Lecture One

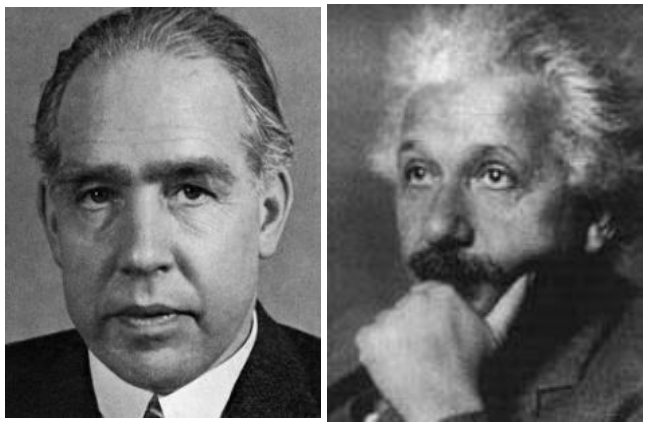
Galilean and Newtonian Relativity

Some Reminders

Strongly encourage you to **re-read** and think about Lecture Zero carefully *… as it sets the tone for this Einstein module.*

The quotes, historical and philosophical accounts/ideas are added for completeness/enjoyment; are important for you to enjoy this Einstein GEM module … some will be tested.

Do note shifts of scientific ideas in each lecture … and discuss with your friends.



General Education Module (GEM)

Einstein's Universe & Quantum Weirdness

An Encouragement for this module !

You do not have to be an artist to appreciate the beauty of the works of Michelangelo.

Why ? … just need to be able to see.

You don't need to be a musician to feel the majesty of a Beethoven symphony.

Why ? … just need to be able to hear.

You do not need to be a trained physicist to appreciate the grandeur of Einstein's theories.

Why ? … just need to be able to think.

Keep an Open mind ! … Ira M. Egdall

Previous lecture shit

Lecture 1
Galilean Relativity
Newtonian Relativity

When told that only 3 persons in the world understood relativity. A. Eddington asked “I wonder who is the 3rd ?”

Pot Pourri of Ideas & Terminologies

Turn of last century … ~ 1900

Recap Newton's 3 Laws

3rd Law (Force Pair law) : For every action there is a reaction.

2nd Law (Force Law) : Force is proportional to acceleration

1st Law (What is this ?) :

A body remains at rest, or moves in a straight line at a constant speed, unless acted upon by a net outside force.

3rd Law application : Rifle & Bullet

Let F represent both the action & reaction force as they are equal.

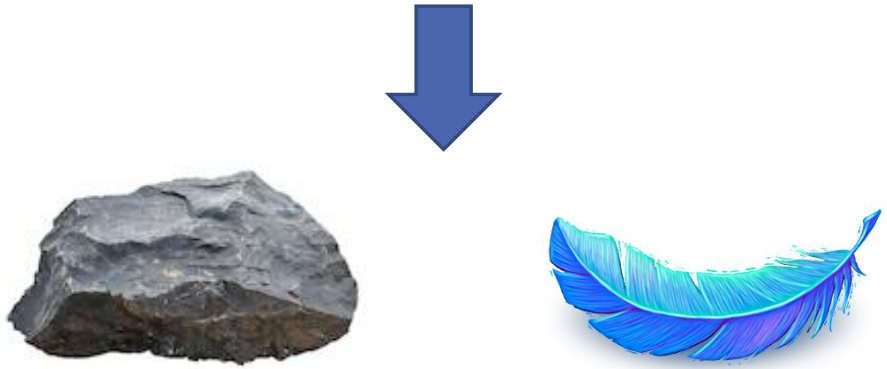
$$\frac{F}{M} = a$$

$$\frac{F}{m} = A$$

The acceleration of the recoiling rifle is small a.

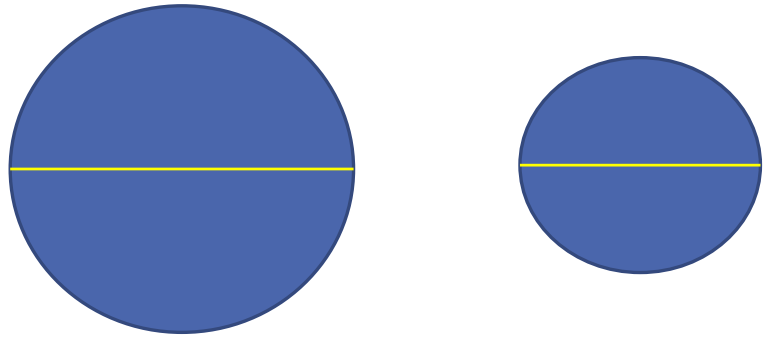
The acceleration of the bullet is *big* A.

2nd Law application : Which will reach the ground first, the stone or the feather ?



$$\frac{F}{M} = a \qquad \frac{f}{m} = a$$

An Analogy



$$\frac{C}{D} = \pi \qquad \frac{c}{d} = \pi$$

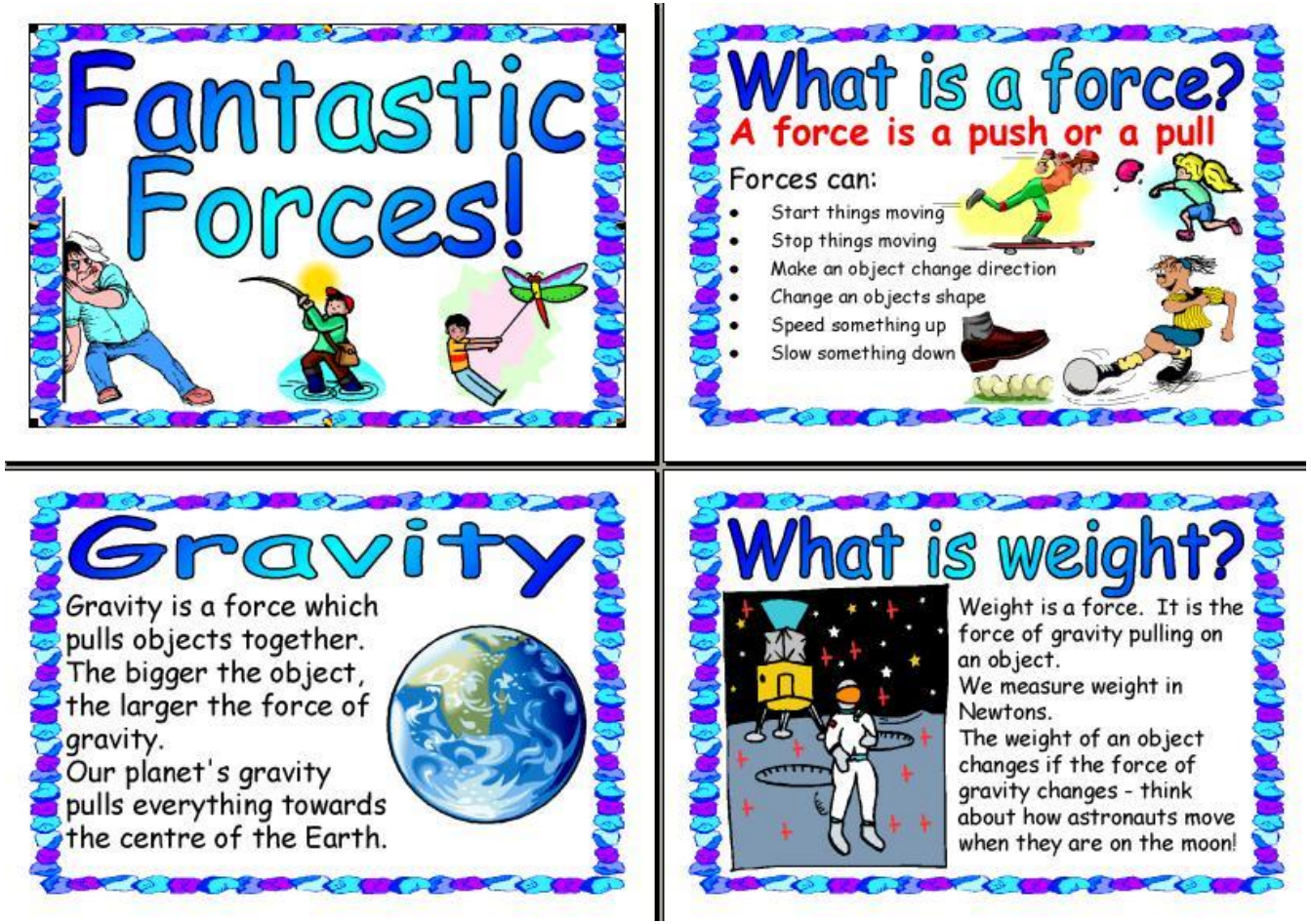
a is the acceleration due to gravity, sometime called g.

Review of familiar Forces

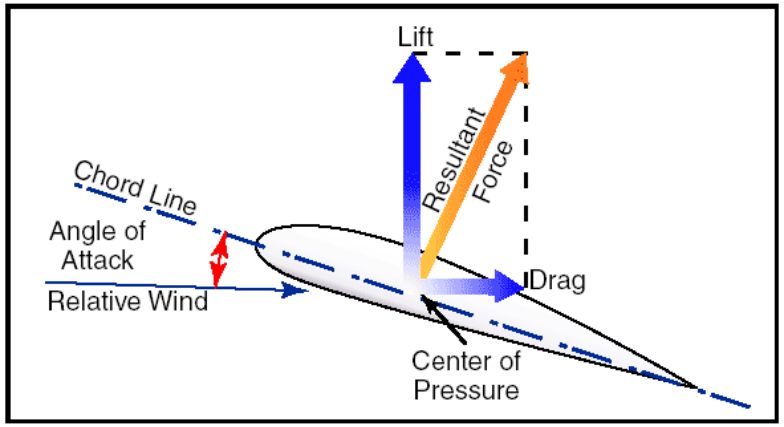
What is force ?
Attractive
or Repulsive

Can we calculate?

Yes, because $F \sim a$
i.e. $F = ma$

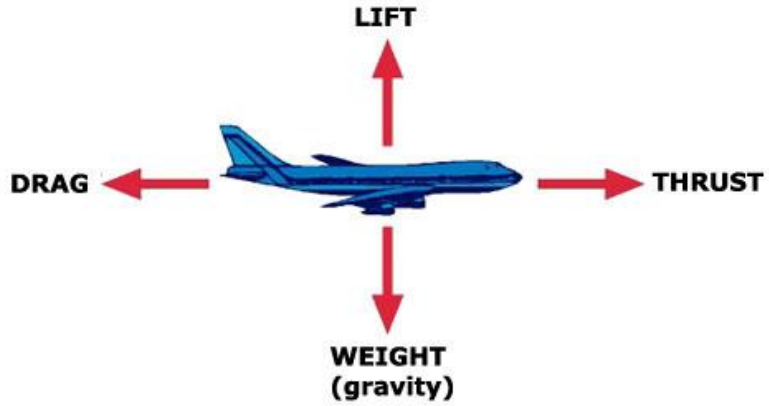


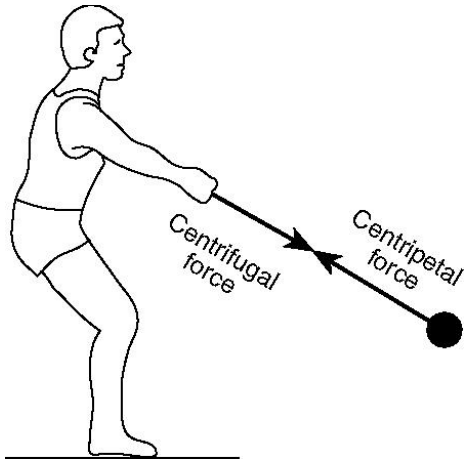
Examples of Forces



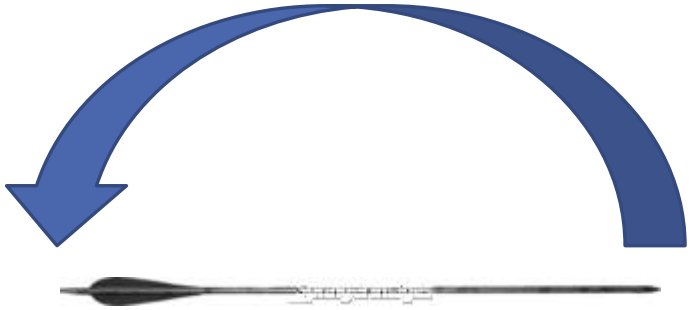
Pressure is average force

$$\text{Pressure} = \frac{force}{Area}$$



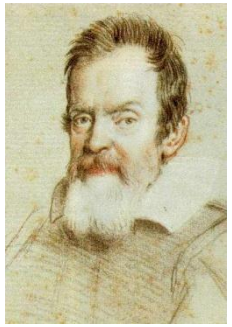


Ancient Greek ideas :
Force is needed for a body to move !



