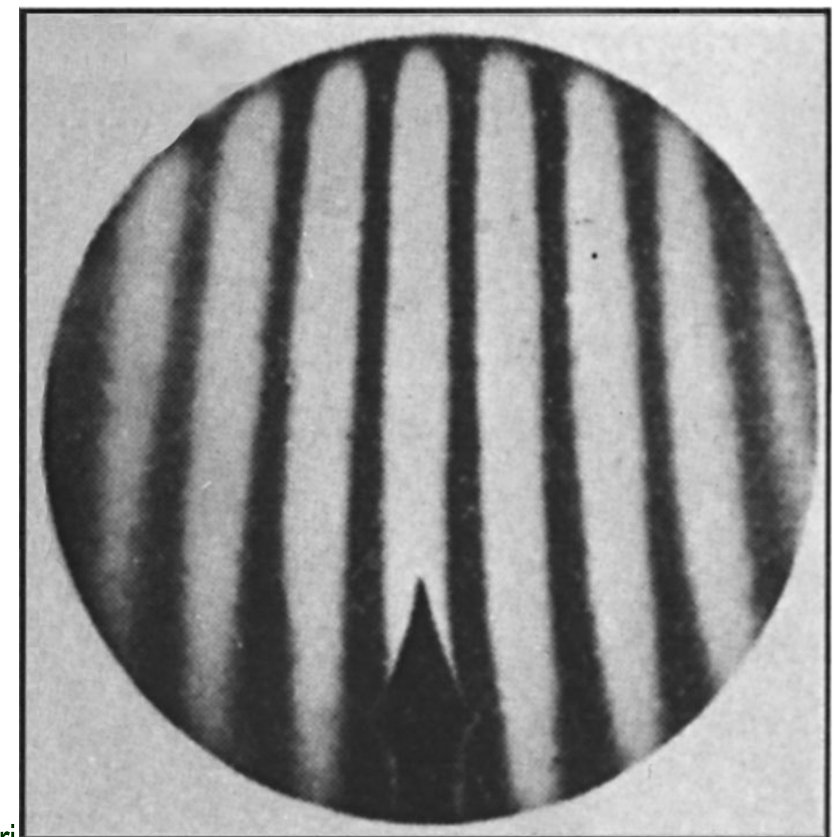
$$v = c = 1/\sqrt{\varepsilon_0 \mu_0}$$

  - The velocity of light between the moving systems must be a constant.
    - Can you see why?
  - Needed a system of medium that keeps this constant!
- Ether proposed as the absolute reference system in which the speed of light is constant and from which other measurements could be made.
- The Michelson-Morley experiment was an attempt to show the existence of ether.

