EE300 - Fundamentos da Física Moderna

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Livro texto

MODERN PHYSICS

Third edition

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Física Moderna

Introdução Histórica:

- Final do Século XIX:
- Dinâmica de Newton;
- Teorias da Eletricidade/Magnetismo Unificadas:

LEIS DE MAXWELL + COMPROVAÇÃO POR HERTZ;

LORENTZ DESCOBRIU → TRANSFORMADA DE LORENTZ

"LEIS DE MAXWELL PODEM SER EMPREGADAS PARA QUALQUER SISTEMA INERCIAL"

- Termodinâmica e Teoria Cinética

↓

Explicam grande variedade de fenômenos

↓

BASE DA REVOLUÇÃO INDUSTRIAL

Física Moderna

Introdução Histórica:

ALGUNS RESULTADOS NÃO EXPLICADOS:

- Experimentos para estudar o meio por onde se transmitem ondas Eletromagnéticas (E.M.) → NECESSITAM DE NOVAS TEORIAS.

NOVAS TEORIAS:

1. RELATIVIDADE RESTRITA: EINSTEIN

Tempo, distância e massa são relativos;

Velocidade da luz é constante;

2. MECÂNICA QUÂNTICA: Planck, Bohr, De Broglie, Heisenberg, Schrodinger, J.J. Thomson, Millikan, Rutherford....

Posteriormente: Física Atômica, Física Nuclear e de Estado Sólido

BASE DA REVOLUÇÃO DA SOCIEDADE DE INFORMAÇÕES

Física Moderna

- RELATIVIDADE;
- TEORIA CINÉTICA DA MATÉRIA;
- QUÂNTICA;
- PROPRIEDADES DOS ÁTOMOS;
- NÚCLEOS DOS ÁTOMOS E SUAS PARTÍCULAS;
- MOLÉCULAS;
- SÓLIDOS;
- ORIGEM E EVOLUÇÃO DO UNIVERSO.

BASE DA NANOTECNOLOGIA:

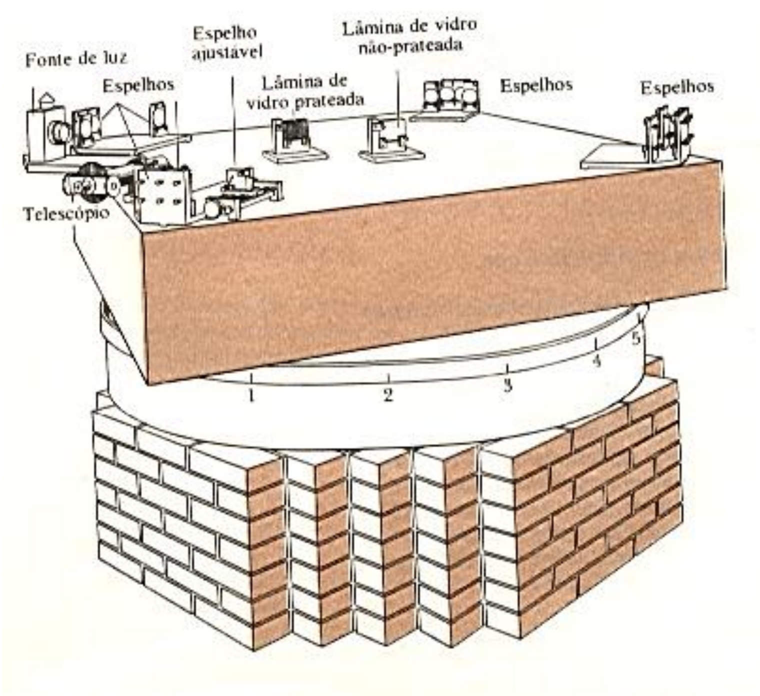
nm = 10^{-9} m →λ→ medido em nm;
Luz vísivel →λ→ 400 − 700 nm;
Átomo →≈ 0.1 nm