Air rushes behind to propel the arrow !

… but Galileo said no such thing !



Socrates, Plato and Aristotle.

Ancient Ideas … leads to Inertia

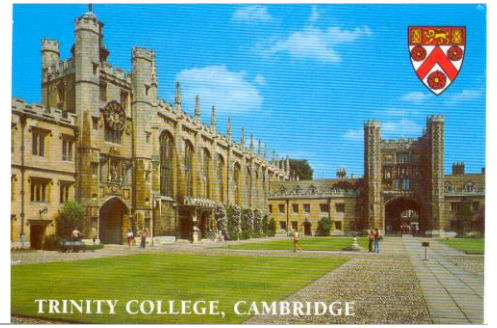
It was believed in ancient times, force is needed to sustain motion

Galileo was the 1st to realize the mistake in this type of reasoning. Force is not needed to sustain motion !

A body on which forces have ceased to act keeps moving with the same speed and in the same direction as it had at the instant when these forces ceased … "reluctance to change" …called simply Inertia. Sometimes called The Law of Inertia … … Inertia property of the body to resist changes in motion.

The word *"Inertia"* comes from Latin *"iners"* (Lazy or inert)

Newtonian Ideas



Newton re-stated the same thing but differently.

A body remains in a state of rest or uniform motion in a straight line unless compelled to change that state by an applied force.

With respect to what does the body remain at rest or in uniform motion ?

Absolute space, in its own nature, without regard to anything external, remains always similar and immovable.

Absolute time, of itself and from its own nature flows equably without regard to anything external.

So Absolute Space and Absolute Time (Separated)

Principle of Relativity

Note 1 (due... Galileo/Newton)

Notice that the law (inertial) treats a state of rest and a state of uniform motion on the same footing.

Newton's laws and all conclusions derived from there would apply equally well to both observers (one at rest & the other in uniform motion)

Formally, the laws of mechanics in a ***frame of reference*** moving rectilinearly & uniformly through absolute space are exactly the same as in another frame which is at rest in absolute space.

Principle of Relativity

Note 2 (Another way of saying)

Consider *O* and *O*' to be observers with *O* at rest (absolute space) and *O*' (called *O* prime) moving with a uniform velocity (again an absolute space)

There is an object in absolute space which is acted on by a force. *O* would describe it by saying $F = ma$ ... and *O*' would say $F' = ma'$

Note:

1) The form of the algebraic expression is the same for both the observers.

2) The mass is the same for both.

Why call Principle ?

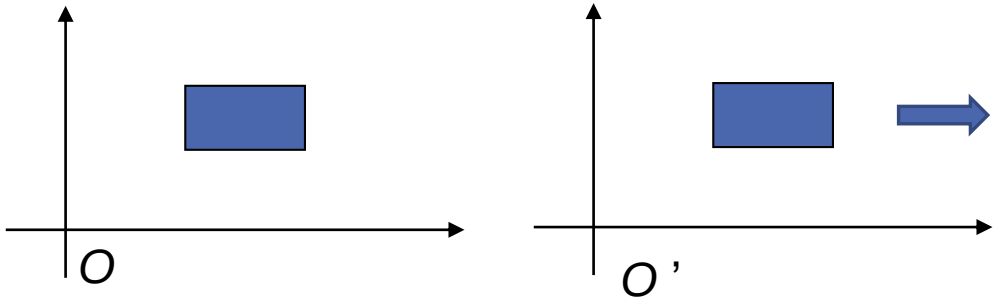
So, rather grand word !

Principles (Scientific) are introduced in order to allow some progress to be made when one has no experimental data to go by.

Cosmologist, Peter Coles
Oxford U Press

Newtonian Relativity

What is a Frame of Reference?



In simple Language, it just mean a suitable set of co-ordinates.

Inertia Frame of Reference

It is a frame that no forces are acting on it (i.e. it is not accelerating … speed is constant)

Therefore, in this frame, Newton’s Laws would hold.

Relative Motion

In reality

Newton realized that in practical problems one is always concerned with relative motion … maintained a dislike for it. … but absolute space is absolutely Sacred for him ! Why ?

Can one really have, in practice, a frame (inertial) on which no forces (not accelerating) whatsoever are acting ?

Not really. Luckily, in many situations the forces acting may either be negligible or produce effects which are hardly observed. e.g. the rotating Earth.

Principle of Relativity

Note 3 (A practical way)

The laws of mechanics remain the same for observers in inertial frames that are in uniform motion with respect to each other.

Note: Relative motion rather than absolute motion is all that can be observed … Newton had only disdain for it … ironically Newtonian mechanics is based on relative motion.

Newtonian Relativity

Recap. by asking Who is moving ?

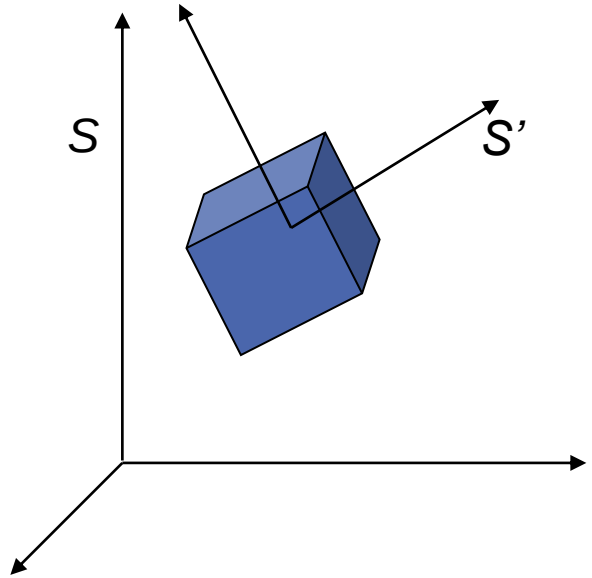
The moral is that when there are 2 systems / inertial frames in uniform relative motion, it is not easy to tell which is at rest and which one is moving.

(Recall the train station experience !)

Newtonian Relativity

Recap

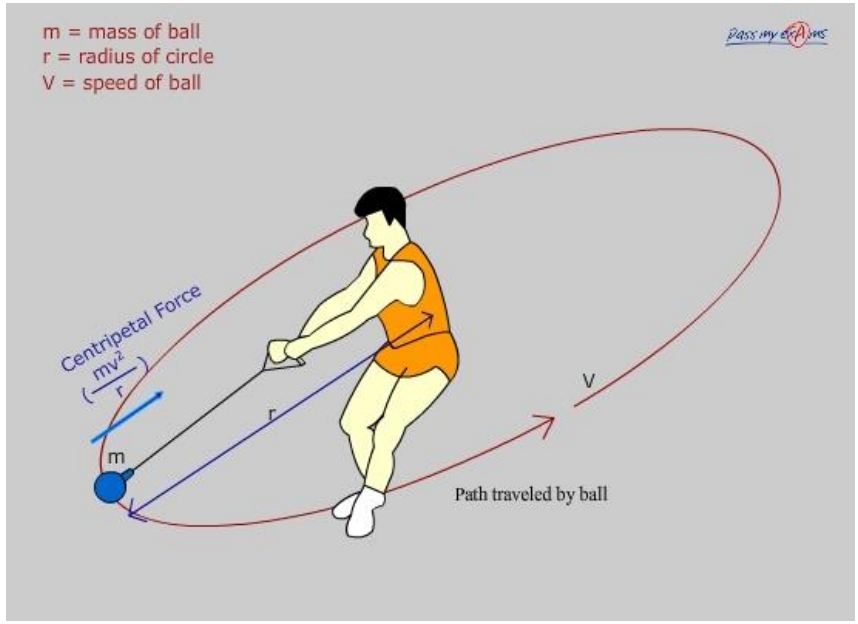
In practice, it is difficult to realize such an inertial frame.

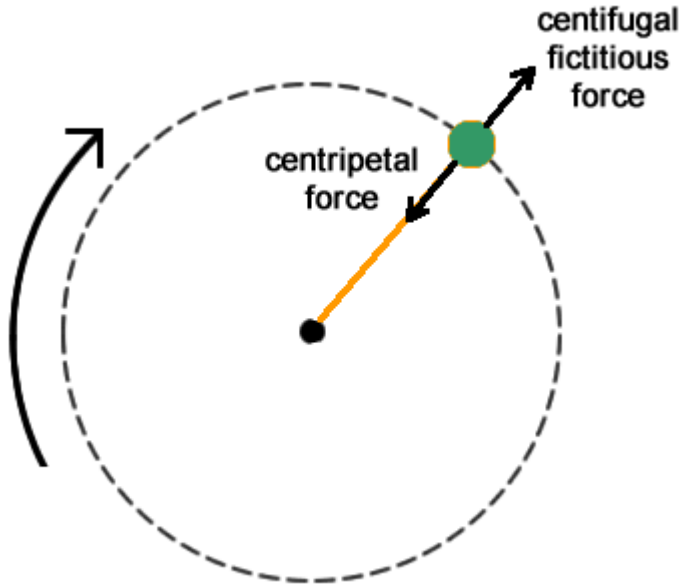


$$F = ma = F_{app} + F_{pseudo}$$

So whenever we treat the Earth as an inertial frame, clearly, it is only an approximation.

Some forces are human constructs ! to make Newton's Law Work !





G. Fowles and G. Cassiday, Analytical Mechanics, Centage Learning (Brooks-Cole Pub), 2005

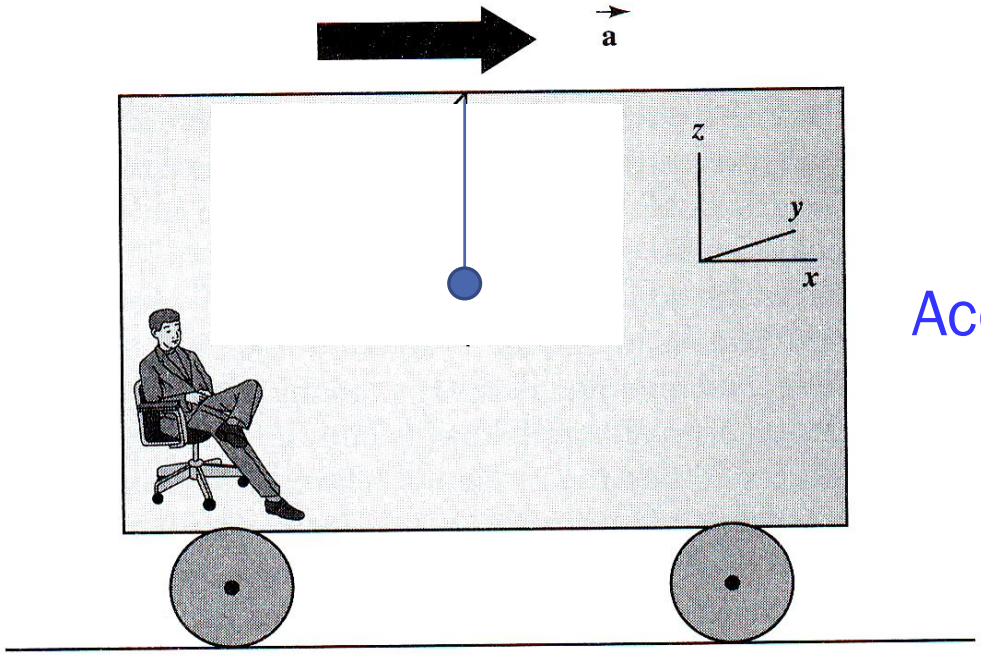
Reading Assignment

Newton's First Law: Inertial Reference Systems

The first law describes a common property of matter, namely, *inertia*. Loosely speaking, inertia is the resistance of all matter to having its motion changed. If a particle is at rest, it resists being moved; that is, a force is required to move it. If the particle is in motion, it resists being brought to rest. Again, a force is required to bring it to rest. It almost seems as though matter has been endowed with an innate abhorrence of acceleration. Be that as it may, for whatever reason, it takes a force to accelerate matter; in the absence of applied forces, matter simply persists in its current velocity state—forever.

