PHYSICISTS TIME-LINE

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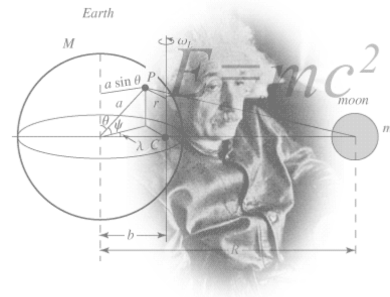


CONFLICT BETWEEN NEWTONIAN MECHANICS & ELECTROMAGNETISM

By 1900 the classical world-view was well established through two main fields: *Mechanics* & Electromagnetism.

BUT..

Attempts to complete physics by **unifying** electromagnetism and mechanics **failed**.

WHY?

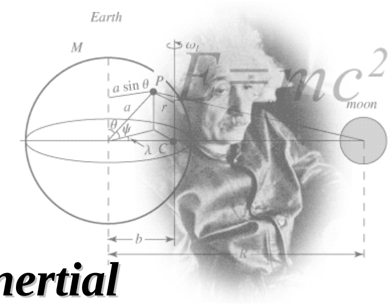
According to the Galilean transformations;

$$v_1 = v_2 + v$$

WHICH MEANS: ***c* *is not invariant.***

Hence, electromagnetic effects ***will not be the same*** for different inertial observers.

I.e. Maxwell's equations ***are not conserved*** by the Galilean transformations, although Newton's laws are.



This fact leads us to one of the followings:

1. Galilean relativity exists only for mechanics, but not for electromagnetic. That is, *in electromagnetism there is an* ***absolute inertial frame*** **(** ***the ether*** **).**

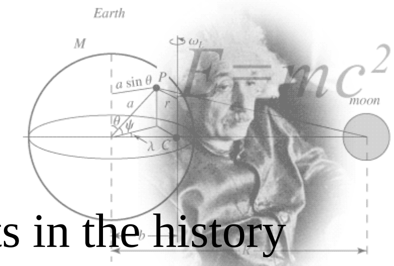
IF THIS IS ☑: we would be able to locate ***the ether*** frame experimentally.

2. Galilean relativity exists both for mechanics and for electromagnetism, but the laws of electromagnetism as given by Maxwell are not correct.

IF THIS IS ☑: we must be able to perform experiments show deviations from Maxwell's laws.

3. Galilean relativity is suitable only for mechanical laws but not for Maxwell's laws.

IF THIS IS ☑: ***the correct transformation laws would not be the Galilean ones,*** but some other ones which are consistent with both mechanics and electromagnetism**.**



MICHELSON-MORLEY EXPERIMENT

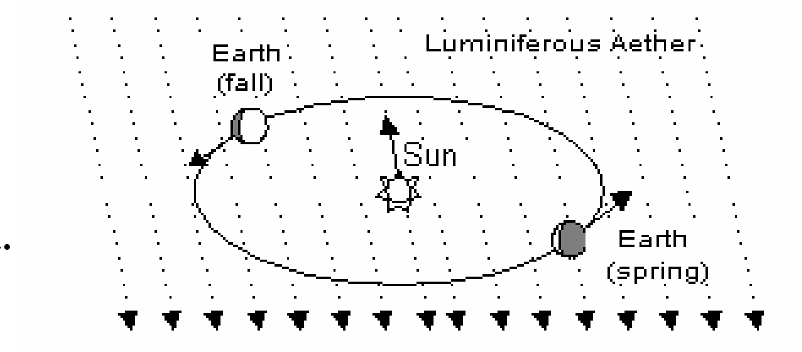
One of the most important and famous experiments in the history of physics, it was performed by **Michelson and Morley** in **1887** to measure the speed of the earth through the ether ***i.e.*** (***locate the absolute frame***).

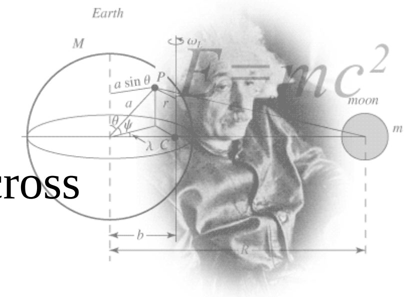
Primarily for this work, **Michelson** was awarded the Nobel Prize in **1907.**

THE EXPERIMENT BACKGROUND:

Physics theories of the late **19th century** postulated that, just as water and sound waves require a medium to move through, also *light waves require a medium*, called the " ***ether***". And because light can travel through a vacuum, it was assumed that the vacuum must contain that " ***ether***".

Because the speed of light is so great, designing an experiment to detect the presence and properties of this *ether* took a considerable effort.