Galileo

Referenciais inerciais

Luz acesa na sala vista de São Paulo

INTERFERÔMETRO DE MICHELSON e MORLEY

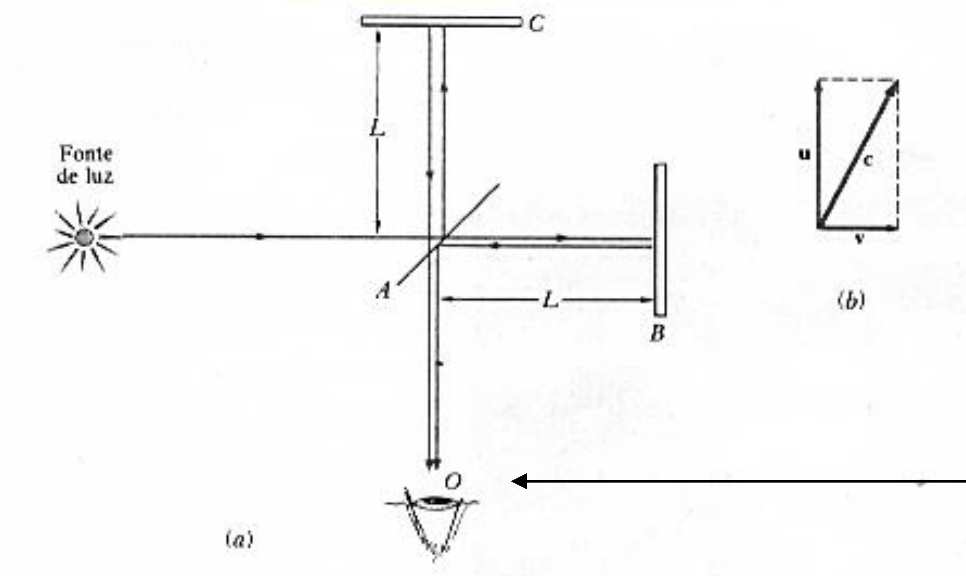


Usado para medir a velocidade do éter v, onde:

c é a velocidade da luz no éter

e

u é a velocidade da luz em relação ao interferômetro



Franjas de interferências construtivas e destrutivas no anteparo O

Postulados de Einstein:

1. O PRINCÍPIO DA RELATIVIDADE: As leis da física são idênticas em todos sistemas inerciais;
2. A CONSTÂNCIA DA VELOCIDADE DA LUZ: A velocidade da luz tem o mesmo valor c em todos os sistemas inerciais.

Do postulado 1 tem-se que: não é possível determinar o sistema de referência universal.

Do postulado 2 tem-se que: o resultado do experimento de Michelson e Morley está correto.

Consequências dos postulados:

Dilatação do tempo:

$$\Delta t' = \frac{\Delta t}{\sqrt{1-\frac{v^2}{c^2}}}$$

Contração do espaço:

$$L' = L\sqrt{1-\frac{v^2}{c^2}}$$

DILATAÇÃO DO TEMPO

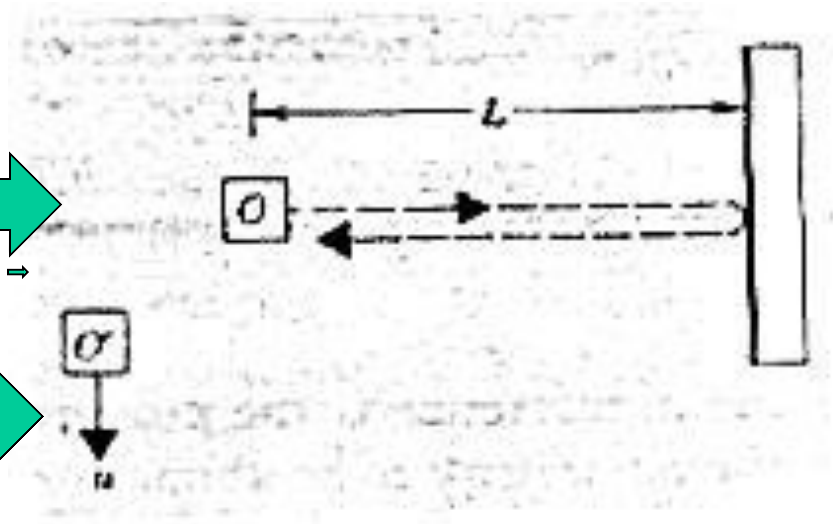
Tempo de ida e de volta do feixe para percorrer a distância L é $2\Delta t$, pois $L = c\Delta t$.