The Michelson-Morley Experiment

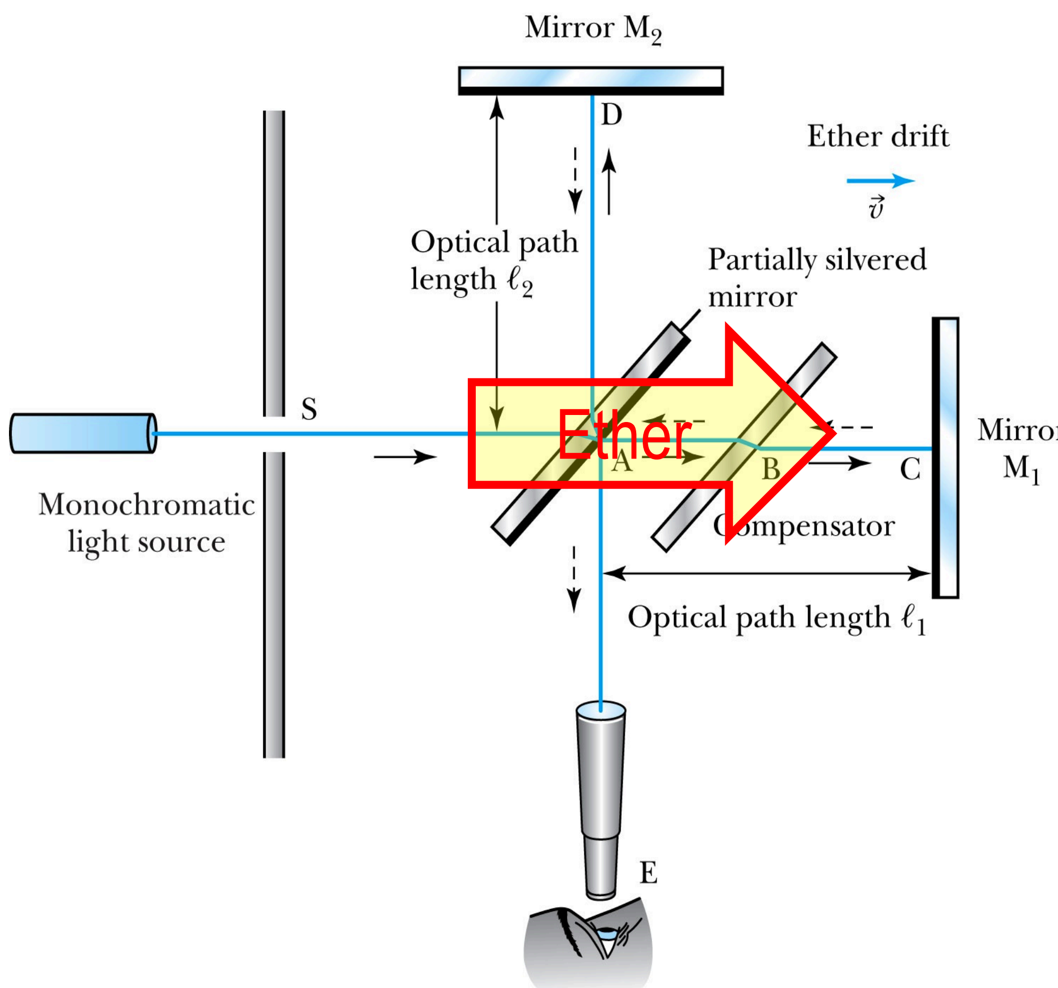
- Albert Michelson (1852–1931) built an extremely precise device called the *interferometer* to measure the phase difference between two light waves traveling in orthogonal directions.





How does Michelson Interferometer work?

1. AC is parallel to the motion of the Earth inducing an "ether wind"
2. Light from source S is split by mirror A and travels to mirrors C and D in mutually perpendicular directions
3. After reflection the beams recombine at A slightly out of phase due to the "ether wind" as viewed by telescope E.



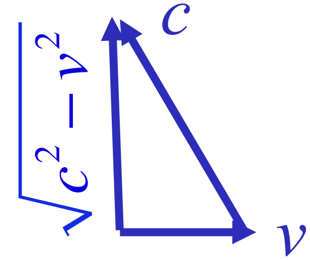
The analysis – Galilean X-formation

- Travel time t_1 for a round trip over AC (the ether direction) is

$$t_1 = \frac{l_1}{c+v} + \frac{l_1}{c-v} = \frac{2l_1 c}{c^2 - v^2} = \frac{2l_1}{c}\frac{1}{1 - v^2/c^2}$$

- Travel time t_2 for a round trip over AD (perpendicular direction to ether) is

$$t_2 = \frac{2l_2}{\sqrt{c^2 - v^2}} = \frac{2l_2}{c}\frac{1}{\sqrt{1 - v^2/c^2}}$$



- The time difference is

$$\Delta t = t_2 - t_1 = \frac{2}{c}\left(\frac{l_2}{\sqrt{1 - v^2/c^2}} - \frac{l_1}{1 - v^2/c^2}\right)$$

The analysis

- After rotating the machine by 90°, the time difference becomes

$$\Delta t' = t_2' - t_1' = \frac{2}{c}\left(\frac{l_2}{1 - v^2/c^2} - \frac{l_1}{\sqrt{1 - v^2/c^2}}\right)$$

