

A Revolution in Space and Time: Einstein's Special Relativity

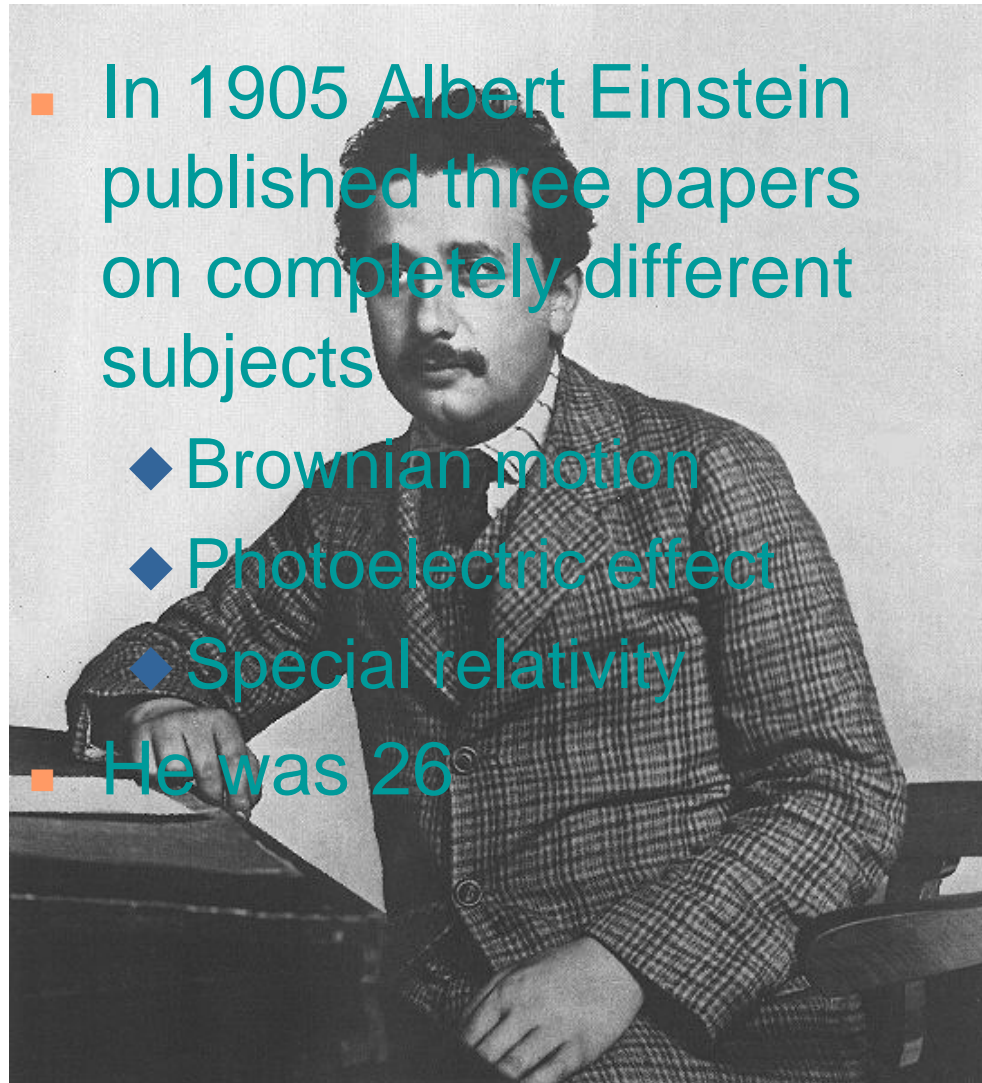


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Das wunderbare Jahr

The wonder year

- In 1905 Albert Einstein published three papers on completely different subjects
 - ◆ Brownian motion
 - ◆ Photoelectric effect
 - ◆ Special relativity
- He was 26



Brownian motion: a path to the atom

- Atomic structure was unknown (nucleus surprise: only in 1911)
- This is the jiggle of atoms and molecules
- Einstein could extract Avogadro number, atom size
- Brownian motion is always there in sensitive instruments



The photoelectric effect: toward quantum mechanics

Nobel Prize
1921



- Current flows from an illuminated metal
- Presence of current does not depend on intensity but on color
- Maxwell: waves of electromagnetic field
- Einstein said, paving the way to quantum mechanics: light is made out of particles, the photons
- Each photon carries energy that depends on the frequency of the wave: color
- CCD cameras use the photoelectric effect
- Lasers are understood in terms of photons

A step backwards: Galileo and relativity

- Galileo in 1632 stated clearly what relativity is about
- Dialogue concerning the two chief world systems: Ptolemaic and Copernican



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SALVATIUS:

Shut yourself up ... in the largest cabin below decks on some sailing ship, and have with you there a large bowl of water with some fish in it; hang up a bottle that empties drop by drop into a wide bowl beneath it

With the ship standing still, observe carefully...The fish swim indifferently in all directions; the drops fall into the bowl beneath...