Observador O:

Envia e recebe luz que é refletida pelo espelho

Observador O´:

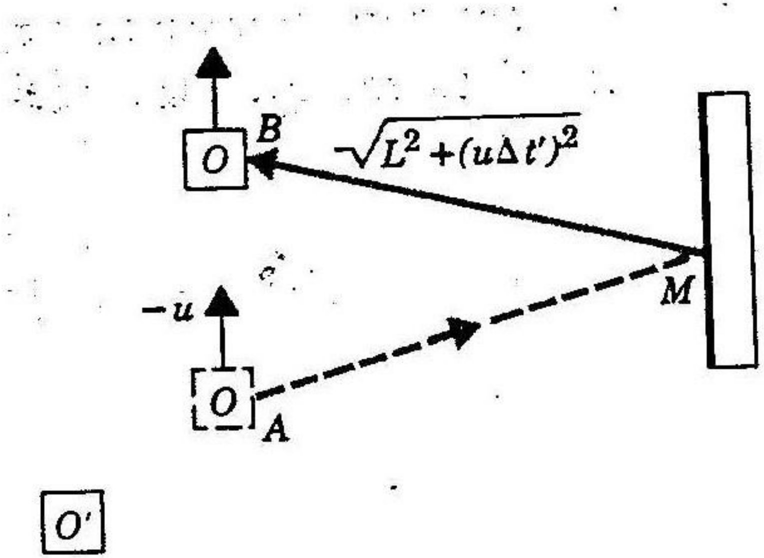
Está em movimento com velocidade u



DILATAÇÃO DO TEMPO

Observador O´:

Vê o feixe de luz como mostrado ao lado



- Para **O´→ O** se move com velocidade –u e a luz é emitida num ponto A e recebida num ponto B após 2Δt´

- A distância AB = 2uΔt´

- A distância AMB $= 2\sqrt{L^2 + (u\Delta t')^2}$

  é percorrida pela luz em 2Δt´

DILATAÇÃO DO TEMPO

•Por Galileu →**Δt=Δt´**

Observador O: mede **velocidade = c**

Observador O´: mede **velocidade** $= \sqrt{c^2 + u^2}$

•Por Einstein →Δt≠Δt´ e ambos observadores medem velocidade = c

Para **O** $\rightarrow c = \frac{2L}{2\Delta t}$

Para O´ $\rightarrow c = \frac{2\sqrt{L^2+(u\Delta t')^2}}{2\Delta t'}$

$$\Delta t' = \frac{\Delta t}{\sqrt{1-\frac{v^2}{c^2}}}$$

EFEITO DA DILATAÇÃO DO TEMPO *

Considere um evento de duração Δt e observador O fixo com relação a este evento, que mede o intervalo Δt:

DENOMINADO TEMPO PRÓPRIO

O observador O´ movendo com velocidade u em relação à O, mede $\Delta t' > \Delta t$ para o mesmo evento, independente da direção da velocidade $\vec{u}$

CONTRAÇÃO DO COMPRIMENTO:

Considere o caso a seguir:

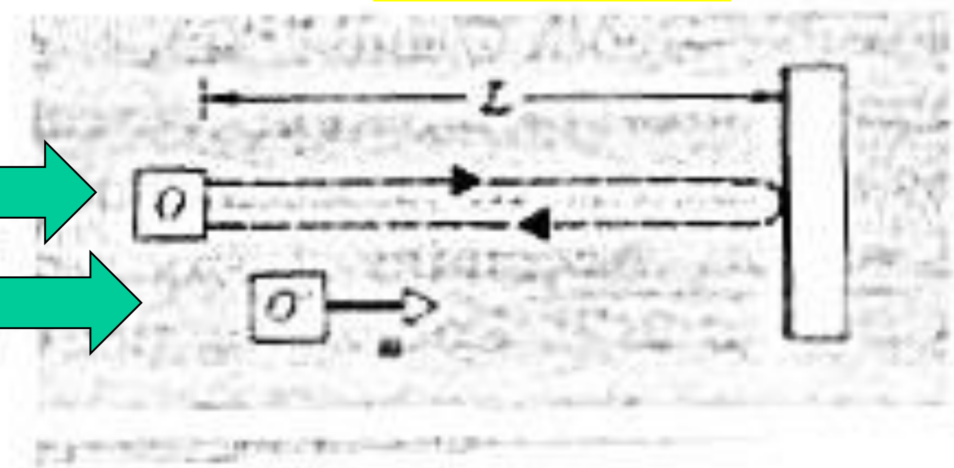
Observador O:

Envia e recebe luz que é refletida pelo espelho

Observador O´:

Está em movimento com velocidade u

Visto por O:



CONTRAÇÃO DO COMPRIMENTO:

Para observador O´ a distância de O até o espelho é L´

Em $\Delta t_1{}'$ o feixe alcança o espelho

↓

que se deslocou de $u\Delta t_1{}'$

↓

$$c\Delta t_1{}' = L' - u\Delta t_1{}'$$

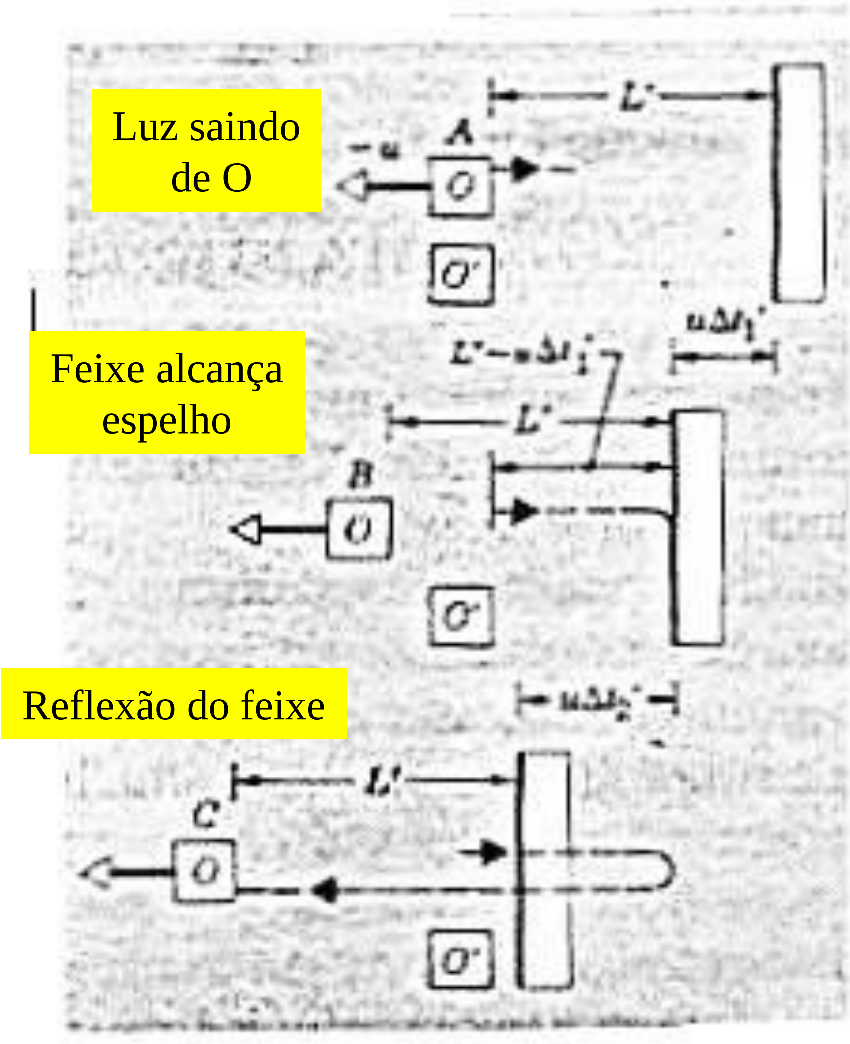
Na reflexão do feixe

O observador O se deslocou de $u\Delta t_2{}'$

↓

$$c\Delta t_2{}' = L' + u\Delta t_2{}'$$

Visto por O´:



CONTRAÇÃO DO COMPRIMENTO:

Seja $\Delta t' = \Delta t_1' + \Delta t_2' \rightarrow$ tempo total de ida e de volta

$$\Delta t' = \frac{L'}{c+u} + \frac{L'}{c-u} = L' \frac{2c}{c^2-u^2}$$

Tem-se para o observador O: $\Delta t = \frac{2L}{c}$

Tem-se para o observador O´ $\rightarrow$ $\Delta t' = \frac{\Delta t}{\sqrt{1-\frac{v^2}{c^2}}}$ EFEITO DA DILATAÇÃO DO TEMPO

$$\Delta t' = \frac{\Delta t}{\sqrt{1-\frac{u^2}{c^2}}} = \frac{2L/c}{\sqrt{1-\frac{u^2}{c^2}}} = L' \frac{2c}{c^2-u^2} = \frac{L'}{c} \frac{2}{(1-\frac{u^2}{c^2})}$$

$$\frac{2L/c}{\sqrt{1-\frac{u^2}{c^2}}} = \frac{2L'/c}{(1-\frac{u^2}{c^2})} \rightarrow L' = L\sqrt{1-\frac{u^2}{c^2}}$$

EFEITO DA CONTRAÇÃO DO COMPRIMENTO

L´observado por O´ é menor que L observado por O

CONTRAÇÃO DO COMPRIMENTO:

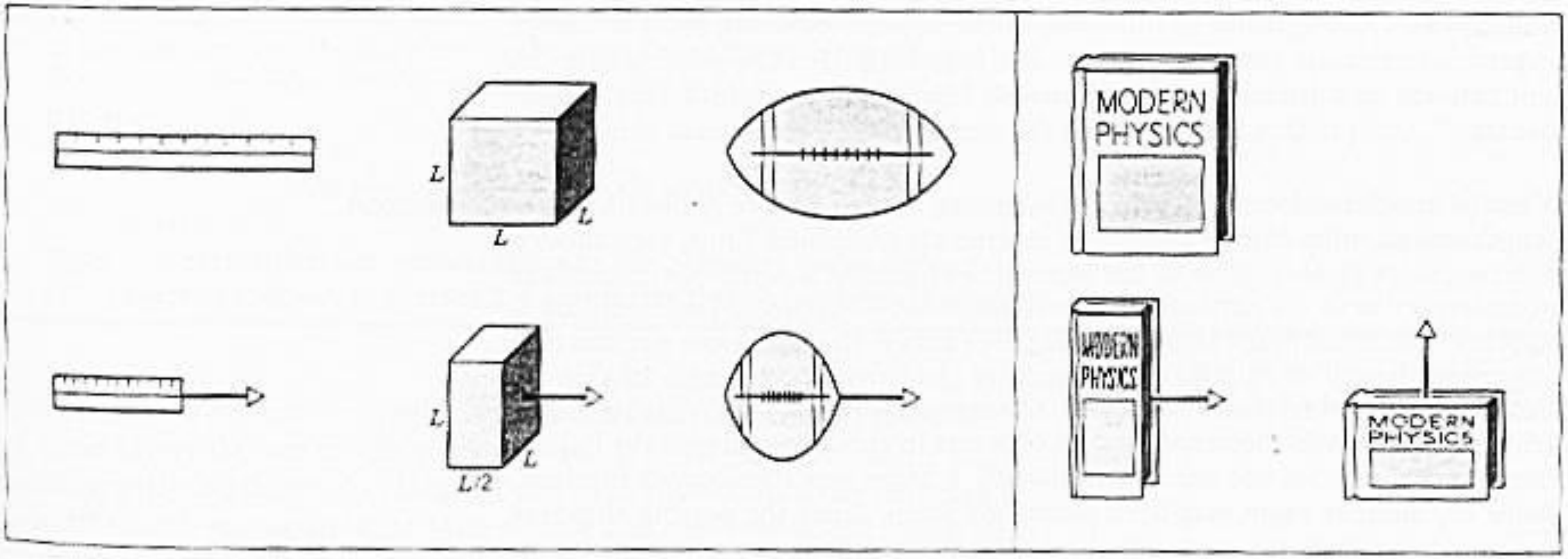


FIGURE 2.7 Some length-contracted objects. Notice that the shortening occurs only in the direction of motion.

$$\frac{2L/c}{\sqrt{1-\frac{u^2}{c^2}}} = \frac{2L'/c}{(1-\frac{u^2}{c^2})} \rightarrow L' = L\sqrt{1-\frac{u^2}{c^2}}$$

EFEITO DA CONTRAÇÃO DO COMPRIMENTO

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MODERN PHYSICS

Foundations of Modern Physics
Part I

The Speed of Light

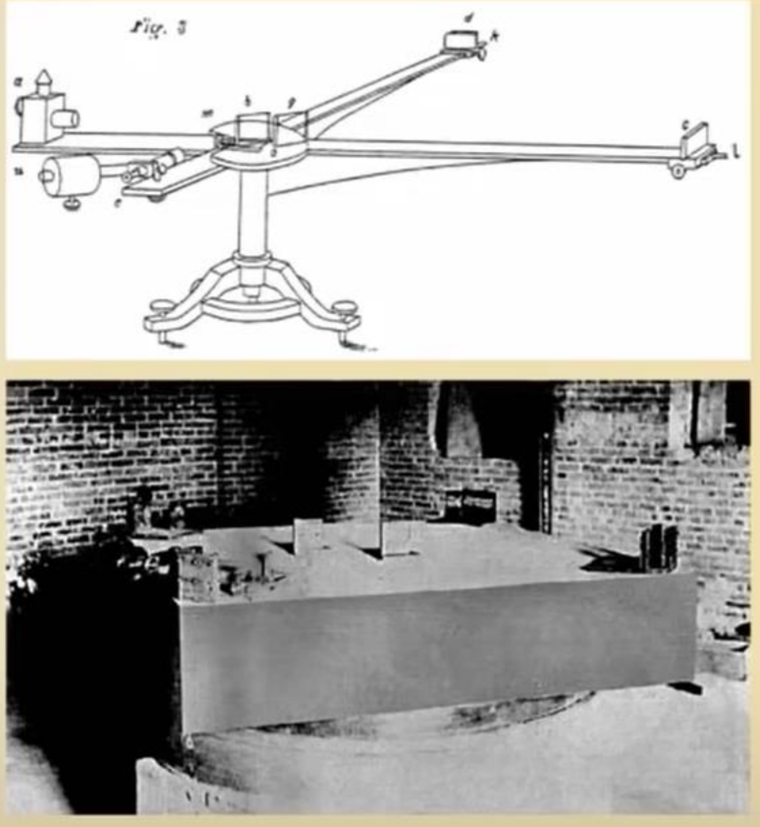
Let's be clear about the speed of light: it is the number of meters light can travel, once emitted by a source, in a certain amount of time.