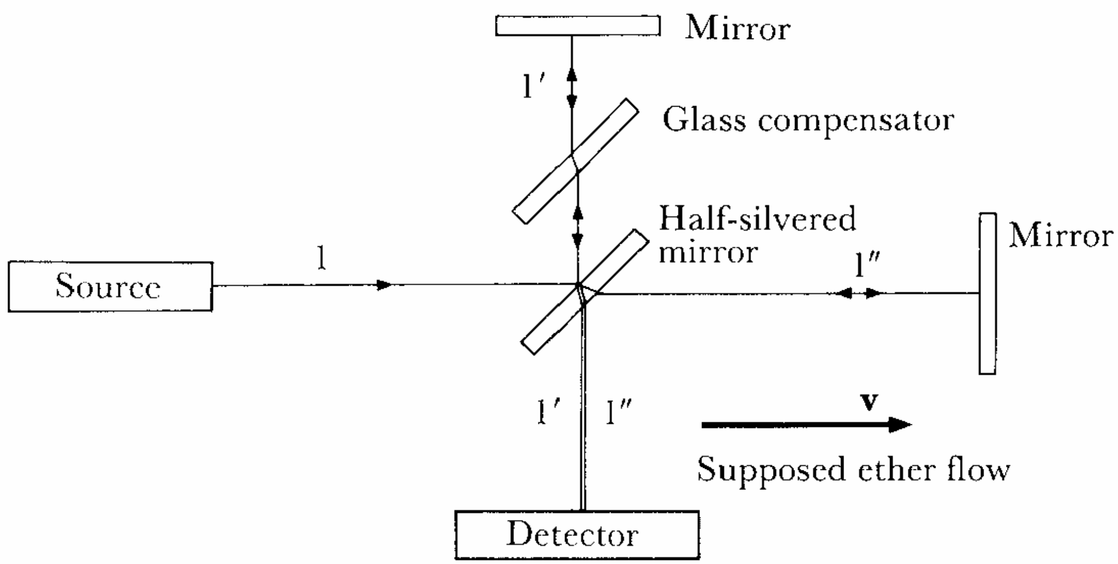
Since the Earth is in motion, it was expected that the flow of ether across the Earth should produce a detectable "ether wind."

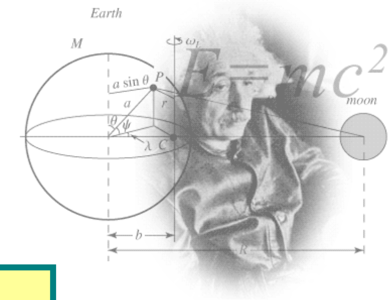
The expected difference in the measured speed of light was quite small. A number of physicists had attempted to make this measurement during the mid-1800s, but the accuracy demanded was simply too great for existing experimental setups.

Michelson had a solution to the problem of how to construct a device sufficiently accurate to detect ether flow using the phenomenon of ***light interference***.

APPARATUS:

The apparatus used was the **Michelson interferometer**. In this device, monochromatic light from a source is split into two separate beams. These beams travel two different optical paths and then come back together to interfere either constructively or destructively.





If the earth were moving through the ether, the device could be aligned with the source "upstream" as the ether flowed by.

$$T' = \frac{2L/c}{\sqrt{1 - v^2/c^2}}$$

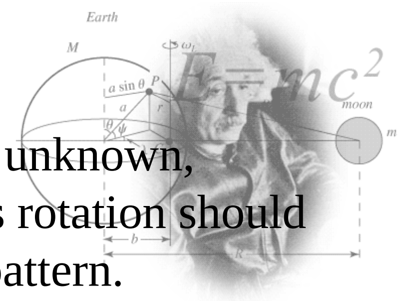
If the arms of the interferometer have equal optical lengths **L**, ray **I'** would move back and forth across the "ether river" in time:
and ray **I''** would move downstream and upstream in time;

$$T'' = \frac{2L/c}{\left(1 - v^2/c^2\right)}$$

The difference in times for rays **I'** and **I''** will be

$$\Delta T = T'' - T' = \frac{2L/c}{\left(1 - v^2/c^2\right)} - \frac{2L/c}{\sqrt{1 - v^2/c^2}}$$

this difference in times will cause a phase difference and a certain interference pattern with light and dark fringes. In other words if the delay can be measured it will tell us the ***Earth's speed w.r.t the ether***.



Since the actual direction of the Earth's motion through the ether was unknown, Michelson and Morley then carefully **rotated the device by 90o.** This rotation should change the times for rays **I'** and **I''** and then change the interference pattern. Although the expected change was nearly **100 times** the sensitivity of their apparatus, ***no shift of the pattern (within experimental error) was discovered***.

Since then, the experiment has been done with greater and greater accuracy in many different versions, but the ***null result*** was always the same.

CONCLUSION:

The experimenters ***could not*** *find the supposed* ***ether***.

And this led to an important fact about reference frames:
There is no such thing as an absolute frame of reference in our universe.

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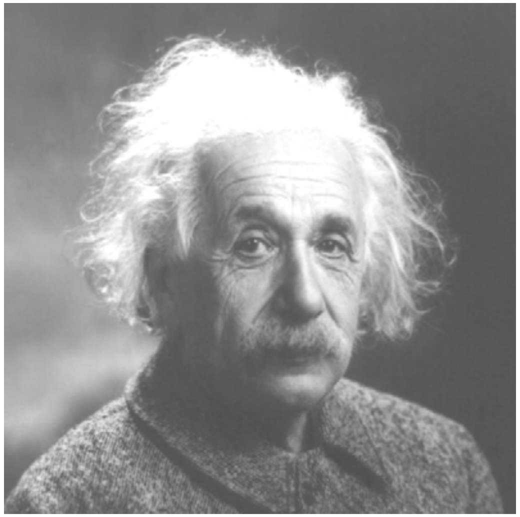
5- PHYSICS AFTER 1900

5.1. THE THEORY OF RELATIVITY



❒ Albert Einstein (1879 –1955)

Albert Einstein was a German-born theoretical physicist who is widely considered as one of the greatest physicists of all time.