A mathematical description of the motion of a particle requires the selection of a *frame of reference*, or a set of coordinates in configuration space that can be used to specify the position, velocity, and acceleration of the particle at any instant of time. A frame of reference in which Newton's first law of motion is valid is called an *inertial frame of reference*. This law rules out accelerated frames of reference as inertial, because an object "really" at rest or moving at constant velocity, seen from an accelerated frame of reference, would appear to be accelerated. Moreover, an object seen to be at rest in such a frame would be seen to be accelerated with respect to the inertial frame. So strong is our belief in the concept of inertia and the validity of Newton's laws of motion that we would be forced to invent "fictitious" forces to account for the apparent lack of acceleration of an object at rest in an accelerated frame of reference.

What will happen to the pendulum ? Discuss a) when the box is in uniform motion and b) in accelerated motion.



Accelerating box car

i.e. how would the person in the box describe the both motions of the pendulum ? which motion has an extra force and why ?

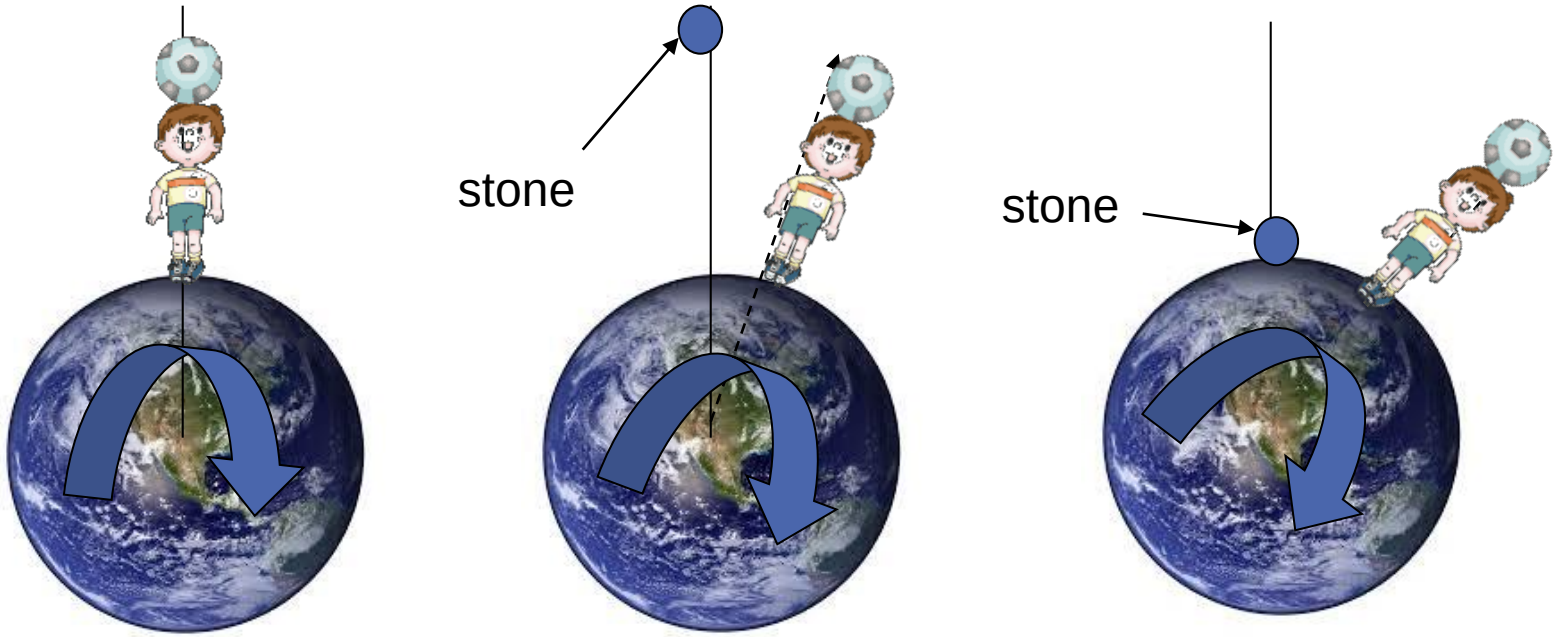
We want to find a relationship

(or transformation) between the rest and moving *"inertial"* frames !

Galilean Transformation

Greek astronomer and geographer

Ptolemy asked: What happens when a stone is thrown up ?



Galileo Galilei

Was at University of Pisa as a medical student.

1585 studied Physics & Mathematics privately.

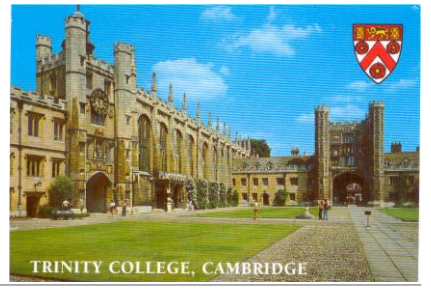
1589 Professor at Pisa, wrote *De motu* (mechanics)
University of Padua; designed compasses

1609 learned lens making from the Dutchman, Hans Lippershey.

1613 "*Letters on Sunspots*" … *earth is not the center*

1632 "*Dialogue concerning the 2 chief world systems* …
Copernican system argument, *Simplicio, Sagredo, Salviati*
Life imprisonment by The Church.
Two New Sciences (kinematics/materials) Died in 1642.

Isaac Newton



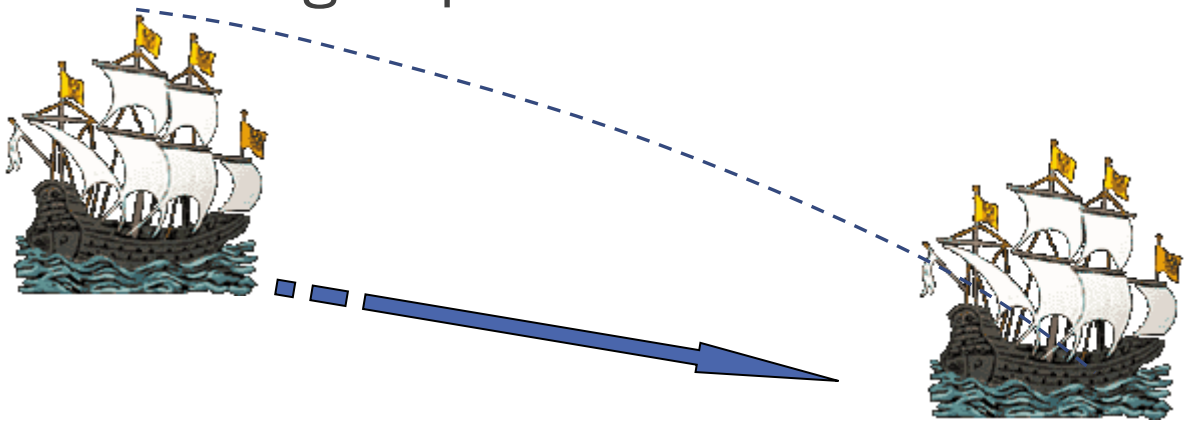
Born on Christmas day, 1642, (from family of farmers)
1665 B. A. Trinity College
Epidemic of plague (18 months)
1667 + 2, Lucasian Professor
1686, *Principia*
President of Royal Society
Member of Parliament
Master of Mint
Flamsteed and Leibnitz quarrels
Robert Hooke $F = -kx$

Galilean Transformation

Galileo thought that this is nonsense !

What happens when a stone is dropped down?

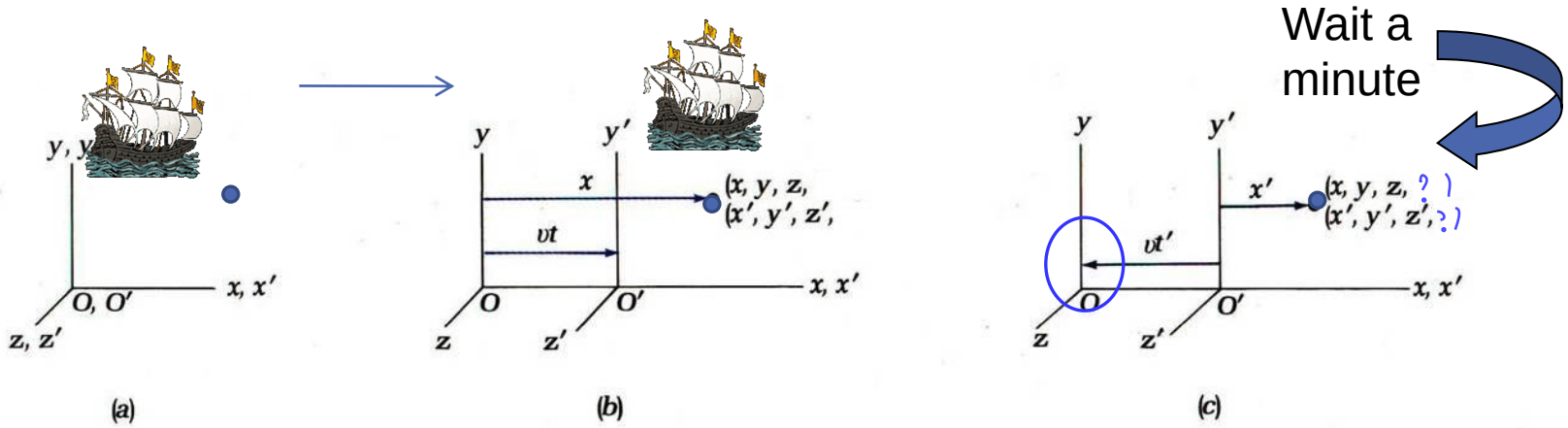
But this time from the mask of a moving ship



He reasoned that the stone would fall at the bottom of the mast different from Ptolemy. And there must be a relationship between the 2 descriptions. He seeks to find these relations … transformations (changes) … “boost”

Galilean Relations

Leaning tower of Pisa



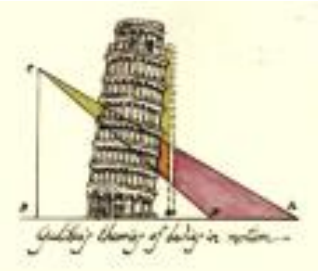
Recall *O'* is the moving frame, initially coincide with *O* frame.

$$Speed = \frac{Dis\tan ce}{Time}$$

$$(x' = x - vt, \quad y' = y, \quad z' = z) \quad and \quad t' = t$$

These rules are simple and follow from common sense. Notice the innocent looking statement ***t' = t.*** It simply means that clocks behave in the same way in the two inertial frames (S and S').