- Galileo Galilei famously attempted to measure this by uncovering a lantern, having an assistant on a distant hill who uncovers their lantern upon seeing his, and upon seeing the assistant's lantern light he records the time for the round trip, taking into account human reaction time. Light moves too fast for this to work with 17th-century technology.
- Ole Roemer would use the period of Jupiter's moon, Io (discovered by Galileo using the telescope), and its cycle of eclipses by Jupiter, to make the first reasonable determination that light travels in finite time (ca 1676); it doesn't travel instantaneously from place to place.
- By the time of Einstein's publications, the speed of light had been established by multiple experimental methods to be within 50km/s of the precision of today's methods. That is remarkable for such a large number, representing such a large speed.

Modern Speed of Light

The speed of light, based on modern definitions of the meter and the second, is defined to be exactly $299,792,458 \mathrm{m/s}$. Light travels roughly one foot in one billionth of a second (1ft/ns).

The Lessons of the Michelson-Morley Experiment



The Michelson Interferometer (1881, top) and the definitive Michelson-Morley Experiment (1887, bottom)

- Light travels at a fixed and constant speed in any medium, regardless of the relative velocity of the light-source and the light-observer $\longrightarrow$ this is unlike any other phenomenon described in mechanics, and implies that Newton's Mechanics is incomplete.
- No medium is required for light to propagate; unlike a mechanical oscillatory phenomenon (wave), to exist light requires no medium to be distorted $\longrightarrow$ this implies Maxwell's Equations are complete.
- These lessons would not be absorbed fully until 1905, when Albert Einstein published the definitive papers explaining how to reconcile mechanics, electricity and magnetism, and the Michelson-Morley experiment

Albert Einstein and the “Miracle Year”

- It would be Albert Einstein in 1905, laboring on the side during regular work in the Swiss Patent Office in Bern (because he was unable to secure a faculty job after completing his PhD *), to change the thinking about the supremacy of assumptions in Newton’s Mechanics vs. Electromagnetism (Maxwell’s Equations).
- That year he published work resulting from his PhD research in a series of 4 papers - his “miracle year” - and in doing so reframed assumptions about space, time, and what is invariant to all observers in all frames of reference.

Albert Einstein, 1904
(1879—1955)

* In part because Einstein could get no recommendations from his professors because he had so irritated them with his behavior in graduate school, including skipping classes and challenging his professors.

Albert Einstein and the "Postulates of Relativity"

- In short, he accepted the conclusion of the Michelson-Morley experiments that light has a fixed speed regardless of the motion of the source relative to the observer, which implied there was no aether as well; using a simple "thought experiment," he explained why time is not absolute even in Newton's Mechanics and abandoned it as the "constant" in transformations from frame to frame, choosing instead to preserve the laws of physics and the speed of light.
- The postulates that allowed him to define his mathematics:
  1. **The forms of the laws of physics are the same for all observers, regardless of their state of relative motion ("frame of reference")**
  2. **The speed of light is the same for all observers, regardless of their frame of reference.**

Albert Einstein, 1904

(1879—1955)

The consequences of the posulates of “Special Relativity”

For his 1905 work, Einstein focused on *inertial frames of reference* - those in which there are no net, unbalanced forces (e.g. $\sum \vec{F}_{external} = 0 \to \vec{a} = 0$). Under this *special condition*, an object in motion will appear to all observers in all frames to have constant velocity, even if observers in different frames disagree on the magnitude and direction of the vector. Let’s recall his postulates again:

1. **The forms of the laws of physics are the same for all observers, regardless of their state of relative motion ("frame of reference")**
2. **The speed of light is the same for all observers, regardless of their frame of reference.**

No Absolute States of Motion — All Motion is Relative

1. **The forms of the laws of physics are the same for all observers, regardless of their state of relative motion ("frame of reference")**
2. The speed of light is the same for all observers, regardless of their frame of reference.