While He is well known for the ***theory of relativity*** (specifically mass-energy equivalence, $E = mc^2$), he was awarded the **1921** Nobel Prize in Physics for his discovery of the law of ***the photoelectric effect.***

Einstein's special theory of relativity, combined **mechanics** with **electromagnetism**, while his general theory of relativity extended the principle of relativity to non-uniform motion, creating a **new theory of gravitation.**

❒ Special theory of relativity (1905):

- Einstein's *special theory* combines **Galilean relativity** with the postulate that **the speed of light, *c***, must be **invarient**.

- The theory was called "***special***" because it is applicable only to **inertial frames.**
- Einstein based his ***special theory of relativity*** on **two** fundamental **postulates:**

❶ THE PRINCIPLE OF RELATIVITY:

> ***All laws of physics have the same mathematical form in all inertial reference frames.***

This means:

- There is no preferred frame of reference.
- There is no a physical experiment, *mechanical, electrical or optical* can be performed to determine our state of uniform motion.
- Galilean transformations are not correct for all laws of physics.

❷ THE CONSTANCY OF THE SPEED OF LIGHT:

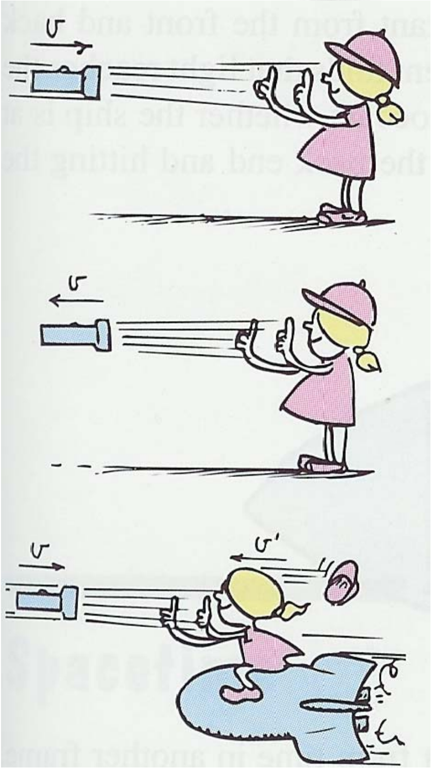
The speed of light in a vacuum has the same measured value (c) in all inertial reference frames.

This means:

- The speed of light is **invariant**.

- *c* is not just the velocity of a certain phenomenon - light- but rather a fundamental feature of the way space and time are tied together. The classical idea that **space & time** are **independent** had to be rejected. (**I.e. there is should be a relationship between space & time**).

- Two events that are simultaneous in one frame of reference **need not be** simultaneous in another frame.



This theory has a variety of surprising consequences that seem to violate common sense, but that have been verified experimentally.

Lorentz Transformations:

Unlike Galilean transformations, Lorentz transformations involve a change of *spatial distance* and a change of *time interval* between two inertial systems.

$$\left.\begin{aligned} x_2 &= \gamma\left(x_1 - vt_1\right) \\ y_2 &= y_1 \\ z_2 &= z_1 \\ t_2 &= \gamma\left(t_1 - \frac{v}{c^2}x_1\right) \end{aligned}\right\}$$

and

$$v_{2x} = \frac{v_{1x} - v}{1 - v_{1x}.v/c^2}$$

$$v_{2y} = \frac{v_{1y}}{\gamma[1 - v_{1x}.v/c^2]}$$

$$v_{2z} = \frac{v_{1z}}{\gamma[1 - v_{1x}.v/c^2]}$$

where

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

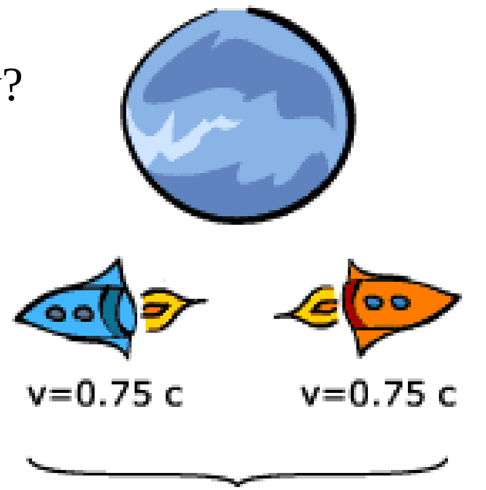
NOTE:

1- the relativistic **Lorentz transformations** reduce to the classical **Galilean transformations** as ***v/c*** approaches **zero**.

2- Nothing can travel faster than light.

FOR EXAMPLE

Imagine that you are standing between two space-ships moving away from you. One space-ship moves to the left with a speed of 0.75 *c* (relative to you) and the other one moves to the right also with a speed of 0.75 *c* (relative to you).
At what speed will each space-ship see the other moving away?



In classical Newtonian mechanics, two different velocities ***v1*** and ***v2*** are added together by the formula

$$v_{2x} = v_{1x} - v$$

So, can the speed we see be ; **0.75 *c* + 0.75 *c* = 1.5 *c***?

No, the speed cannot, of course, be faster than the speed of light c.

However, in special relativity, the velocities are added together as

$$v_{2x} = \frac{v_{1x} - v}{1 - v_{1x}.v / c^2}$$

Hence, their ***relative speed*** will be **0.96 *c*** .