When you have observed all of these things carefully, have the ship proceed with any speed you like, so long as the motion is uniform and not fluctuating this way and that.

You will discover not the least change in all the effects named,



nor could you tell from any of them

whether the ship was moving or standing still.

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Relativity : about space and time and how we see them

- What is the speed of a wave riding the tide ?
- Sum both speeds and you'll get the speed with respect to ground
- Send light in flowing water, what is the speed?
- Speed is not the sum of both
- In vacuum supposed to be filled with aether speed of light is always the same
- How to relate the speed seen by two observers in motion ?



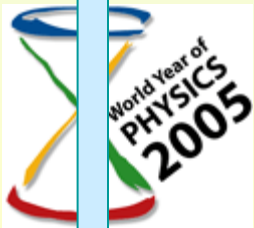
Galilean relativity

- There is no absolute motion
- If two observers look at the same phenomenon,
 - ◆ one observer can predict what the other sees using only
 - ◆ relative position and speed
- Implicitly: time is the same for all observers



Space

- Take a ruler, go straight, mark
- Repeat along a straight line
- Repeat along a perpendicular direction
- Space is paved with coordinates, distances, direction



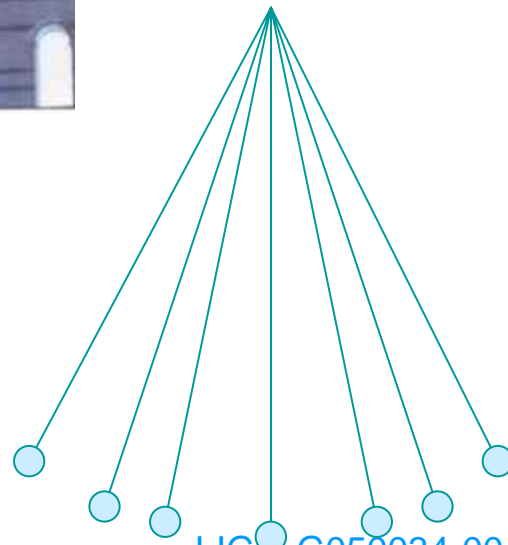
Time

- Completely different experience
- Find some simple phenomenon that repeats itself and count
- Clepsydra: depends on manufacturer
- Heartbeat: not so stable
- Local option
 - ◆ Pendulum: good, depends on length
 - ◆ Earth rotation
- Cosmic option:
 - ◆ Frequency of light in atomic emission
 - ◆ Light bouncing back and forth between two mirrors



Galileo: isochronism of pendulum

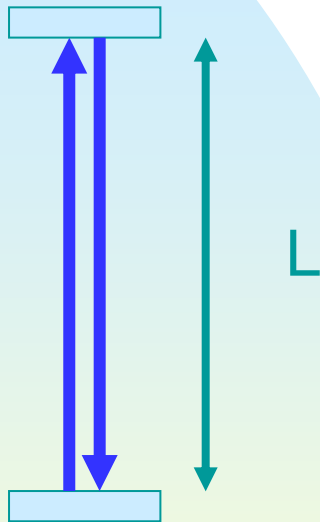
- Same period even with varying amplitude
- He said he checked it with heartbeat and his music knowledge
- Dependence on length and not on materials



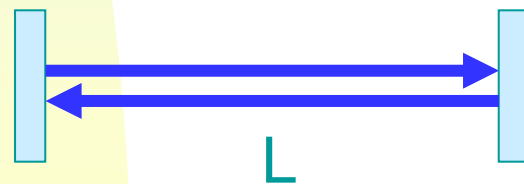
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The light clock



- Progress in timing: relevant for trade, longitude determination
- Scientific needs: astronomy, frequency measurements
- The simplest and conceptually reproducible clock: light back and forth



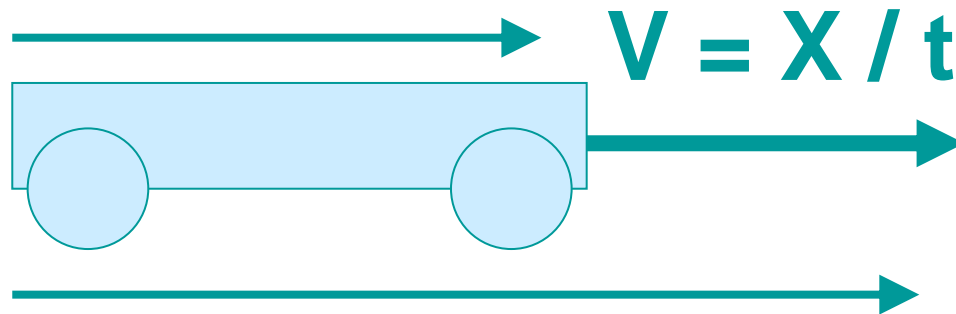
$$2 L / T = c$$

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Our intuition of relative motion