Galilean Relativity



Some Consequences

$\frac{x'}{t} = \frac{x}{t} - \frac{vt}{t}$

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

$u = \frac{x}{t}$ (speed)

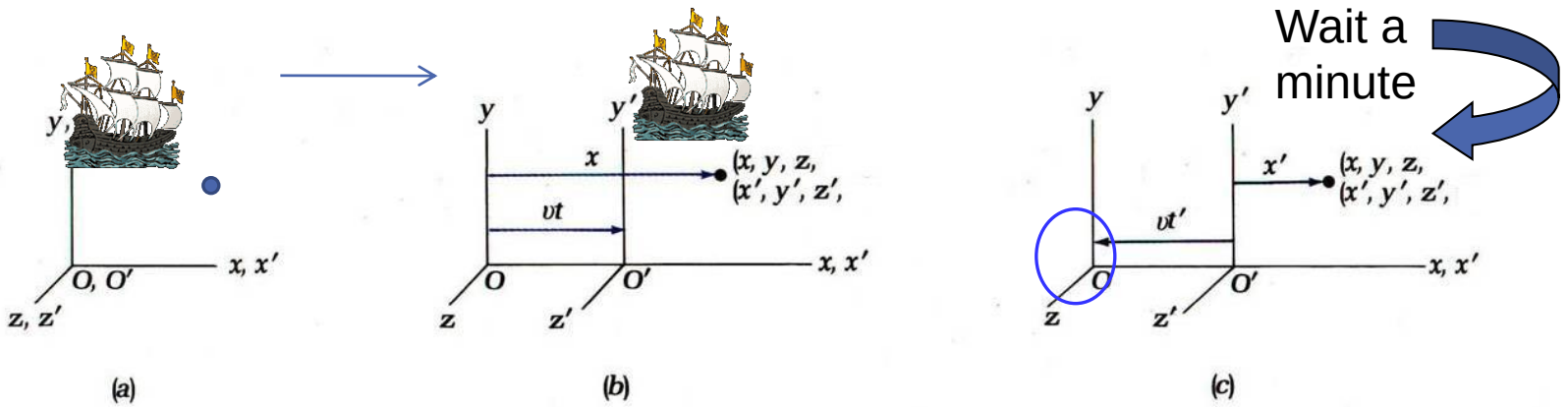
Law of addition of velocities. $u' = u - v$ $\Rightarrow$ $u = u' + v$

This is common experience we all have had before.

Given 2 frames *S* and *S'*, the form of the equations ($F = ma$) of mechanics for observers at *O* and *O'* remain the same.

Can you see why ?

Galilean Transformation (Relations)



Recall *O'* is the moving frame, initially coincide with *O* frame.

$$(x' = x - vt, \quad y' = y, \quad z' = z) \quad and \quad t' - t$$

Differentiating again

$$u' = u - v \qquad Speed = \frac{Distance}{Time}$$

$$a' = a$$

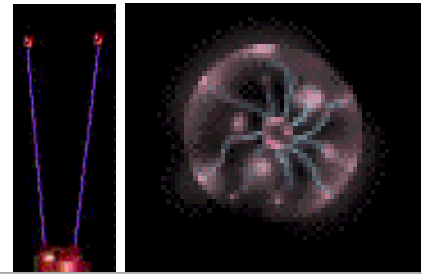
$$\Rightarrow ma' = F' \sim ma = F$$

Conclusion :

Newton's 2nd Law obeys Galilean Relations

but Physics is not all mechanics

Pre-Einstein Relativity



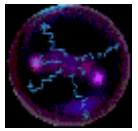
… but Physics is not all Mechanics

Light and Ether ? ? ?

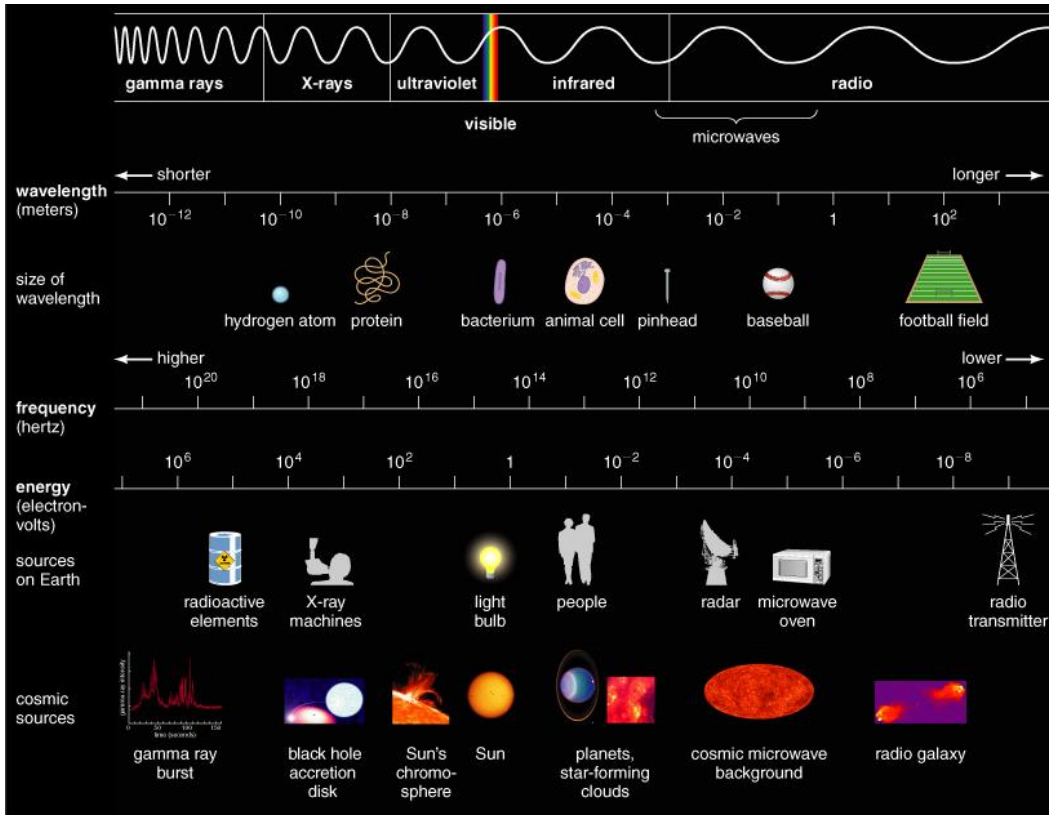
Cavendish, Faraday, Ampere, Heaviside

Maxwell (4 Equations)

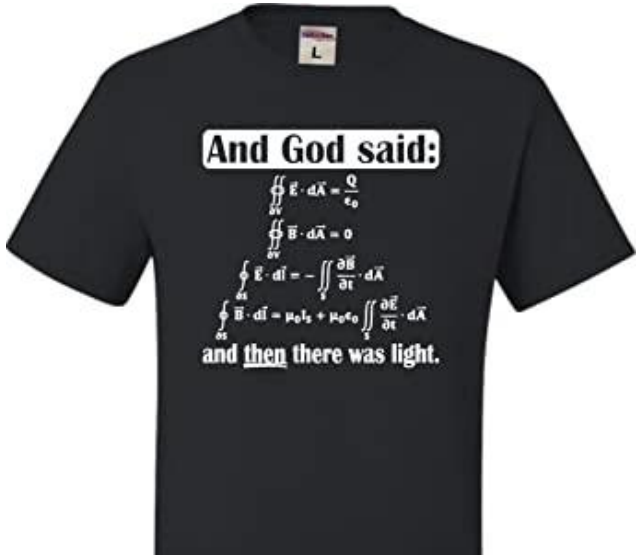
He “discovered” the Laws of electricity & magnetism and connected the equations with Light propagation.

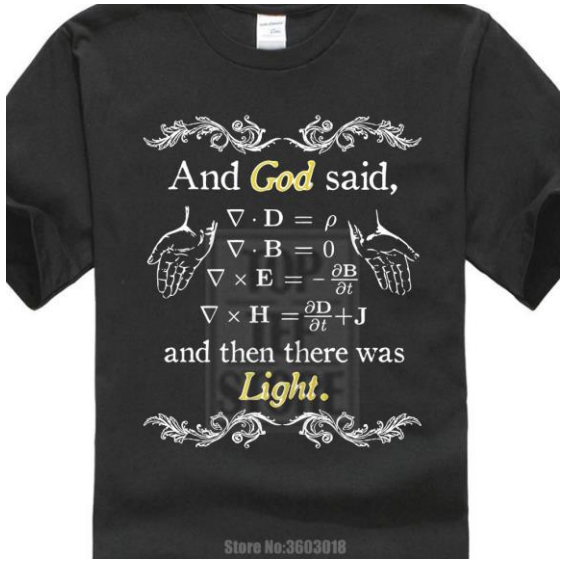


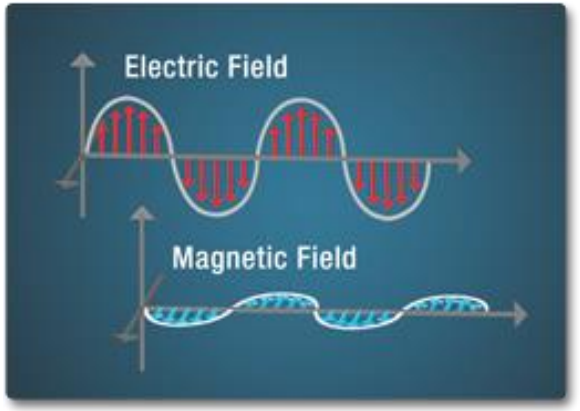
and

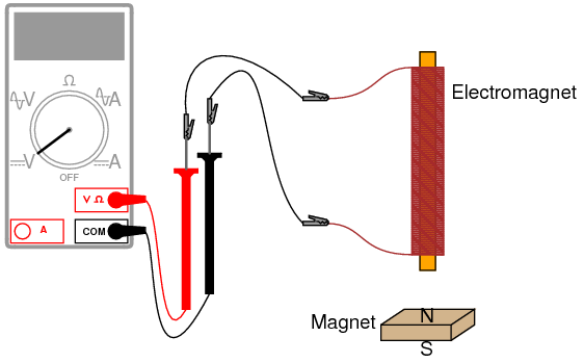


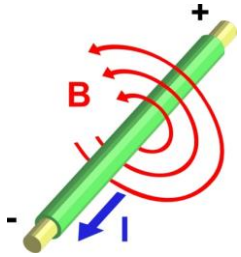
Maxwell's & Wave Equations











Text books

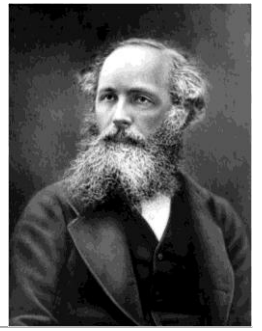
$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

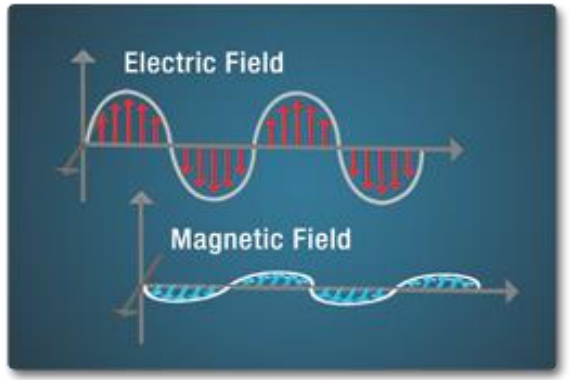
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

Combining Maxwell's equations



$$\nabla^2 \vec{B} = \mu_0 \varepsilon_0 \frac{\partial^2 \vec{B}}{\partial t^2} \qquad \nabla^2 \vec{E} = \mu_0 \varepsilon_0 \frac{\partial^2 \vec{E}}{\partial t^2}$$