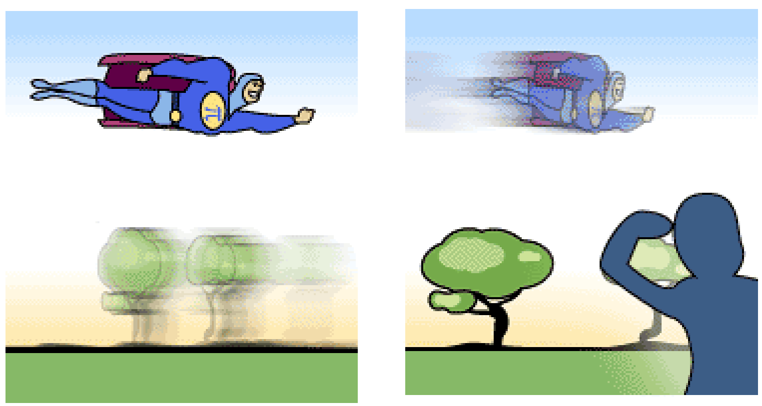
❐ Length Contraction & Time Dilation

(As Consequences of Einstein's 2 Postulates)

1- LENGTH CONTRACTION: Moving objects appear contracted along the direction of motion (by factor of γ.) Lengths perpendicular to the direction motion are unchanged.

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

Because the Lorentz factor γ **is always greater than** unity, then ***L*** **is always less than** L_o.



2- TIME DILATION:

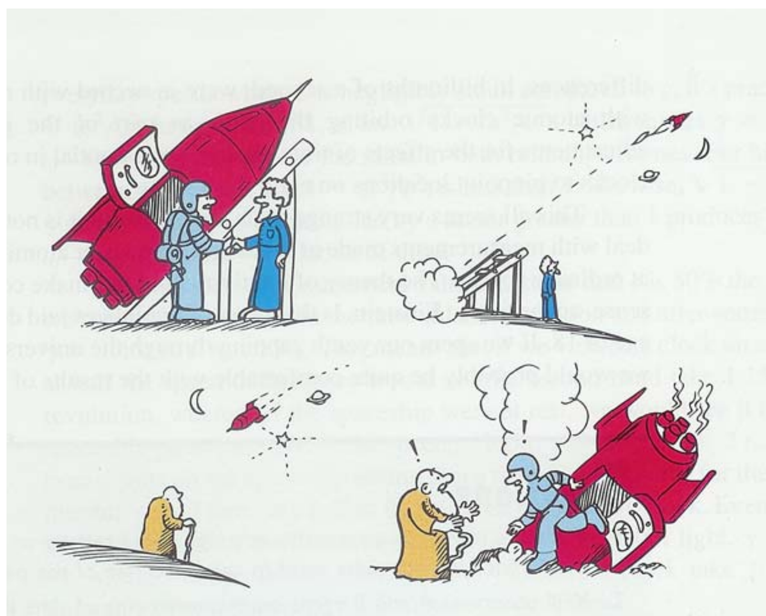
Moving clocks appear to run slower (by factor of γ.)

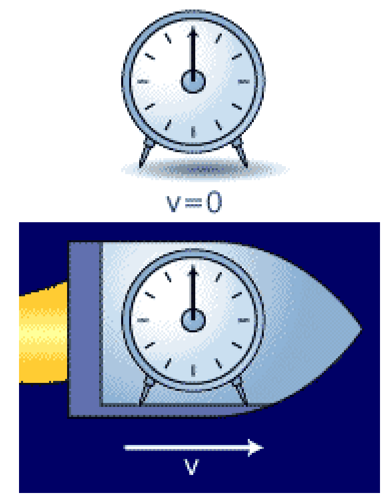
$$\Delta t = \frac{\Delta t_0}{\sqrt{1 - v^2 / c^2}} = \gamma \Delta t_0$$

I.e. a clock fly by us at **the speed of light**, ***would not appear to be running at all***.

- ***Time dilation*** has been confirmed in the laboratory. It is found that the *lifetime of a fast-moving* radioactive particle is ***greater** than its rest lifetime*.

- **TWIN PARADOX !!**





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5- PHYSICS AFTER 1900

5.1. THE THEORY OF RELATIVITY

EXAMPLE (1);

A spaceship captain sees us attempting to measure lengths in the direction of her motion with a measuring tape she measures to be **40 m** long. Her spaceship is moving past us at **0.60c**. **How long do we say the measuring tape is**?

SOLUTION:

First, v = 0.60c gives γ=1.25

We want to find L_0 (since the measuring tape is at rest with respect to us). Thus;

$$L_0 = \gamma L = 1.25 \times 40 \text{ m} = 50 \text{ m}.$$

EXAMPLE (2);

When a charged *pion* (π^+) is at rest, its mean lifetime is 2.6 X 10^{-8} s, or **26 ns**. What is the mean lifetime of charged pions when they are moving at **0.98c** ?

SOLUTION:

First, at v = 0.98c, γ = 5.0. The rest time interval, T_0, is 26 ns. This interval dilates to;

$$T = \gamma T_0 \, (5.0)(26 \text{ ns}) = 130 \text{ ns}.$$

However, any observer moving along with the charged pions would have no relative velocity with respect to them and would still measure their mean lifetime to be 26 ns. To this moving observer, the particles are still at rest.

❒ Equivalence of matter and energy:

Energy and mass are just two equivalent ways of describing the same thing.

