Special Theory of Relativity
Part I

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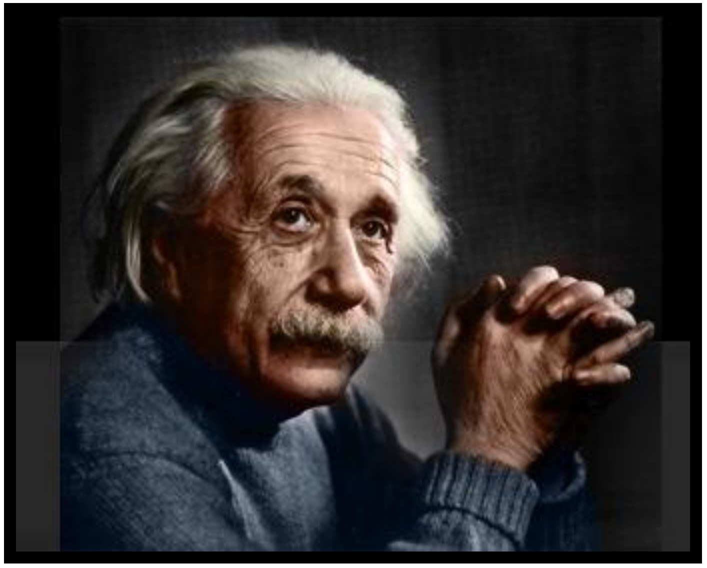
Theory of Relativity



Albert Einstein (1879 – 1955) : Nobel Prize, 1921

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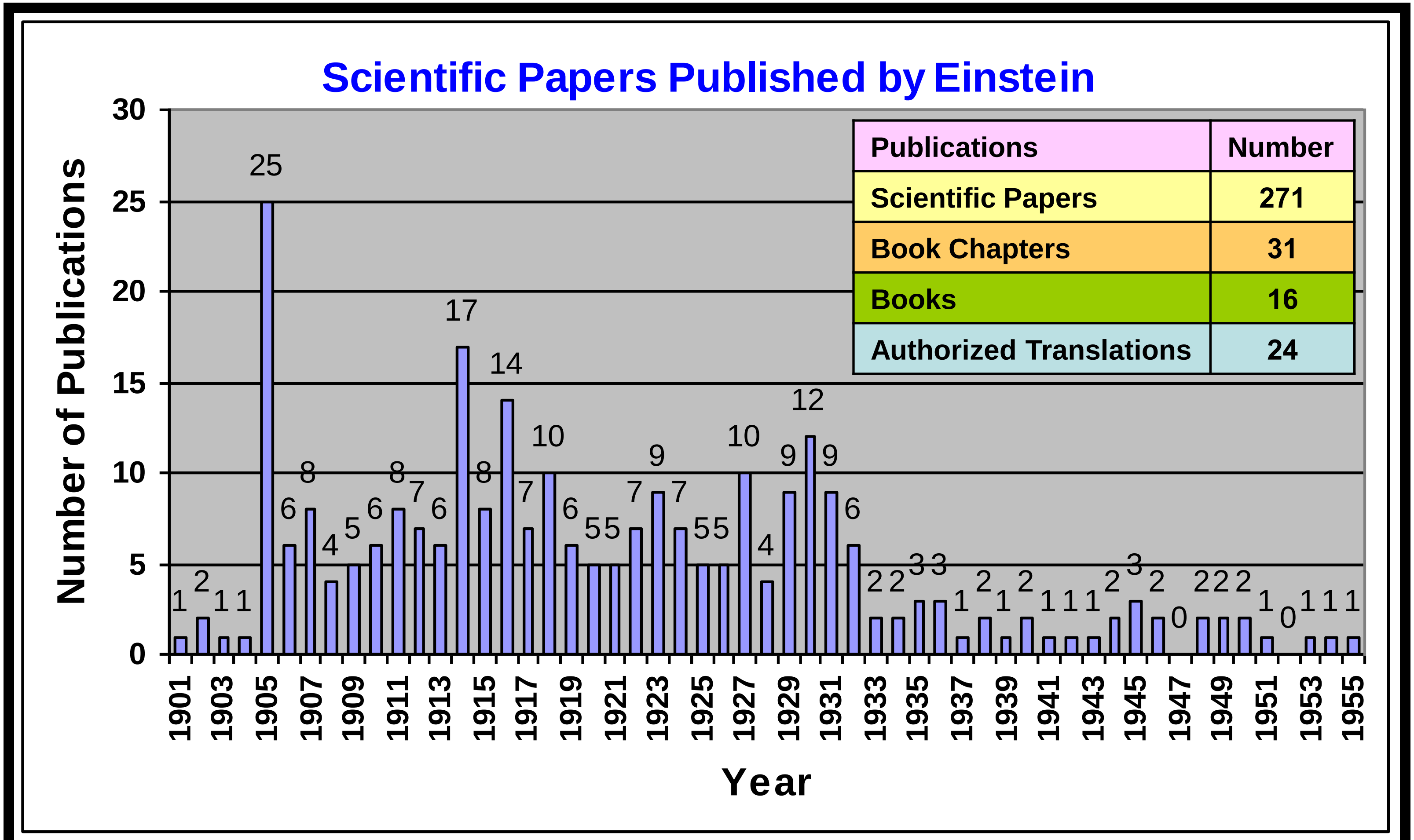
Einstein's Most Important Accomplishments