- Distances sum up
- Time is the same for both
- Speeds sum up

$$V' = x' / t$$



$$V = x / t = (x' + X) / t$$

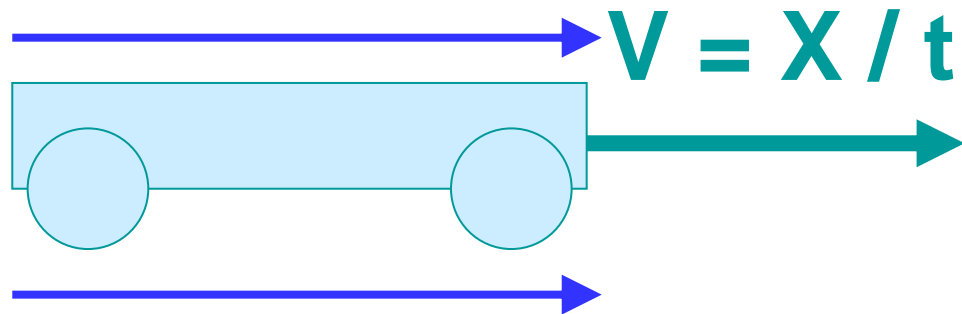
$$V = V + V'$$



What happens for light

- Distances?
- Time ?
- Speed of light is the same

$$c' = x' / t'$$



$c = c'$ experimentally



~~$c = V + c'$~~

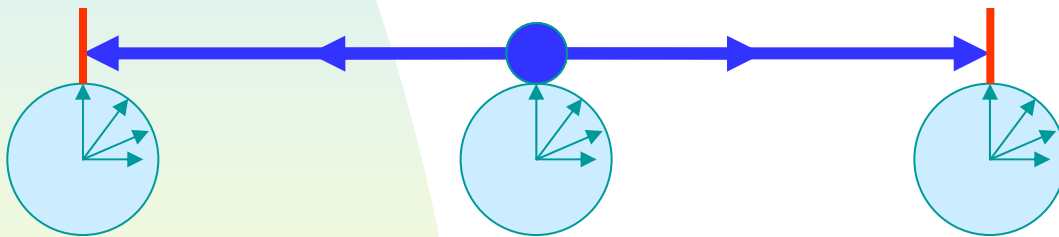
How is it possible ?

- Take speed of light for granted
- See consequences on time and space



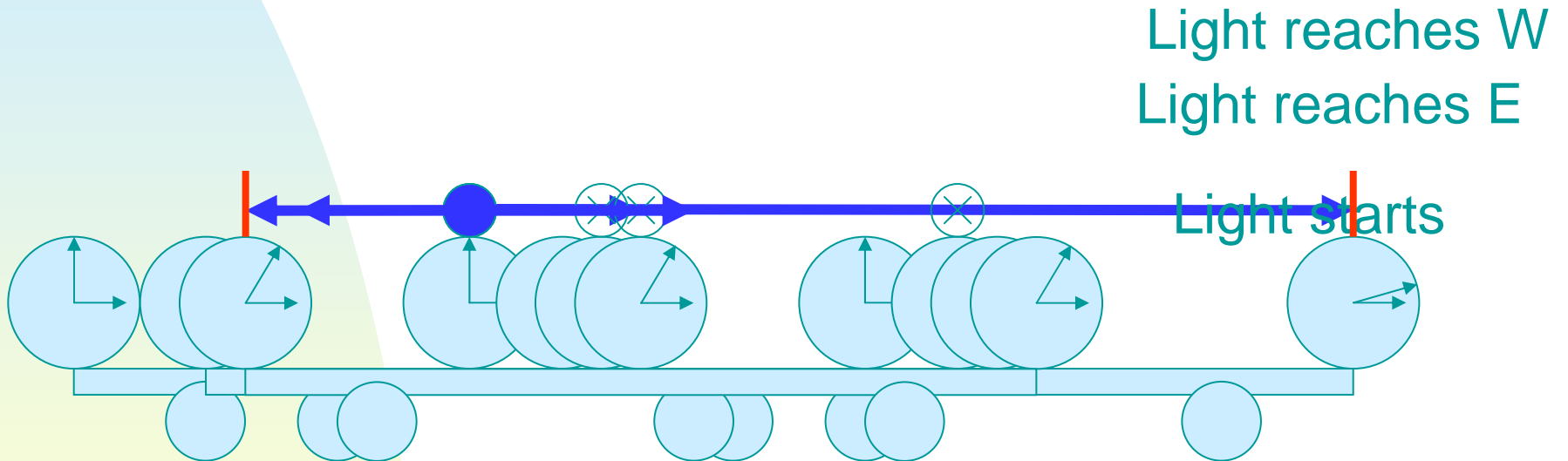
Simultaneity (I)

- If the clocks are at a distance, use a signal, a light signal to synchronize them
- You can take into account the delay by asking acknowledgement



Simultaneity (II)

- Now what if the clocks are on a moving train ?