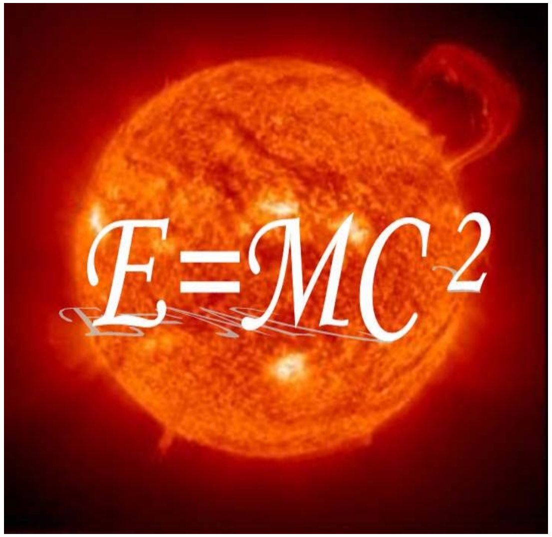
Where;

$$E = mc^2$$

This law unified two things which appeared to be completely unrelated in the old model (classical physics).

❒ The equation ***E = mc2*** states that if you want to know how much energy is in a system, measure its mass.

❒ The decrease of mass in the sun by the process of thermonuclear fusion bathes the solar system with radiant energy. **There is sufficient hydrogen fuel for fusion to last another 5 billion years !!**



❒ When we strike a match, phosphorus atoms in the match head rearrange themselves and combine with oxygen in the air to form new molecules. The resulting molecules have very slightly less mass than the separate phosphorus and oxygen molecules.

❒ The equation $E = mc^2$ **is not restricted to chemical and nuclear reactions. It applies to ALL** forms of energy and mass. **For example;**

•The filament of a light bulb energized with electricity has more mass than when it is turned off.

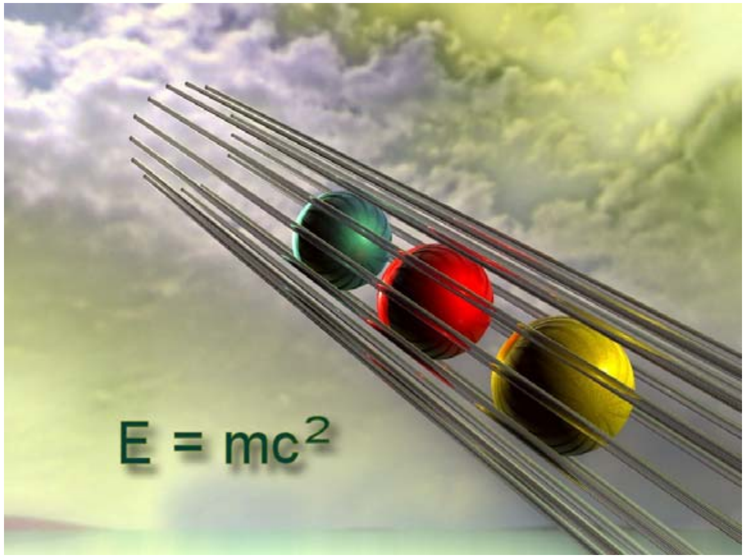
•A hot cup of tea has more mass than the same cup of tea when cold.

•A wound-up spring clock has more mass than the same clock when unwound.

But these examples involve incredibly small changes in mass-too small to be measured.

❒ Nuclear energy involves larger changes in energy, because the rest mass of nuclei converted into kinetic energy.

1 gram of mass ~ energy released in an atomic bomb

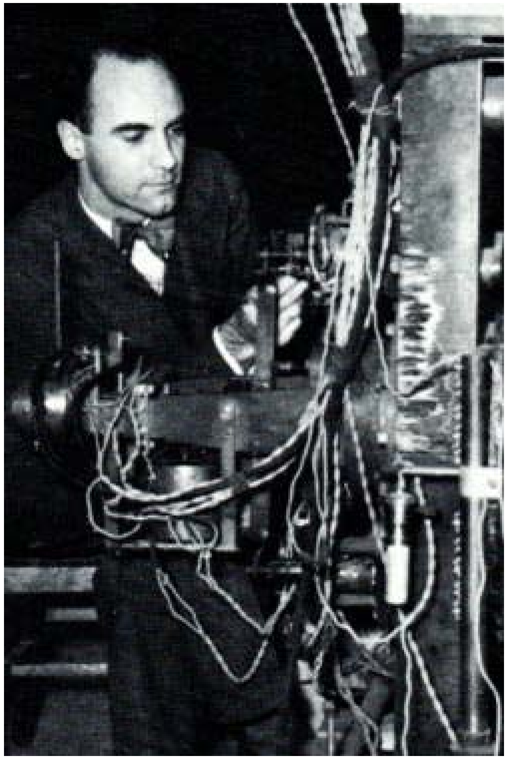


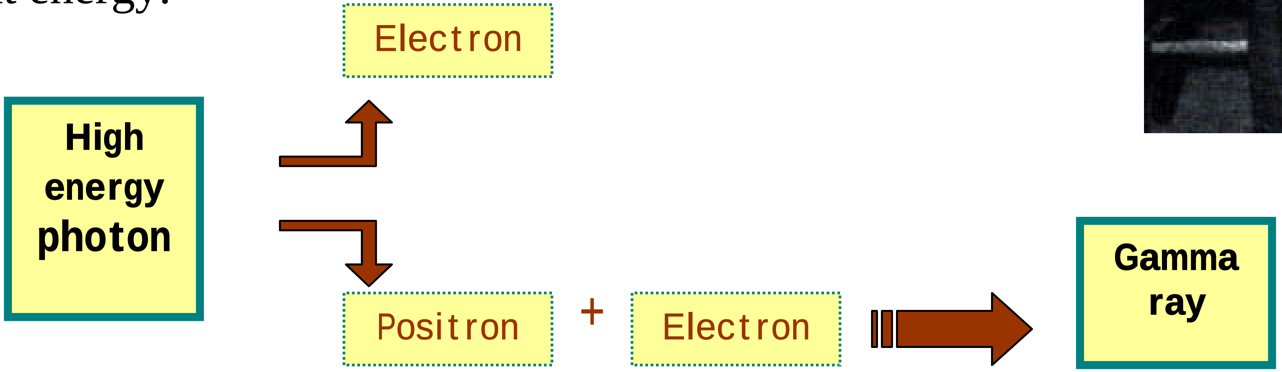
- The first evidence for the conversion of radiant energy to mass was provided in **1932** by the American physicist **Carl Anderson, who discovered the *positron*** by the track it left in a cloud chamber.