Electric permittivity, ε_0 Magnetic permeability, μ_0

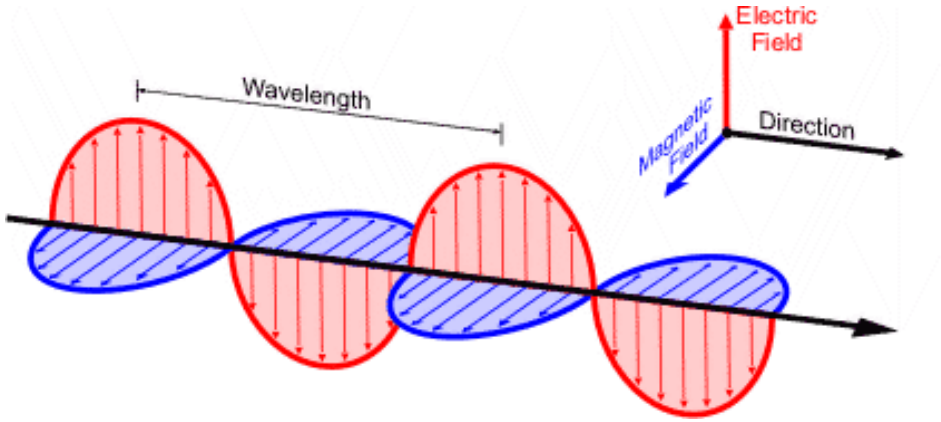
Comparing with mechanical wave equation $\nabla^2 \vec{w} = \frac{1}{v^2} \frac{\partial^2 \vec{w}}{\partial t^2}$

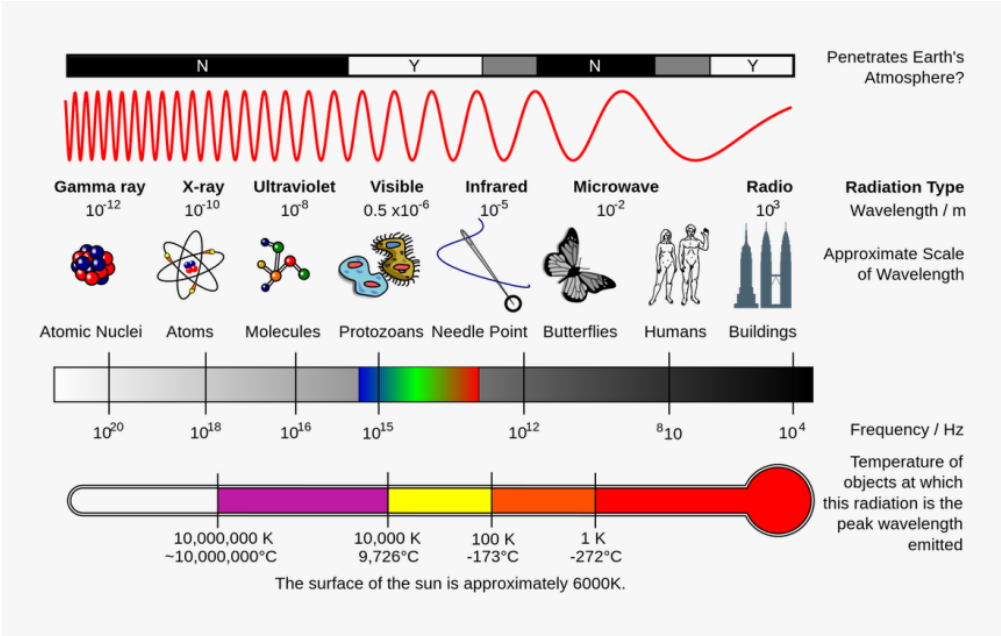
We have the speed of this wave $v = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3 \times 10^8 \, m/s = c$

The Speed of light, c

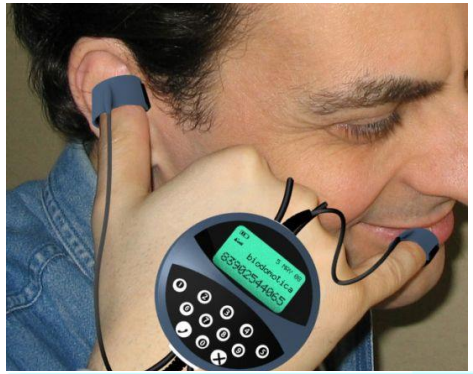
How to see or think about this invincible E& M waves ?

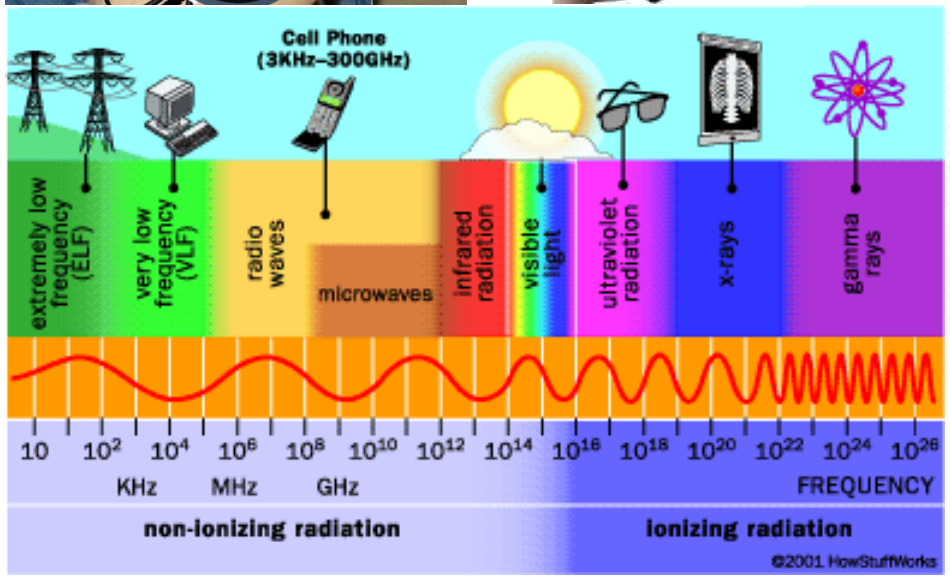
$$\nabla^2 \vec{B} = \mu_0 \varepsilon_0 \frac{\partial^2 \vec{B}}{\partial t^2} \qquad \nabla^2 \vec{E} = \mu_0 \varepsilon_0 \frac{\partial^2 \vec{E}}{\partial t^2}$$

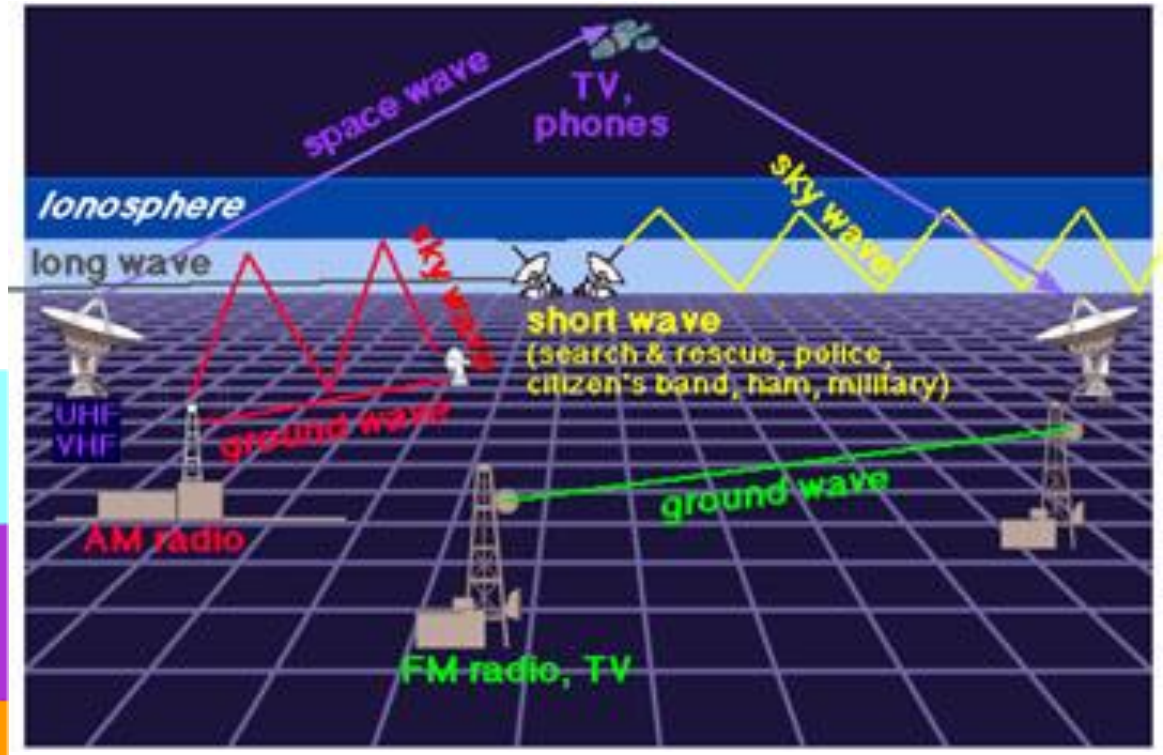




Applications of Electromagnetic Spectrum







Physics is also Electricity & Magnetism

This is a “Light” problem ?

Pre-Einstein's Relativity

Maxwell's Equations and Galilean Transformations.

The Laws of Newtonian mechanics remain the same under the Galilean transformations.

Do the laws of electromagnetism behave similarly?
This is a fair question ? We want to make sure that the laws of electromagnetism are the same for observers in different inertial frames (*Invariance*! or *Covariance*!)

According to Maxwell … Laws of Electro-magnetism are intimately related to light.

Some Terminology for Relativity Theory

Invariance

When **something** (a quantity or a parameter) **does not change**, one says it is invariant.

Covariance

This term is usually applied to **equations**. What it means is that there is **no change in form**.

Recall $F = ma$

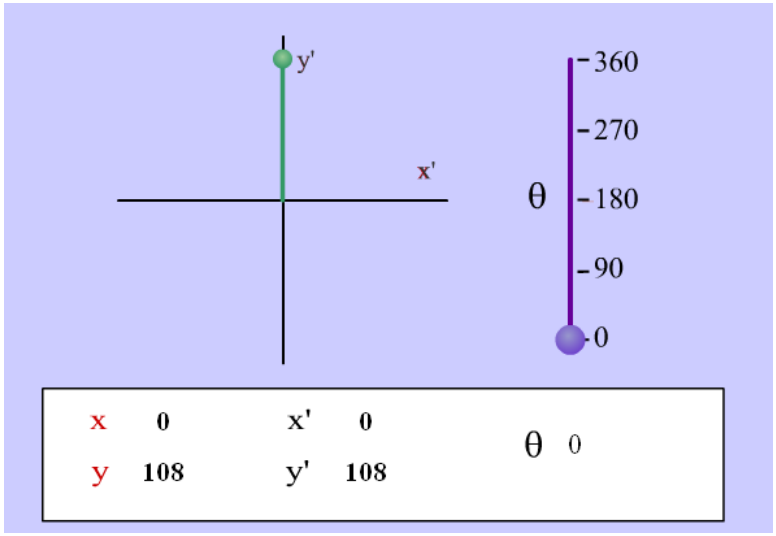
http://en.wikipedia.org/wiki/Electromagnetic_wave_equation

Einsteinian Relativity

Example of Invariance

Show one important example.