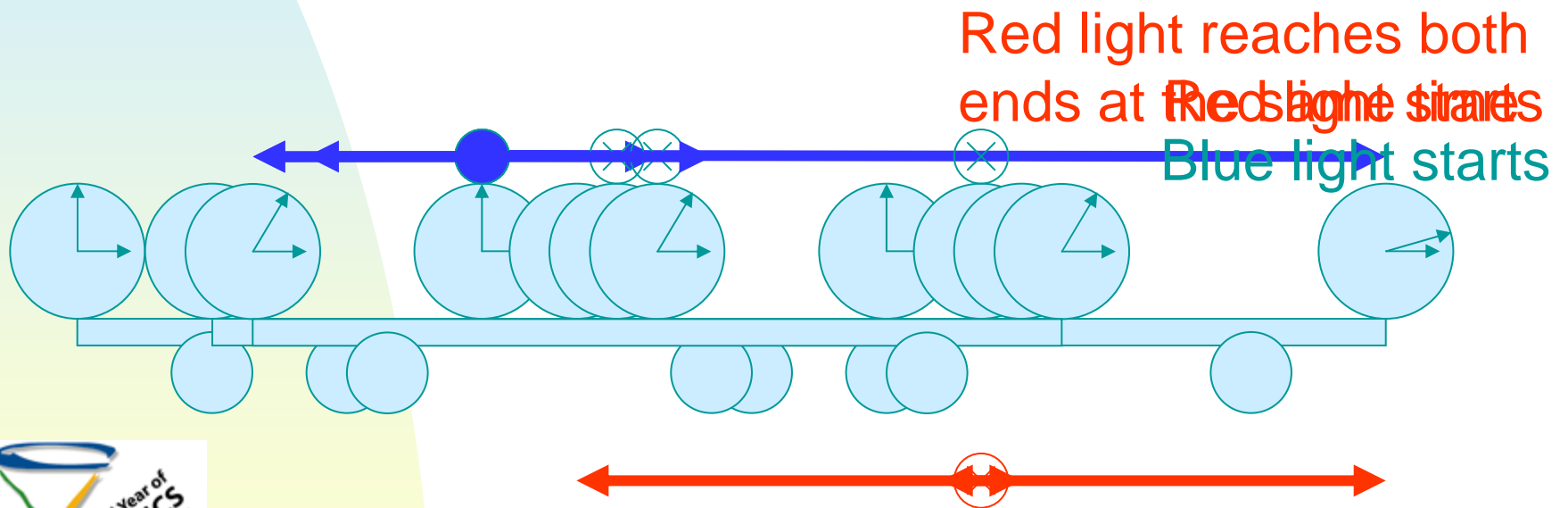


Simultaneity is lost for the observer off the train

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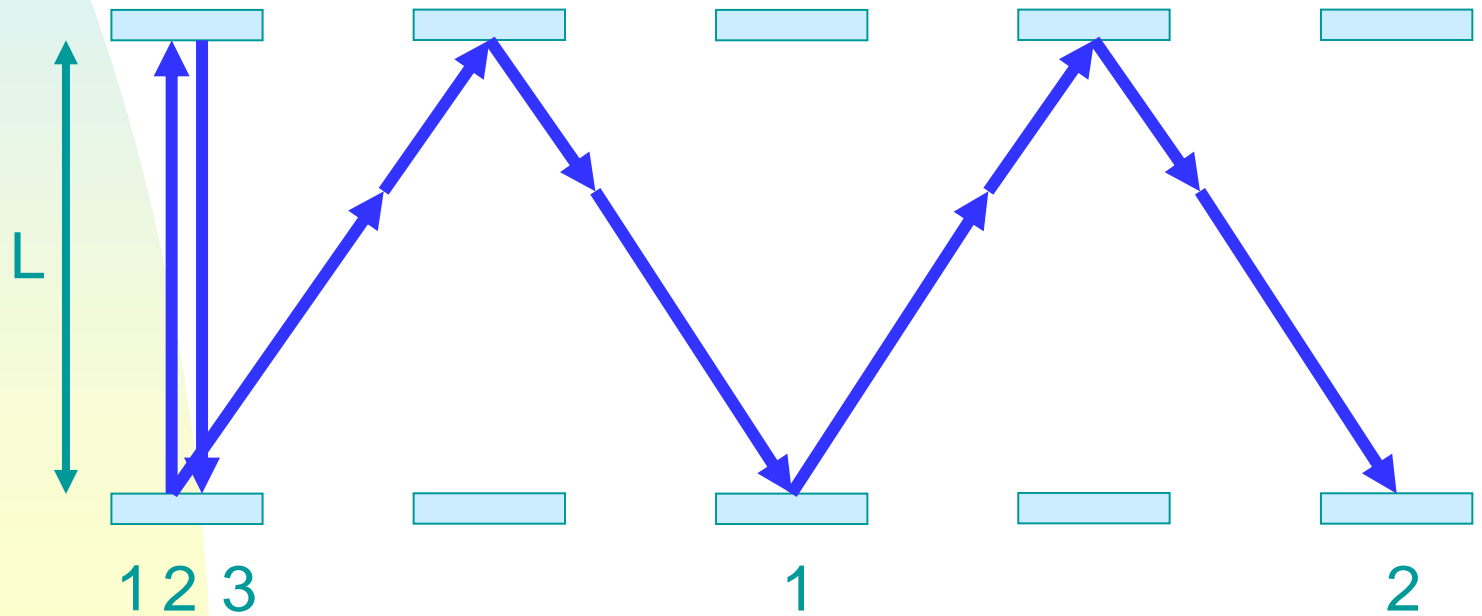
Simultaneity and length