- ***The positron*** *is the antiparticle of the electron, equal in mass and spin to the electron but opposite in charge*.

- When a photon comes close to an atomic nucleus, it can create an electron and a positron together as a pair, thus creating mass. The created particles fly apart.

- The positron is not part of normal matter because it lives such a short time in the presence of matter. As soon as it encounters an electron, the pair is annihilated, sending out two gamma rays in the process. Then mass is converted back to radiant energy.





❒ General theory of relativity (1915):

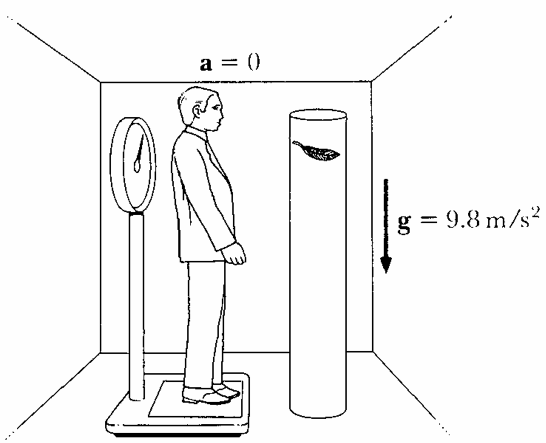
General relativity is a theory of gravitation developed between the years **1907–1915**. It began with ***the principle of equivalence*** introduced by Einstein in **1907.**

❒ THE PRINCIPLE OF EQUIVALENCE:

❍ Suppose that you are in a small closed room. You drop an object in a vacuum from rest and you find that its acceleration toward the floor is **9.8** m/s². Where is your room?

One possible answer: your room is at rest on the surface of the earth, where all freely falling bodies accelerate downward at g = 9.8 m/s².

Another possible answer: your room is in outer space (in a region where **g=0**), but your room is accelerating "upward" at a constant 9.8 m/s².



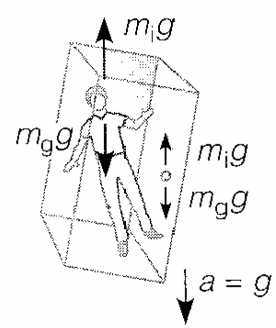
(a) On earth

The point is that you have no way of deciding from your experiment whether your closed room is ***at rest in the earth's gravitational field*** or ***accelerating in distant space***.
This is the basis of Einstein's ***principle of equivalence***:

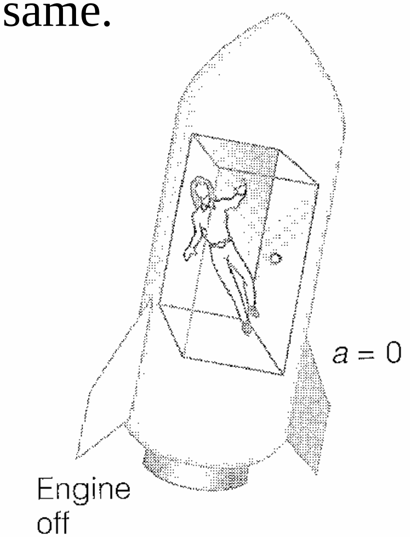
> *No experiment can distinguish between a **uniform gravitational field** and an equivalent **uniform acceleration**.*

This means:

- Free fall (*acceleration inside a gravitational field*) is an inertial motion.
- Inertial mass m_i and gravitational mass m_g are the same.



Free-falling frame



Inertial frame

- Phenomena that in classical mechanics are recognized as the action of the **force of gravity** (such as free-fall, orbital motion, and spacecraft trajectories) are taken in general relativity to represent **inertial motion in a curved space-time.**

- The relationship between stress-energy and the curvature of space-time is described by the *Einstein field equations* (EFE) which may be written in the form:

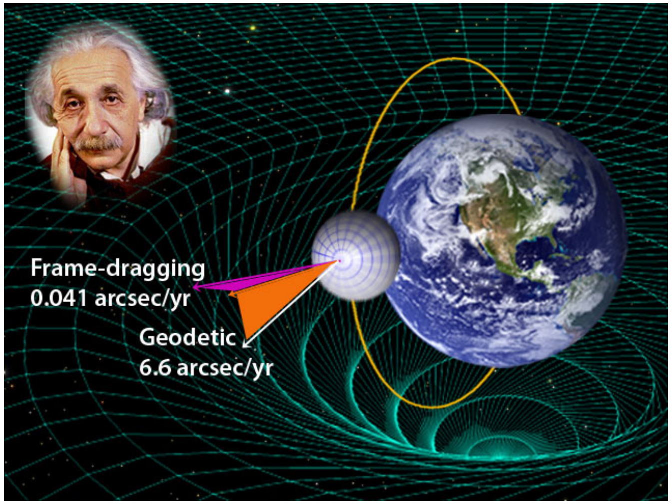
$$R_{ij} - \frac{1}{2} g_{ij} R = \kappa T_{ij}$$

where R_{ij} is the curvature tensor, T_{ij} is the stress-energy tensor and κ is a constant called the *Einstein constant of gravitation*, which equals to

$$\kappa = -\frac{8\pi G}{c^4}$$

where ***G*** & ***c*** are the *universal gravitational constant* and the *speed of light* respectively.