The consequences of the first postulate are both straight-forward and surprising:

1. All physical laws (e.g. Newton's Laws or Maxwell's Equations) all have the same observed form in all inertial reference frames. This is "helpful" in that the basic laws of physics are not dependent on your state of motion.
2. But as a consequence of this, *it is impossible to tell from the laws of physics in your frame whether you are in motion or not.*

As a result of this postulate, there is no such thing as an absolute state of rest or motion - all motion is relative.

Light's Speed is a Fundamental Invariant of Nature

1. The forms of the laws of physics are the same for all observers, regardless of their state of relative motion ("frame of reference")
2. **The speed of light is the same for all observers, regardless of their frame of reference.**

The consequences of the second postulate are typically more surprising, and well outside of the comfort zone of typical human experience:

1. All observers agree that light moves at a fixed speed — this is the singular invariant independent of states of relative motion;
2. But as a consequence of this, *the belief that time or space or both are experienced in the same way by observers in different states of motion must be abandoned.*

As a result of this postulate, there is no such thing as an absolute measures of time or space; measurements in one frame of reference need not agree with those in another, but all observers will agree that light signals travel at a fixed speed.

Distances in space and time are not observed to be the same in different reference frames

1. The forms of the laws of physics are the same for all observers, regardless of their state of relative motion ("frame of reference")
2. **The speed of light is the same for all observers, regardless of their frame of reference.**

Since time and space displacements are not experienced the same in frames with different relative states of motion…

1. Observers at rest will observe the physical dimensions of objects in motion, relative to them, to be *contracted along the direction of their motion* $\rightarrow$ **length contraction**
2. Observers in motion relative to other observers will experience a slower passage of time $\rightarrow$ **time dilation**

These will be easier to appreciate as we explore the postulates of relativity in class and in the next section of the course on the *Lorentz Transformation*, the correct way to relate observations between frames of reference.

Hendrik Lorentz and “Compression of Bodies in the Aether”

- The mathematics that would later become the replacement for the Galilean Relativity equations would be laid down for a different purpose by Hendrik Lorentz.
- In considering the effects of the aether on bodies in motion through it[1, 2], bodies held together by chemical bonds (which are just electromagnetism in action), he arrived at a few hypotheses:
  - Mechanical bodies would compress along the direction of motion in the aether, with a precise mathematical description for the process;
  - In transforming observations from the aether frame to other frames of reference, he would conceive of an alteration of time that also had a mathematical description.
- Lorentz conceived of this during a period when the aether was still believed to exist - the results of the Michelson-Morley experiment were not fully digested. The aether’s existence would be disproven in the decades that follows, but the mathematics would still prove useful.

Portrait of Hendrik A. Lorentz by Jan Veth

The Lorentz Transformation

We have finally arrived at a mathematical transformation that obeys all of the postulates of special relativity:

$$\begin{aligned} x &= \gamma(x' + vt') \\ t &= \gamma(\frac{v}{c^2}x' + t') \end{aligned}$$

Observations are made in S' and converted to S

$$\begin{aligned} x' &= \gamma(x - vt) \\ t' &= \gamma(-\frac{v}{c^2}x + t) \end{aligned}$$

Observations are made in S and converted to S'

The multiplicative factor, γ, depends on the relative velocity of the two frames and is a measure of the degree of the "relativistic effects" between the two frames, as we will see. It is given by:

$$\gamma = \left(1 - \frac{v^2}{c^2}\right)^{-\frac{1}{2}} = \frac{1}{\sqrt{1 - v^2/c^2}}$$