- Can we measure the length of the moving train?
- Length must be measured using simultaneity



Time dilation

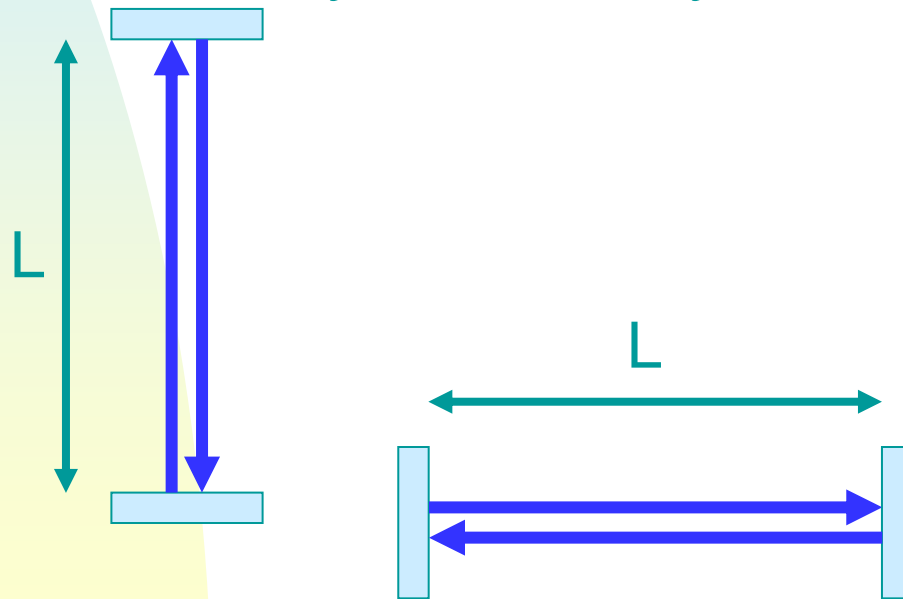
- What happens to a moving clock?



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The moving clock beats slower

Clocks in all directions

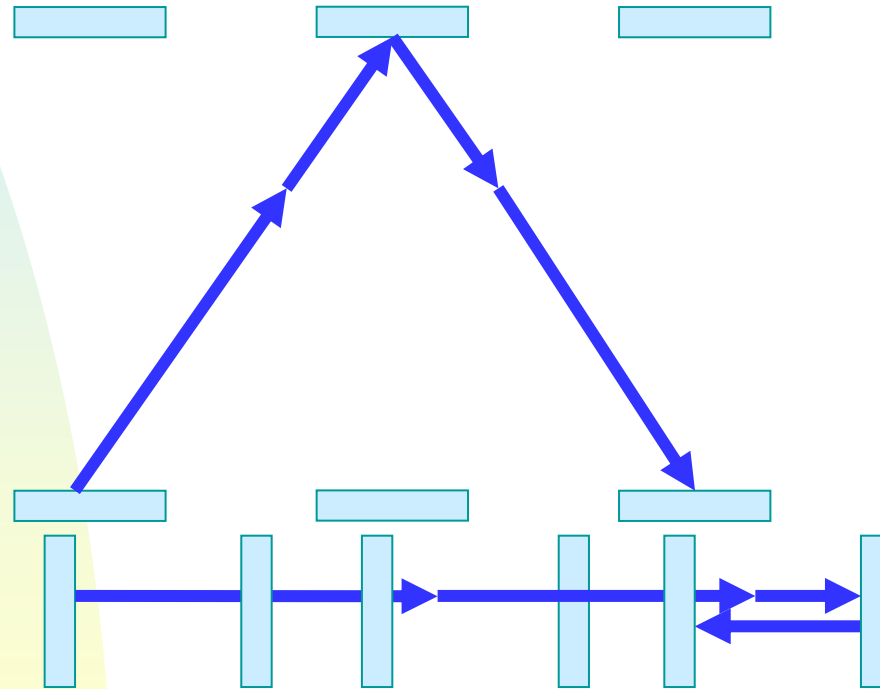
- From Relativity: cannot tell a preferred direction of motion
- Two clocks at rest beat synchronously



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What happens to the two moving clocks?