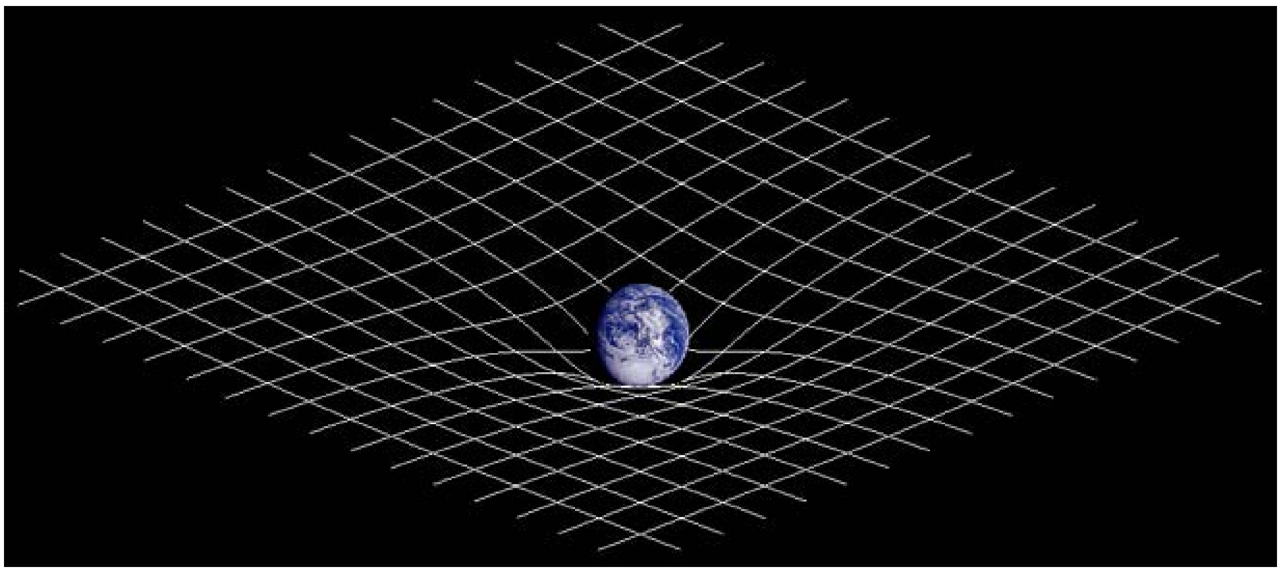
- The **EFE** reduce to **Newton's law of gravity** in the limiting cases of a **weak gravitational** field and **slow speed** relative to the speed of light.



❒ CURVED SPACE-TIME:

❍ If all accelerated systems are equivalent, then **Euclidean geometry** cannot hold in all of them. Thus the ***equivalence principle*** led Einstein to search for a gravitational theory which involves **curved space-time.**

❍ The defining feature of general relativity is the idea that **gravitational 'force**' is replaced by **geometry.**