- The difference of the time differences

$$\Delta t' - \Delta t = \frac{2}{c}\left(\frac{l_1 + l_2}{1 - v^2/c^2} - \frac{l_1 + l_2}{\sqrt{1 - v^2/c^2}}\right) = \frac{2}{c}(l_1 + l_2)\left(\frac{1}{1 - v^2/c^2} - \frac{1}{\sqrt{1 - v^2/c^2}}\right)$$

- Since v (the Earth's speed) is 10^{-4} of c, we can do binomial expansion of the above

$$\Delta t' - \Delta t = \frac{2}{c}(l_1 + l_2)\left[\left(1 + \frac{v^2}{c^2} + \cdots\right) - \left(1 + \frac{v^2}{2c^2} + \cdots\right)\right] \approx \frac{v^2}{c^3}(l_1 + l_2)$$

The Results

- Using the Earth's orbital speed as:

$$V = 3 \times 10^4 \text{ m/s}$$

together with

$$\ell_1 \approx \ell_2 = 1.2 \text{ m}$$

So that the time difference becomes

$$\Delta t' - \Delta t \approx v^2(\ell_1 + \ell_2)/c^3 = 8 \times 10^{-17} \text{ s}$$

- Although a very small number, it was within the experimental range of measurement for light waves.
- Later with Morley, they increased the path lengths to 11m and improved precision better than a factor of 10
- Yet, Michelson FAILED to "see" the expected interference pattern

Conclusions of Michelson Experiment

- Michelson noted that he should be able to detect a phase shift of light due to the time difference between path lengths but found none.
- He thus concluded that the hypothesis of the stationary ether must be incorrect.
- After several repeats and refinements with assistance from Edward Morley (1893-1923), again *a null result.*
- ***Thus, ether does not seem to exist!***
- Many explanations ensued afterward but none worked out!
- This experiment shattered the popular belief of light being waves

The Lorentz-FitzGerald Contraction

- Another hypothesis proposed independently by both H. A. Lorentz and G. F. FitzGerald suggested that the length ℓ_1, in the direction of the motion was *contracted* by a factor of

$$\sqrt{1-v^2/c^2}$$

- Thus making the path lengths equal to account for the zero phase shift.
  - This, however, was an ad hoc assumption that could not be experimentally tested.

Einstein's Postulates

- Fundamental assumption: Maxwell's equations must be valid in all inertial frames
- **The principle of relativity**: The laws of physics are the same in all inertial systems. There is no way to detect absolute motion, and no preferred inertial system exists
  - Published a paper in 1905 at the age 26
  - Believed the principle of relativity to be fundamental
- **The constancy of the speed of light**: Observers in all inertial systems measure the same value for the speed of light in a vacuum.

The Lorentz Transformations

General linear transformation relationship between P=(x, y, z, t) in frame S and P'=(x',y',z',t') in frame S' ➔ these assume measurements are made in S frame and transferred to S' frame

- preserve the constancy of the speed of light between inertial observers
- account for the problem of simultaneity between these observers

$$x' = \frac{x - vt}{\sqrt{1 - v^2/c^2}} \quad y' = y \quad z' = z \quad t' = \frac{t - \left(vx/c^2\right)}{\sqrt{1 - v^2/c^2}}$$

- With the definitions $\beta \equiv v/c$ and $\gamma \equiv 1\Big/\sqrt{1-\beta^2}$

$$x' = \gamma\left(x - \beta ct\right) \quad y' = y \quad z' = z \quad t' = \gamma\left(t - \beta x/c\right)$$

Properties of the Relativistic Factor γ

What is the property of the relativistic factor, γ?

Is it bigger or smaller than 1?

Recall Einstein's postulate, $\beta = v/c < 1$ for all observers

- $\gamma = 1$ only when $v = 0$

$$\gamma = 1\Big/\sqrt{1-\beta^2} \geq 1$$