- Note how short the horizontal clock appears



They are synchronized after the round trip!

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Nature's conspiracy

- The vertical clock slows down
- The horizontal clock appears shorter
- The net result is that also the moving clocks are synchronized !
- By imposing a constant speed of light we see space and time changing
- Nature conspires to make us see a constant speed of light !



The spacetimestamp

- Light rules everything
- The speed of light connects space and time
- Light puts its stamp on each space time coordinate
- Light weaves space-time



Transformation of space and time

- Galileo

$$x = x' + Vt'$$

$$t = t'$$

- Lorentz

(almost)

$$\mathbf{x} \equiv \mathbf{x} \begin{pmatrix} \frac{V}{c} & \frac{V'}{c} \\ -\frac{ct'}{c} & ct' \end{pmatrix}$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{V^2}{c^2}}}$$

$$ct \equiv \gamma t \begin{pmatrix} \frac{V}{c} & \frac{V'}{c} \\ -\frac{ct'}{c} & ct' \end{pmatrix}$$



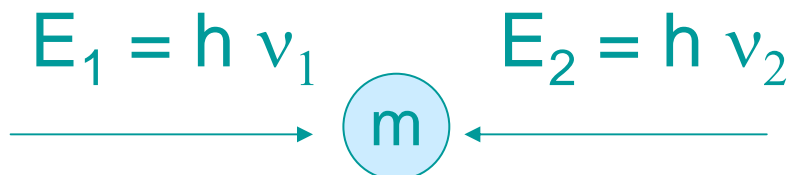
The Energy link

- The frequency at which light waves oscillate and the energy of the photons are related, said Einstein
- $E = h \nu$, h is the Planck constant
- Frequency is $1 / T$ so it is related to our clocks and how they transform



Mass, light and energy (I)

- Nowadays we know we can obtain matter from the collision of two photons
- Take photons with same energy and momentum
- We obtain a mass m at rest

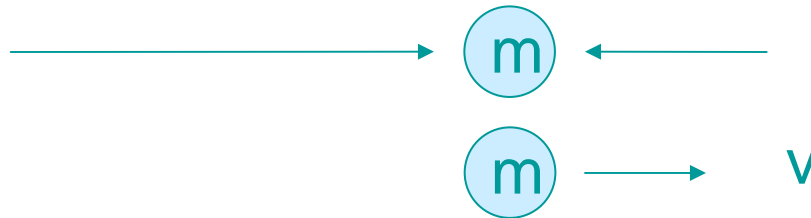


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Mass, light and energy (II)

- If an observer analyzes the same process moving at speed v

$$E'_1 = h \nu'_1 \quad E'_2 = h \nu'_2$$



- For small v the energy has to be
- $E = m c^2$
- and momentum $p = mv$



Mass, light and energy (App)

- Take a source that sends light pulses at frequency ν
- The rate the pulses are seen changes depending on the source and observer relative speed v
- Police car siren pitch changes when car comes towards us and then goes away
- We find taking into account time dilation



$$\nu' = \sqrt{\frac{1 + v/c}{1 - v/c}} \nu$$

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Is it really that way ?

- One hundred years of laws of physics have been written with speed of light hard wired in it
- This has become a “quality seal”
- (Bio)Chemistry is based on electromagnetism
- There is a unique description for electromagnetism and radioactivity: the electroweak force
- Atomic nuclei are described by the strong force, which has c wired in it



After 100 years : no way to fool Special Relativity...

- The standard model of particle physics introduces matter: electrons, quarks, neutrinos
- It introduces also exchange particles that convey the interactions: the photon, the vector bosons W and Z, the gluon
- Matter emits and absorbs continuously the exchange particles which are the generalization of light
- So wherever there is matter there is going to be the texture of space time, weaved by photons, gluons, W and Z



After 100 years : no way to fool Special Relativity...

- There is no way to escape predictions of Relativity
- No mechanical or radioactive clockwork escapes time dilation
- as space and time exist by light and matter and vacuum, which all obey Special Relativity





...but for gravitation

- What happens in presence of gravitation?
- What is uniform motion now ?
- Universality of free fall was known
- In a free falling train all objects fall in the same way and appear weightless
- Einstein equivalence principle: the free falling train is the place where Special Relativity holds and where the speed of light is constant

Speed of light is not constant?

- When including gravitation Einstein had to move from Special Relativity to General Relativity
- Speed of light is constant for an observer in free fall
- A non falling observer has to change once again his view of space and time:
- For him light doesn't go straight anymore!
- Pythagora has to go home, spacetime is curved
- This is General Relativity, you will meet it again in 2016



Do we care about Relativity?