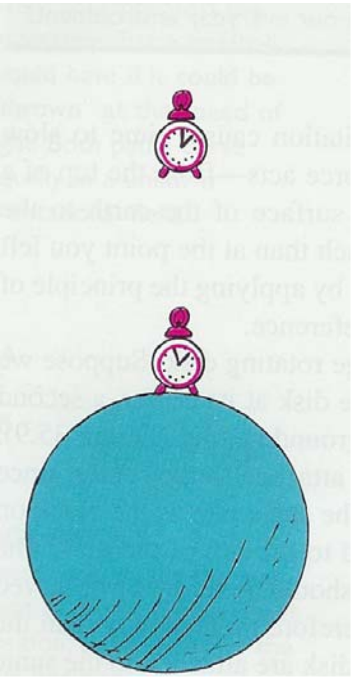


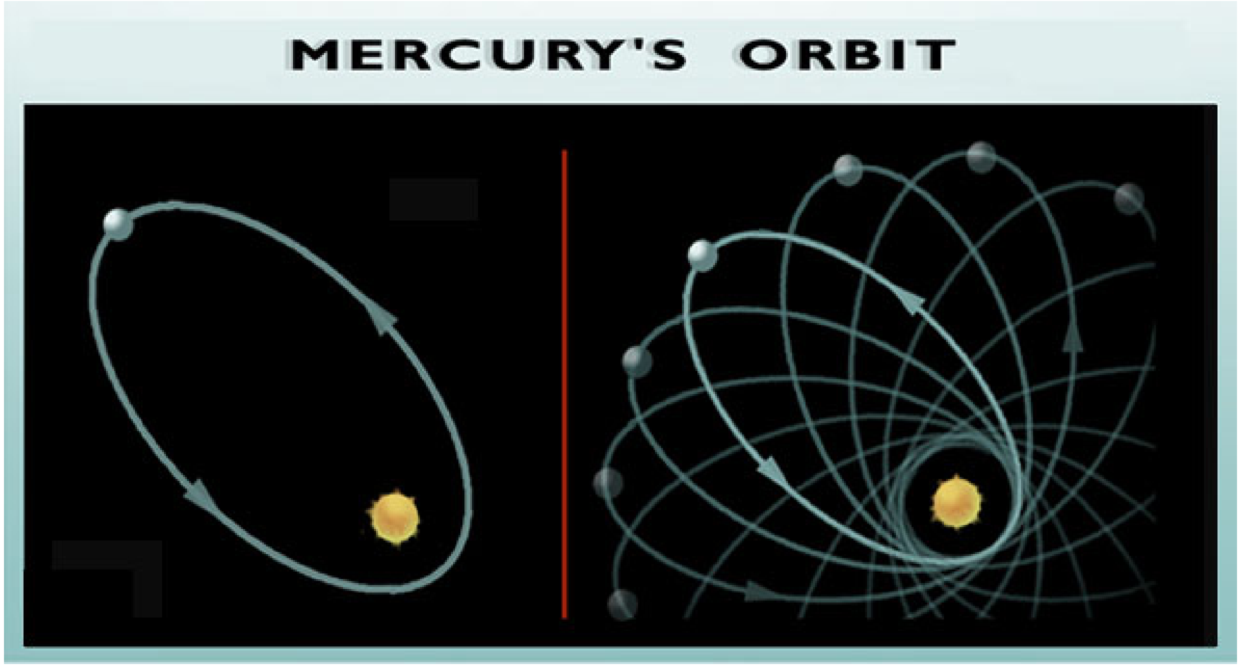
❍ In this theory, **space-time** is **curved** by the presence of **mass** **(or energy)** within it**.** ***The presence of matter changes the geometry of space-time***, this (curved) geometry being interpreted as **gravity**.

❒ SOME OF THE GENERAL RELATIVITY CONSEQUENCES:

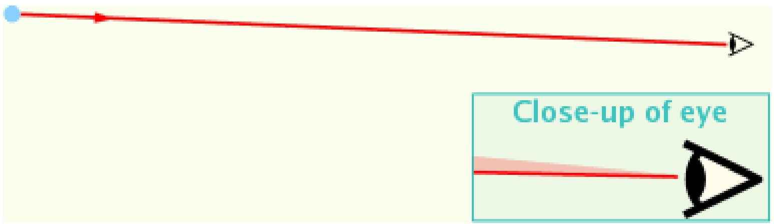
1- Time goes **slower** as we move **toward** the gravitational field. This is called **gravitational time dilation**. For example, an atom on the sun should emit light of a lower frequency (slower vibration) than light emitted by the same kind of atom on the earth. This effect is called ***the gravitational red shift***.

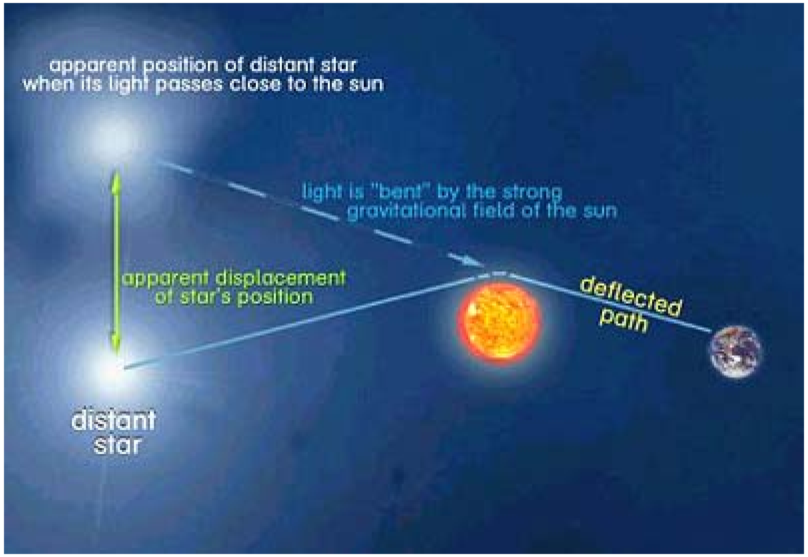
2- Orbits **precess** in a way unexpected in Newton's theory of gravity, (i.e. the points of **aphelion** and **perihelion** gradually creep around in a circular fashion). This has been observed in the orbit of Mercury .





3- ***Rays of light*** (which are weightless) **bend** ***in the presence of a gravitational field***. Einstein predicted that starlight passing close to the sun would be deflected by an angle of 1.75 s of arc, which is large enough to be measured.
Measurements of the deflection of starlight during 1919 sun ***eclipse*** had supported Einstein's prediction.





On the other hand, it is theoretically possible for an object to be so dense that light simply cannot escape its gravitational potential energy at all. Such objects are known as ***black holes***.

❒ GRAVITATIONAL WAVES:

In his General Theory of Relativity Einstein predicted that there must be ***gravitational waves*** which are *disturbances in the curvature of spacetime caused by the motions of matter*. These waves propagating at (or near) the speed of light. Though gravitational waves pass straight through matter, their strength weakens proportionally to the distance traveled from the source. A gravitational wave arriving on Earth will alternately stretch and shrink distances, on an incredibly small scale (by a factor of 10^{-21}) for very strong sources.
No wonder these waves are so hard to detect.

The existence of these waves considered as ***a unification between EM and GR***.