Rotate1.swf



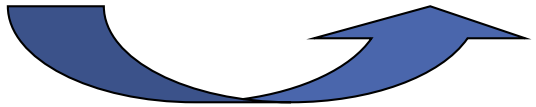
Radius is an invariant quantity

Einstein Relativity

Example of Covariance

Show one example " if "

$$\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} = -\frac{\partial B_x}{\partial t} \qquad \frac{\partial E'_z}{\partial y'} - \frac{\partial E'_y}{\partial z'} = -\frac{\partial B'_x}{\partial t'}$$



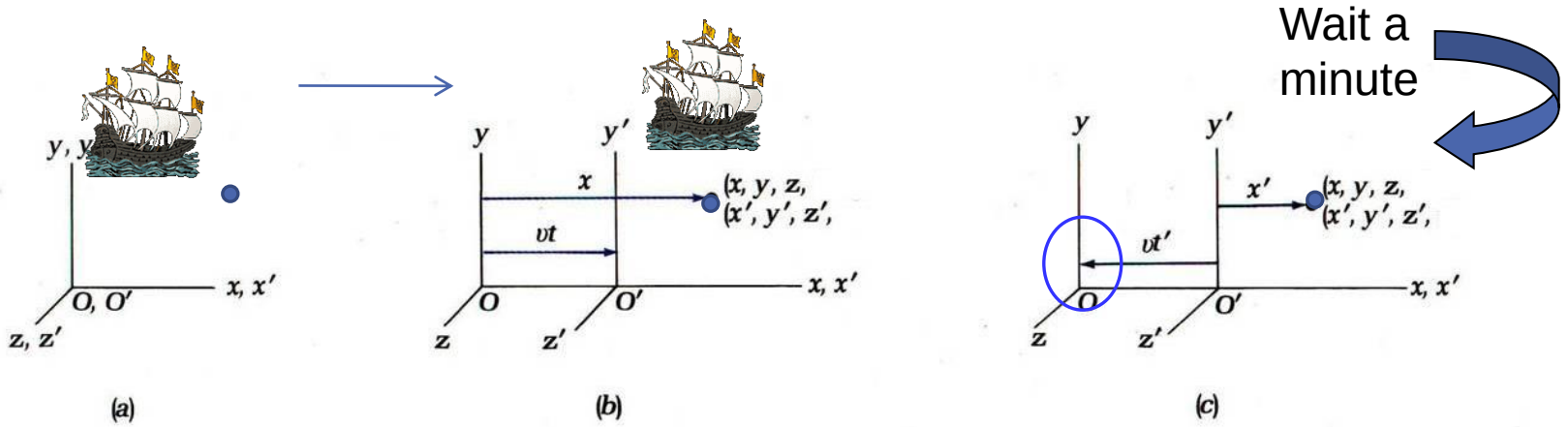
We say this equation above is covariant

Newtonian Relativity

It turns out that the form of Maxwell's equations (E&M Laws) get changed under Galilean transformations. Oops ! So not Covariant !

Galilean Transformation

Leaning tower of Pisa



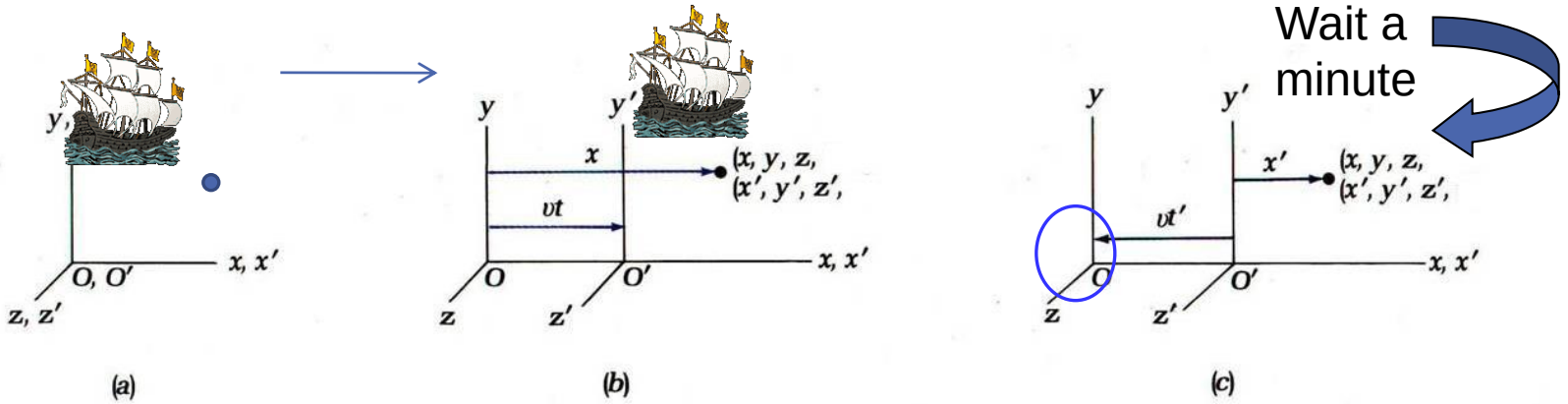
Recall *O'* is the moving frame, initially coincide with *O* frame.

$$Speed = \frac{Dis\tan ce}{Time}$$

$$(x' = x - vt, \quad y' = y, \quad z' = z) \quad and \quad t'$$

These rules are simple and follow from common sense. Notice the innocent looking statement ***t' = t***. It simply means that clocks behave in the same way in the two inertial frames (S and S').

Galilean Transformation



Recall *O'* is the moving frame, initially coincide with *O* frame.

$$(x' = x - vt, \quad y' = y, \quad z' = z) \quad and \quad t' - t$$

$$u' = u - v \qquad Speed = \frac{Distance}{Time}$$

$$a' = a$$

$$\Rightarrow ma' = F' \sim ma = F$$

Conclusion :

Newton's 2nd Law obeys Galilean Relations

Galilean transformation along the x -direction, where E represents the electric field in the wave equation :

$$\frac{\partial^2 E(x,t)}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 E(x,t)}{\partial t^2}$$

$$\left(1-\frac{v^2}{c^2}\right)\frac{\partial^2 E(x',t')}{\partial x'^2} + \frac{2v}{c^2}\frac{\partial^2 E(x',t')}{\partial x'\partial t'} = \frac{1}{c^2}\frac{\partial^2 E(x',t')}{\partial t'^2}$$

Extra terms … implies not covariant

University Physics by Young and Freedman, P1259

Hint : $\frac{\partial f(x,t)}{\partial t} = \frac{\partial f(x,t)}{\partial x}\frac{\partial x}{\partial t} + \frac{\partial f(x,t)}{\partial t}\frac{\partial t}{\partial t}$

Why we cannot get covariance ? along the x-direction, where E represents the electric field in the wave equation :

$$\frac{\partial^2 E(x,t)}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 E(x,t)}{\partial t^2}$$

The expected if convariant

$$\frac{\partial^2 E(x',t')}{\partial x'^2} = \frac{1}{c^2}\frac{\partial^2 E(x',t')}{\partial t'^2}$$

Implies covariant

University Physics by Young and Freedman, P1259

Newtonian Relativity

It turns out that the form of Maxwell's equations (E&M Laws) get changed under Galilean transformations. Oops ! So not Covariant !

This is bad news and it could mean one of the 3 things:

A) The principle of relativity does not apply to E & M

B) The problem is with Maxwell's Equations

C) or the problem is with Galilean Transformation (Relations)

May be there is a preferred or absolute frame after all !

There was another concern … Ether or Aether problem !

not Either !

Pre-Einstein Relativity

Light and Ether

With respect to what does light travel at a speed of, **c** = 3 x 10^8 m/s?

Interesting fact : c = 299,792,458 m/s

wave needs a medium to travel in

Is this an odd Question?

We say that sound travels at a speed of 330m/s, what we really mean is that sound travels in air at this speed.

Pre-Einstein Relativity

Is there an equivalent of the air medium; absolute frame?

Aether ! or Ether

People wondered: about what happens when the medium ether is moving or the light source is moving with respect to the ether.

Will the speed of light for this moving person become modified as in the case of sound?

About Ether ?

By the way, what is Ether ?

It is supposed to be perfectly transparent, have zero density and penetrate everything including a piece of solid steel.

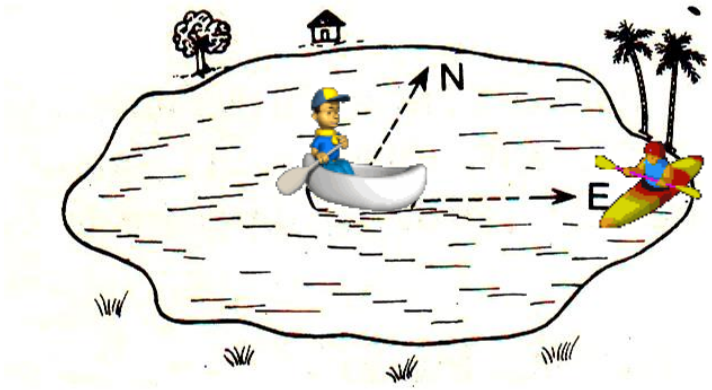
… strange properties indeed !

Yet sufficiently elastic to support E&M waves but it had no resistance to bodies moving through it.

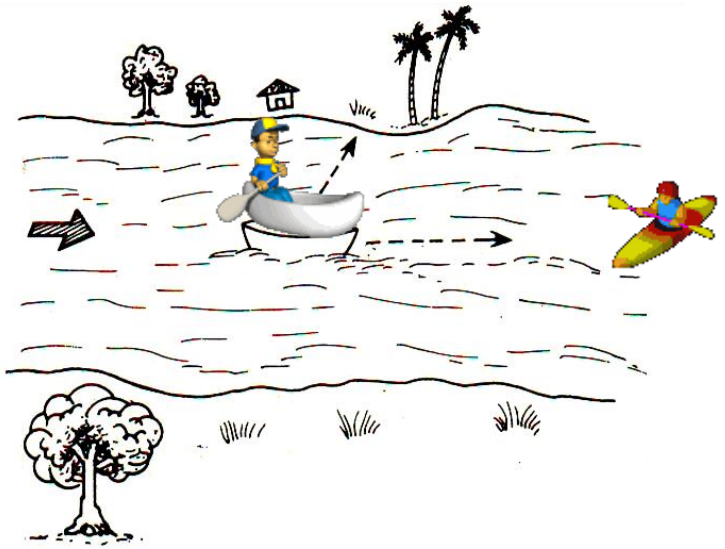
… contradictory properties again.

There should also be ether wind. Why ?

Pre-Michelson-Morley Experiment: People were also anxious to prove (?) that Ether existed



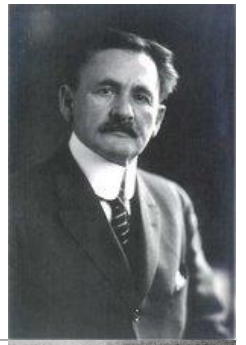
The boat is in the center of a lake. Water here is still and no wind. So it will be easy to row in any direction. The time taken to reach the edge of the lake will be the same.



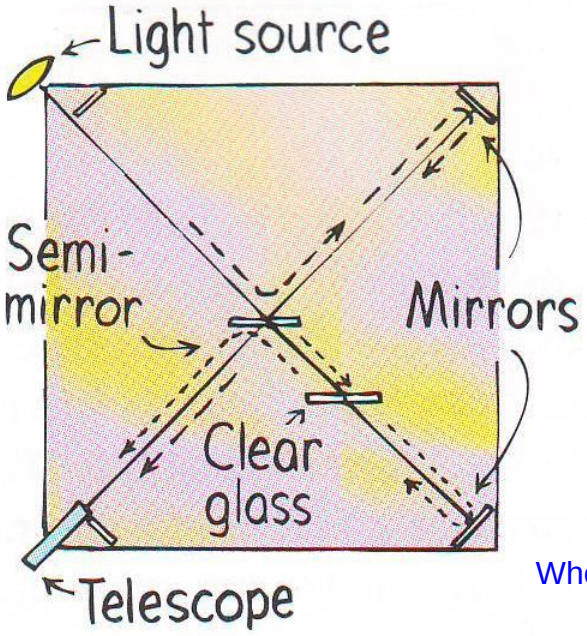
The boat is in the center of a lake with water current. Water here is not still. So it will not be easy to row in any direction. The time taken to reach the edge of the lake will not be the same.