- Global Positioning System
- Based on distances measured with light
- Need satellites with known position and known clock reference
- The satellites place spacetime stamp but they are instructed to tell us explicitly
- We get position and time by measuring the travel time of light
- Not including Relativity (Special and General) would give tens of kilometers of error after one day



Do we care about Relativity (II)

- $E = m c^2$ comes from Special Relativity when we discuss energy
- Antimatter and matter can annihilate producing only energy
- Positrons and electrons annihilate producing two photons
- Positron emission tomography:
- Two light quanta allow to reconstruct where the annihilation occurred
- This is used to see where some marked protein is being absorbed by sick cells.



Do we care about Relativity (III)

- Yesterday's discoveries are today's science and tomorrow's tools (or background)
- Projects for gravitational wave detection: a signal of the highest energy events present in the Universe
- Interferometers check in a very precise way the speed of light: signs of variation due to gravitation are what we are looking for



Relativity at work for science



- One of Einstein's predictions out of General Relativity is that gravitation has to carry its attraction message using waves
- These waves, coming from most catastrophic events happening in the sky, can be detected on Earth using Special Relativity

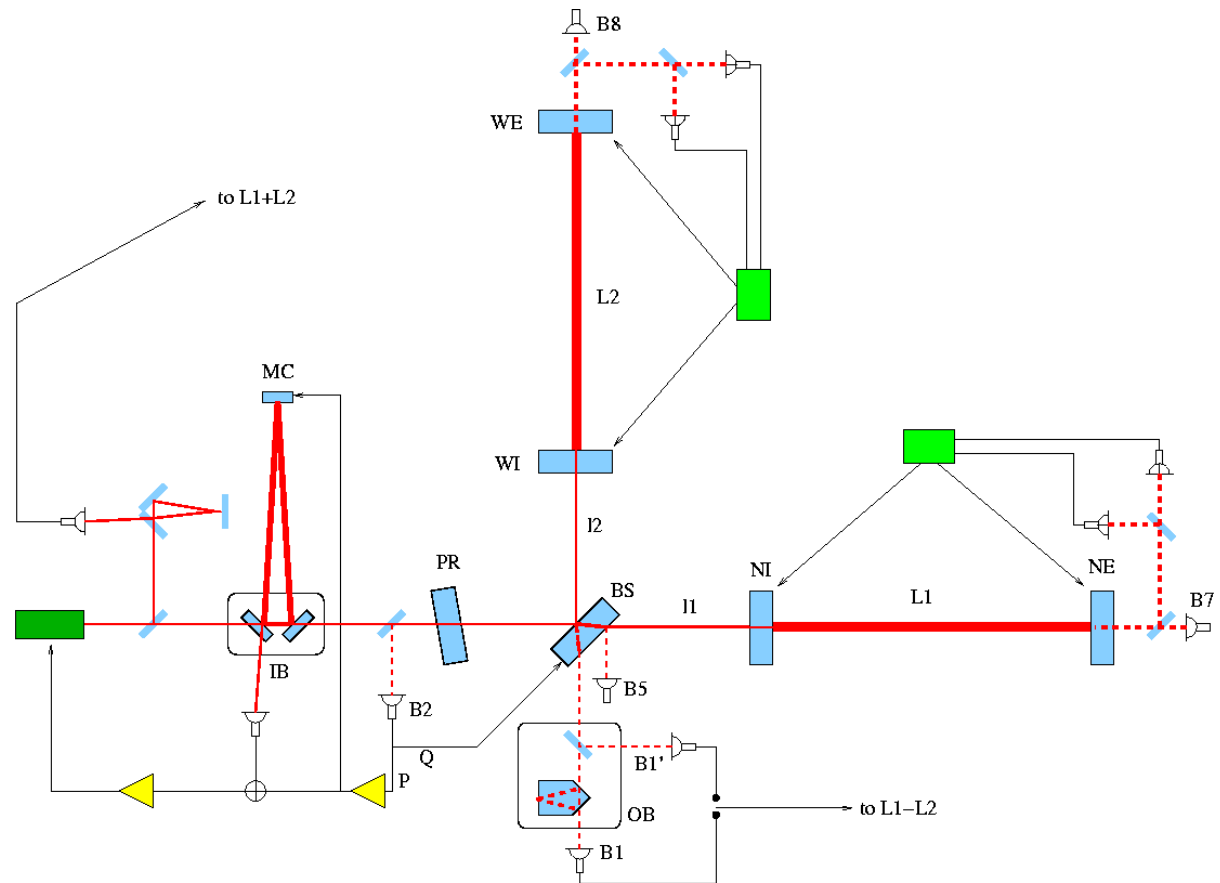
Gravitational wave detectors

- Repeat the experiment of the two clocks
- Detect lack of synchronization
- Incoming gravitational waves are changing spacetime
- By a tiny amount
- $1/1\,000\,000\,000\,000\,000\,000\,000$ (18 zeroes) meter