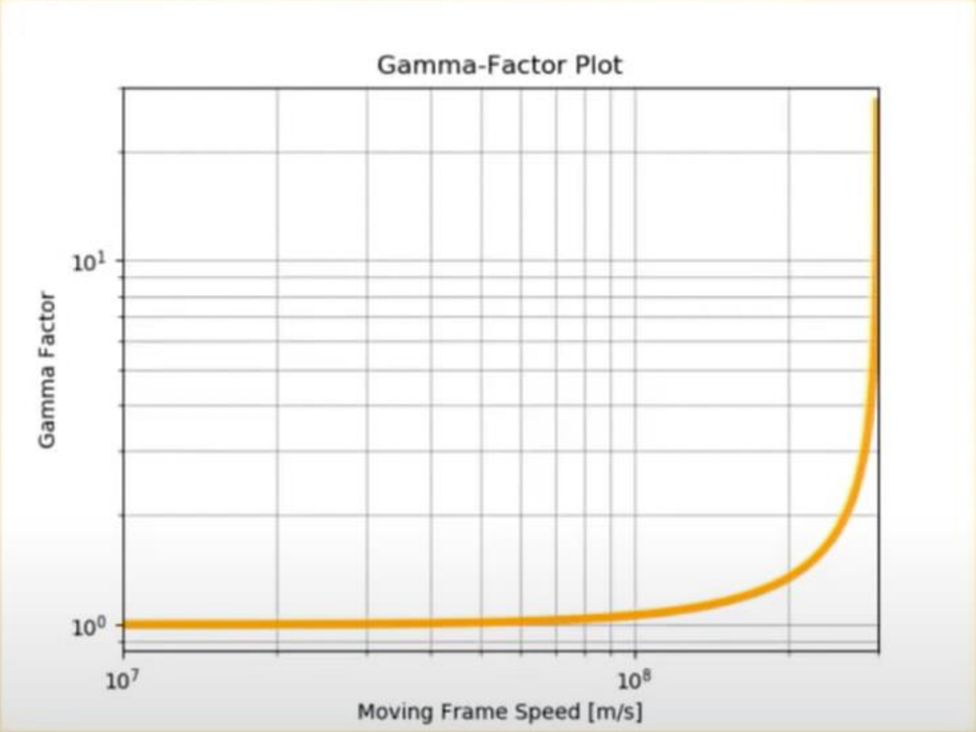
The Gamma Factor - Some Intuition-Building

The "gamma factor," γ, will appear *everywhere* in relativity calculations. It's largely unavoidable for all of the physics calculations you will do going forward. Let's build some intuition about this fascinating quantity.

- What is γ for a frame S' at rest with respect to frame S?
  - We would expect to find that the two frames are the same, since they are then in the same state of motion. Indeed, for $v = 0$ we observe that $\gamma(v = 0) = 1$.
- What is γ for a frame, S', that achieves a velocity of c relative to S?
  - This would be like riding a beam of light, moving at $v = c$. It's another special case, and we see that:

$$\gamma(v = c) = \frac{1}{\sqrt{1 - c^2/c^2}} = \frac{1}{0} = \infty$$

- So γ is a frame-velocity-dependent number whose range is $[1, \infty]$ (inclusive).



Recovering Classical Physics

Are the Galilean/Newton view of space and time and relative motion totally gone? Not really - after all, the Galilean Transformation worked in real computations for centuries before special relativity was needed. A good theory of nature describes all new phenomena while including the old ones that were successful in some more limited regime.

To recover the Galilean/Newtonian view, we need only slow nature down from speeds close to that of light. For example, in the special case that $v \ll c$, let's look at what happens to γ using the *Binomial Expansion*:

$$\gamma \;=\; (1 - v^2/c^2)^{-1/2} \xrightarrow{\alpha^2 = v^2/c^2 \leq 1} = (1-\alpha^2)^{-1/2} \xrightarrow[\text{Expansion}]{\text{Binomial}} \approx 1 + \frac{1}{2}\alpha^2 + \ldots \text{higher order terms of } \mathcal{O}(\alpha^4) \ldots$$

For the case where $\alpha \ll 1$ so that $\alpha \to 0$, we see that $\gamma \approx 1$. That makes sense - it's approaching the limiting case when $v = 0$. So what happens to the Lorentz Transformation Equations?

$$x \;=\; \gamma(x' + vt') = \left(1 + \frac{1}{2}\alpha^2 + \mathcal{O}(\alpha^4)\right)(x' + vt') \xrightarrow{v \ll c} x' + vt'$$

$$t \;=\; \gamma\left(\frac{v}{c^2}x' + t'\right) = \left(1 + \frac{1}{2}\alpha^2 + \mathcal{O}(\alpha^4)\right)\left(\frac{\alpha}{c}x' + t'\right) \xrightarrow{v \ll c} t'$$

We have recovered the Galilean Transformation, and reconciled with classical physics in the limit of low velocities.

Tarefa 2h a 2h17

https://www.youtube.com/watch?v=3lTQqEehEhI

Demonstra a transformada de Lorentz