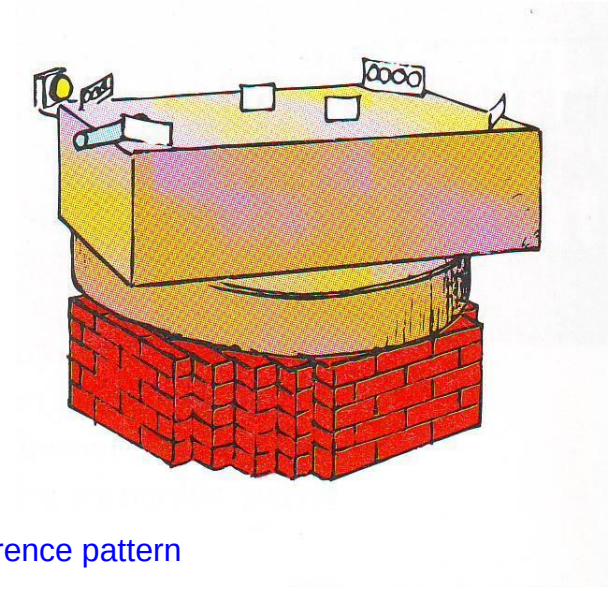
Michelson-Morley Experiment

Michelson



morley

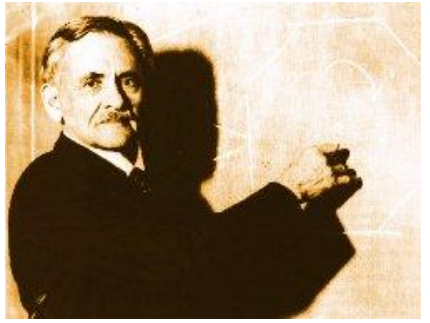


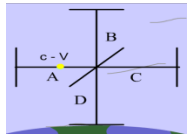


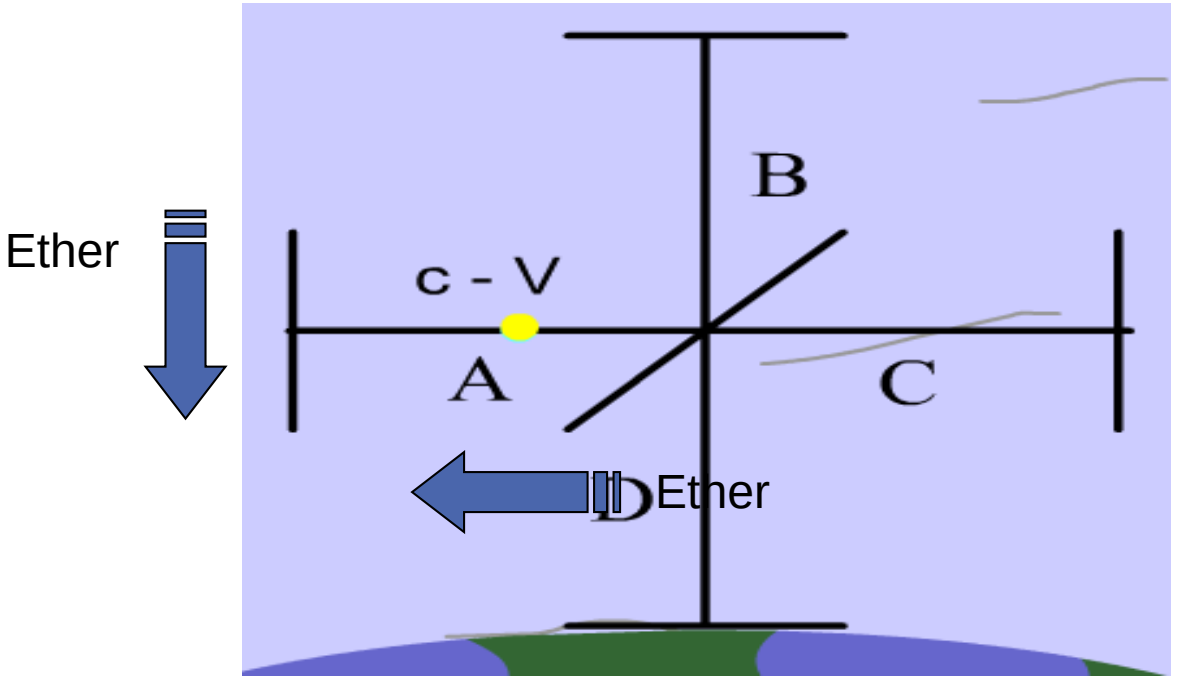
When they recombine, they will form an interference pattern

From the time the wave theory of light was proposed, everyone imagined that light propagated in Aether. Michelson and Morley rotated the apparatus above over a period of many months.

Michelson-Morley Experiment





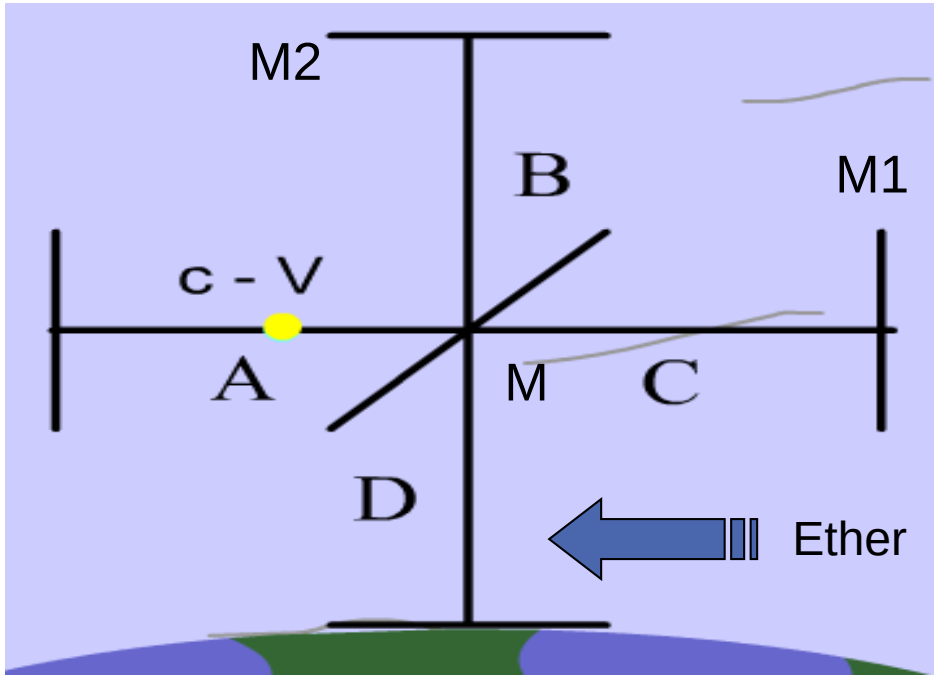


Everyone imagined that light propagated in ether ... **the absolute frame**.
People were also anxious to prove that Ether did exist if one can detect ether wind.

About Michelson-Morley Experiment

Distance from M to mirror M1 = l_1

Consider light path from mirror M to mirror M1 and back to mirror M.
Call time taken by this light path t_A



time for light to go there and back

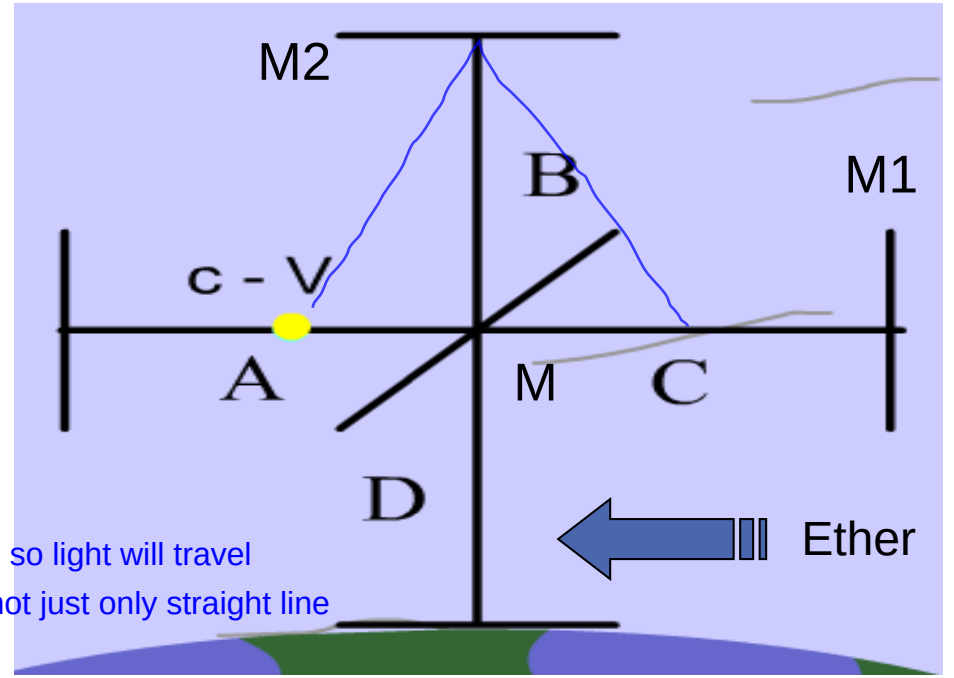
$$t_A = \frac{l_1}{c-v} + \frac{l_1}{c+v} = \left(\frac{2l_1}{c}\right)\frac{1}{\left(1-\left(\frac{v}{c}\right)^2\right.}$$

Note : V = v
An ether wind blowing in the direction M1to M

About Michelson-Morley Experiment

Distance from M to mirror M2 = l_2

Consider light path from mirror M to mirror M2 and back to mirror M.
Call time taken by this light path t_B



Because the apparatus is moving, so light will travel a little more like in a triangle and not just only straight line

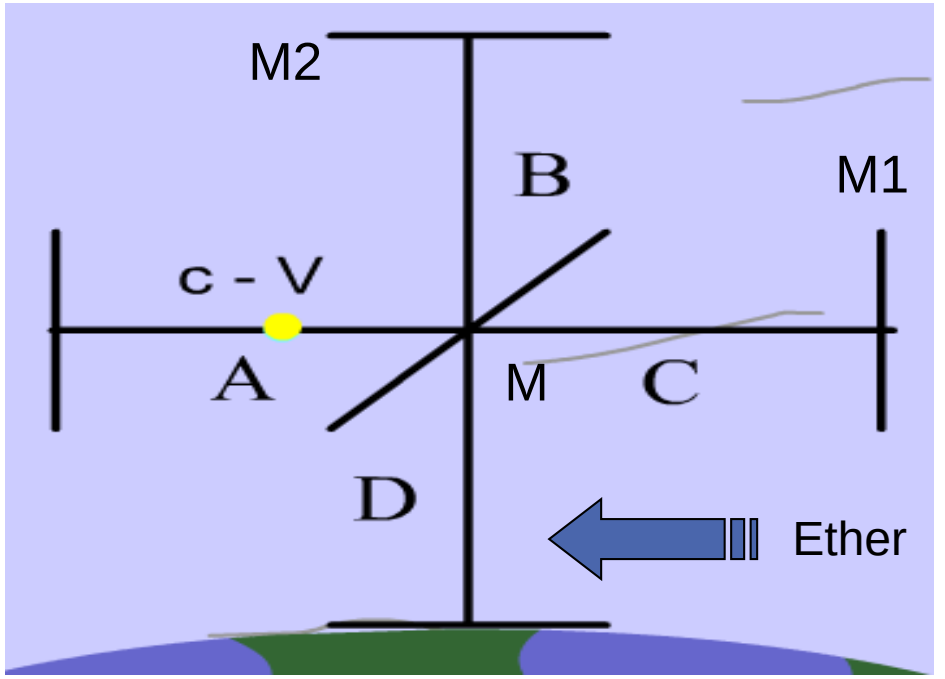
$$t_B = \left(\frac{2l_2}{c}\right)\frac{1}{\sqrt{\left(1-\left(\frac{v}{c}\right)^2\right.}}$$

Note : V = v
An ether wind blowing in the direction M1to M

About Michelson-Morley Experiment

Note that $v << c$.