From our science meeting

- Here is a gw interferometer



Francesco Fidecaro

Lisa Barsotti Pisa





- Ligo in Livingston (LA) and Hanford (WA)
- Virgo (Pisa)

LIGO-Auriga (Padova)
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The noise fight

- The waves we are searching for could be heard
- Their frequency is comparable with the one of sounds we hear (20Hz-10 kHz)
- Mirror motion can mimick gravitational waves by changing the distance
- Light is used as a meter, if the meter elongates you get a wrong result
- Mirrors are suspended in vacuum to minimize this effects
- Brownian motion is there
- Photoelectric effect is there too

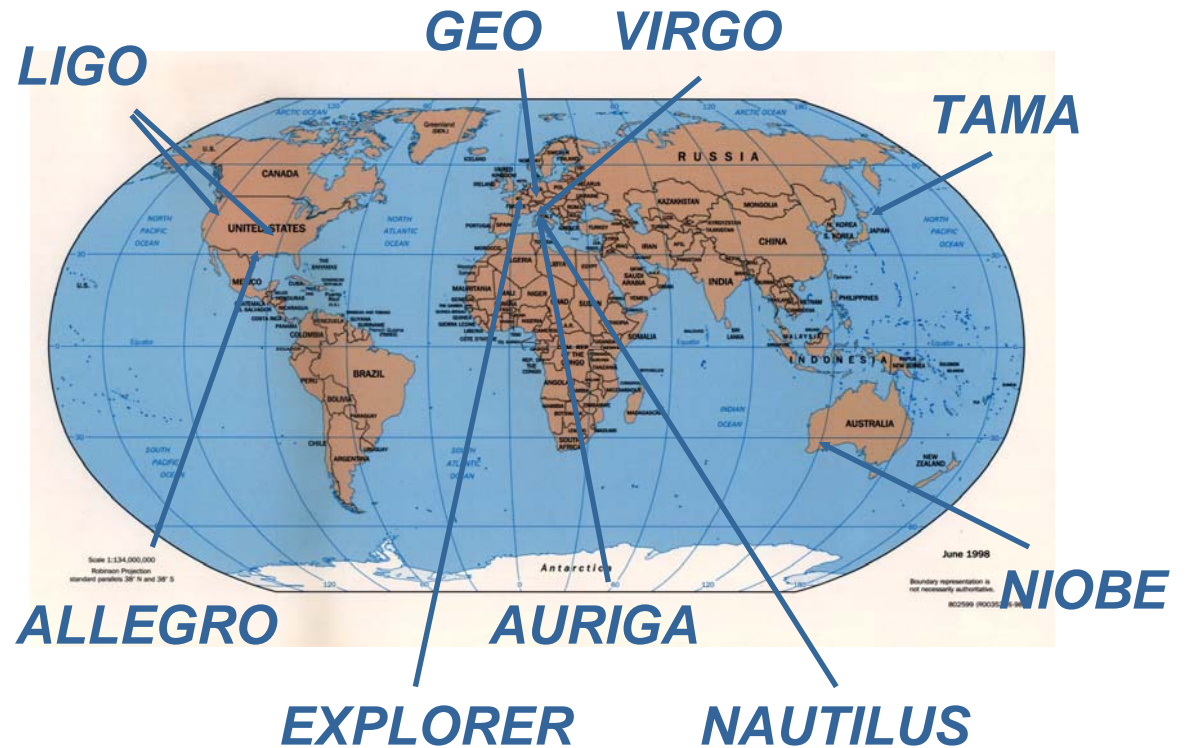


The noise fight parable

- Imagine the suspended mirror motion to be the sound level of a really heavy mechanics workshop (120 dB)
- Compare it with the tiniest sound you can hear (0 dB)
- Imagine that you have such a good ear that this tiniest sound is again the sound of a heavy mechanics workshop
- If you are able out of that noise to detect the tiniest sound you can hear this could be produced by gravitational waves



Collaborative Searches



Patrick Sutton LIGO lab



- Most confident detection and maximum exploitation of gravitational waves may come from cooperative analyses by the various observatories

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The future of spacetime

- Gravitational waves
- The mass mechanism: the Higgs boson
- Dark matter and energy
- Quantum gravity
- ...and all applications that come out of researchers ingenuity



1905 : miraculous year

- When the atomic nucleus was not discovered
- And the elementary electric charge not identified
- Albert Einstein elaborated in a single year
 - ◆ Special Relativity
 - ◆ Light Quanta
 - ◆ Brownian motion
- From there knowledge has increased at breathtaking pace, it has left the lab to enter daily life, it helps in comfort, health, communication and will continue to do so on tracks of Relativity



Thank you !



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