Finally, the time difference taken by the 2 light paths is $t_B - t_A$



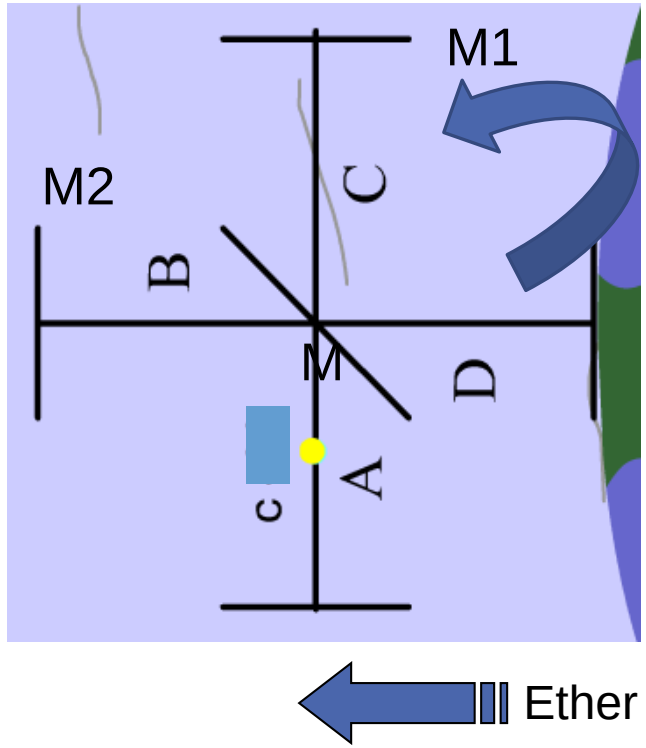
$$t_B - t_A = \frac{2l_1}{c}\left(1+\left(\frac{v}{c}\right)^2\right) - \frac{2l_2}{c}\left(1+\frac{1}{2}\left(\frac{v}{c}\right)^2\right)$$

Note : V = v
An ether wind blowing in the direction M1to M

About Michelson-Morley Experiment

Note that $v << c$ and apparatus rotated 90 degrees

Finally, the time difference taken by the 2 light paths is $t_B^R - t_A^R$



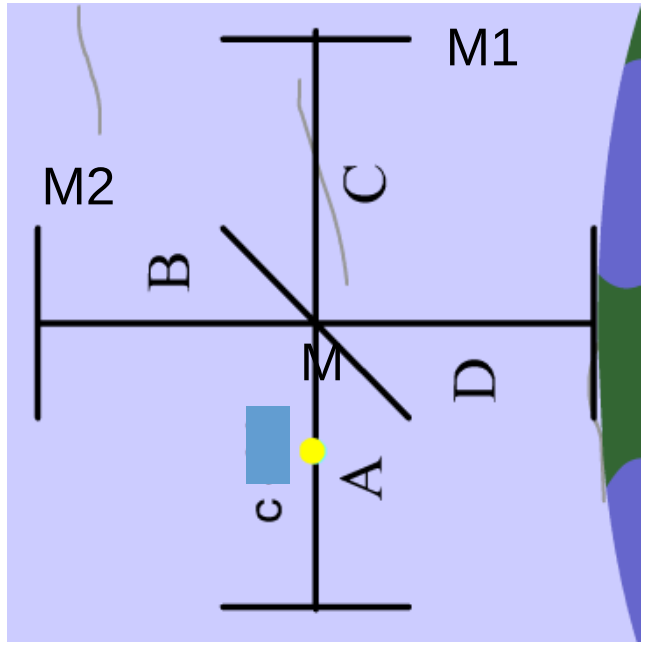
$$t_B^R - t_A^R = \frac{2l_1}{c}\left(1+\frac{1}{2}\left(\frac{v}{c}\right)^2\right) - \frac{2l_2}{c}\left(1+\left(\frac{v}{c}\right)^2\right)$$

About Michelson-Morley Experiment

Note that $v << c$ and apparatus rotated

Finally, the difference of the two time difference is given as δ

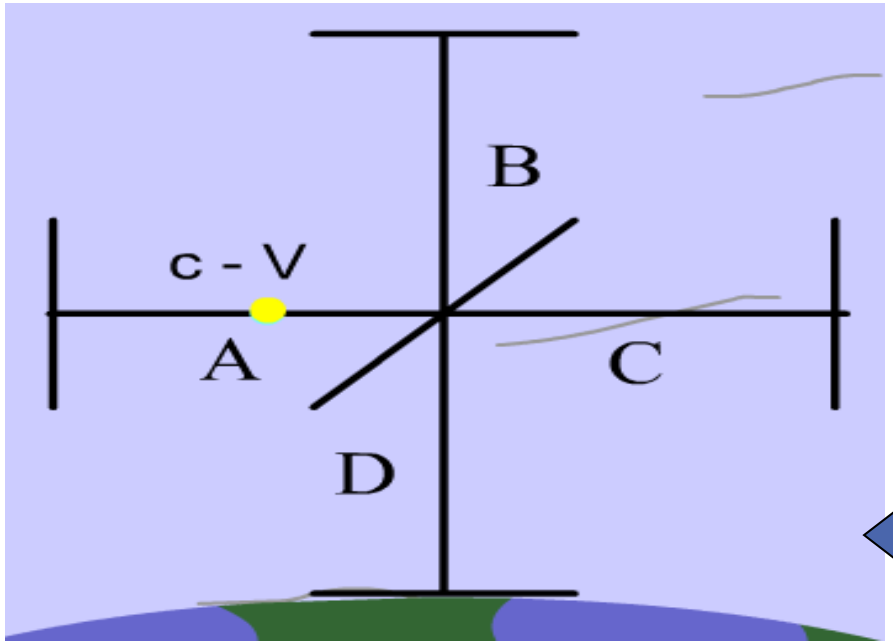
$$(t_B{}^R - t_A{}^R) - (t_B - t_A) = \delta$$



The **theoretical** (expected) fringe shift should be given as : *Visible light :* λ = 5.5 x 10^{-7} m,
$(l_1 + l_{2)}$ = 22 m, (v/c) = very small.
i.e. earth is very slow compared to light.

Fringe shift $\dfrac{\delta\, c}{\lambda} = \dfrac{l_1 + l_2}{\lambda}\left(\dfrac{v}{c}\right)^2$

Michelson-Morley Experiment



Morley

The expected fringe shift was about 0.4 fringes. (Interference patterns)
Michelson and Morley got a shift of less than 0.01 fringe. $\pm errors$
i.e. … **almost no shift … no ether wind … no ether**

Albert A. Michelson

Polish but join US Naval Academy in Annapolis,

1875-1879, Exp. To determine the speed of light. Basically did one experiment all his life

1880, Berlin, Potsdam experiment … measure the velocity of the solar system through ether

1881, Case School of Applied Physics Cleveland

1887, Michelson and Morley Experiment

1907, 1st American to receive the Nobel Prize, Negative Result !

Pot Pourri of Ether ?

Aether Hypothesis (absolute frame/space)

Maxwell also believed in Ether

Ether wind

Ether drag

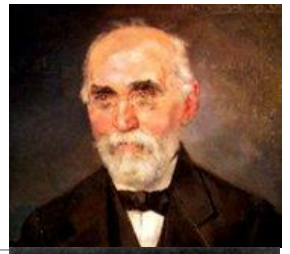
During that time, people still want Aether & Galilean transformation but not aether wind (It is ok if not there).

People come up with more ideas … If there is ether … was it still, partially dragged or fully dragged ?

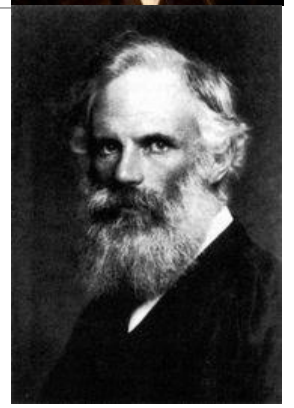
some enlightenment about ether!

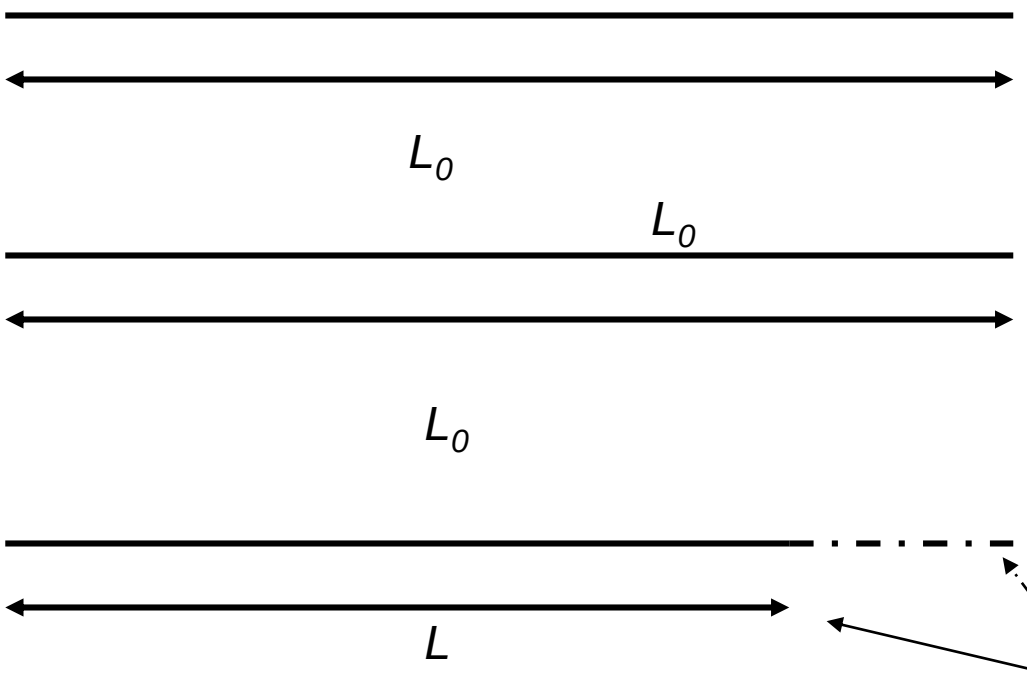
FitzGerald-Lorentz contraction (1892)

lorentz

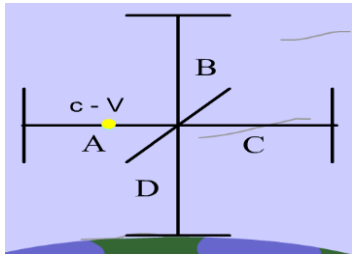


Fitzgerald





$$L = L_0\sqrt{1-\frac{v^2}{c^2}}$$



Length contraction

$$L = \frac{L_0}{\gamma} \qquad \text{where} \quad \gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

One last attempt to retain Aether.

Michelson-Morley Experiment

Definitive Conclusion

Michelson and I have begun a new experiment. It is to see if light travels with the same velocity in all directions … Then we shall have to make observations for a few minutes every month for a year …

Morley wrote to his father

In the end ….No Ether or Aether … but a Negative result that won a Nobel Prize.

The Principle of Relativity

For your coming weekend study and meditation :

What is this principle, can you explain to someone this principle in your own words ?

Can you summarize the above to one word ?

What does it mean by there is no Aether ?

So it is a "Light" problem ?

But the problem is not Light !

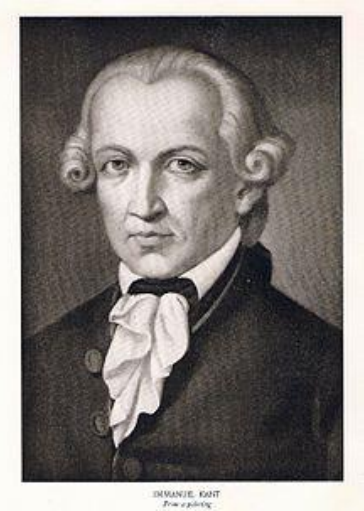
Is this discussion a waste of *Time* ?

so let there be Light … and there was Light … Genesis 1.3

Nature and Nature's Laws lay hid in night,
God said, "let Newton be" and all was Light

Alexander Pope

Immanuel Kant (1724-1804)



"2 things fill the mind with ever increasing wonder and awe …

the ***starry heavens*** above me and the moral law within me"