Albet Einstein (1879–1955) was a renowned theoretical physicist of the 20th century, best known for his theories of special relativity and general relativity. He also made important contributions to statistical mechanics, especially his treatment of Brownian motion, his resolution of the paradox of specific heats, and his connection of fluctuations and dissipation. Despite his reservations about its interpretation, Einstein also made influential contributions to quantum mechanics and, indirectly, quantum field theory, primarily through his theoretical studies of the photon.

Einstein's Publications



Publications	Number
Scientific Papers	271
Book Chapters	31
Books	16
Authorized Translations	24

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Review of Pre-Einstein Physics

- Newtonian Mechanics
- Electricity and Magnetism
- Electromagnetism
- Quantum Mechanics

Newtonian Mechanics (1)

- Kinetic Energy: $K = \frac{1}{2} m v^2$
- Potential Energy: $U = mgh$ (In a gravitational field)
- Linear Momentum: $\vec{p} = m\vec{v}$
- Mechanical Energy: $E = K + U$
- Mechanical Energy is conserved for conservative forces. (Example: Collisions)
- Linear Momentum is conserved (Example: Collisions)
- $\vec{F} = \frac{d\vec{p}}{dt}$ $\Rightarrow$ (Newton Laws)

Newtonian Mechanics (2)

- $F_x = -\dfrac{dU}{dx}$ (One dimension)

$$\int_i^f F_x dx = -\int_i^f dU \quad \Rightarrow \quad W = -\Delta U = \Delta K$$

or

$$W = \int_i^f F_x dx = \int_i^f m a\, dx = m\int_i^f \frac{dv}{dt} dx = m\int_i^f v\, dv = \frac{1}{2} m[v_f^2 - v_i^2]$$

$$= K_f - K_i = \Delta K$$

- Work-Energy Theorem $W = \Delta K$
- Angular Momentum $\vec{\ell} = \vec{r} \times \vec{p}$
- Angular Momentum is conserved

Electricity and Magnetism (1)

- Coulomb force: $F = \frac{1}{4\pi\varepsilon_\circ}\frac{q_1 q_2}{r^2}$
- Potential Energy: $U = \frac{1}{4\pi\varepsilon_\circ}\frac{q_1 q_2}{r}$
- $\vec{E}$ due to a point charge at distance r: $E = \frac{1}{4\pi\varepsilon_\circ}\frac{q}{r^2}$
  (In the raidal direction)
- Electric current I in a loop of radius r $\Rightarrow$ $B = \frac{\mu_\circ I}{2\pi r}$
  (At the center of the loop and perpendicular to it)
- ε_o= permittivity of empty space
- μ_o= permeability of empty space

Electricity and Magnetism (2)

- Magnetic Moment $\vec{\mu}$: $|\vec{\mu}| = I\,A$
  (A=area of the loop, $\vec{\mu}$ is perpendicular to the plane of the loop)
- Torque: $\vec{\tau} = \vec{\mu} \times \vec{B}_{ext}$
- Potential Energy: $U = -\vec{\mu} \cdot \vec{B}_{ext}$
- Electromagnetic waves
- EM waves travel at $c = \lambda\,\nu$, c = velocity of light, λ is the wavelength, ν is the frequency.
- $c = \dfrac{1}{\sqrt{\varepsilon_\circ \mu_\circ}}$ = constant = 2.99792458 x 10^8 m/s
  (Predicted by Maxwell)

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Electromagnetism (1)

- **Maxwell Equations:**

  - **Integral Form:**

Gauss's Law: $$\oint_s \vec{E}\cdot d\vec{s} = \frac{q_{in}}{\varepsilon_\circ} \quad (1)$$

Gauss's Law of magnetism: $$\oint_s \vec{B}\cdot d\vec{s} = 0 \quad (2)$$

Faraday's Law if Induction: $$\oint_s \vec{E}\cdot d\vec{\ell} = -\oint \frac{\partial \vec{B}}{\partial t}\cdot d\vec{s} \quad (3)$$

Ampere's Law: $$\oint_s \vec{B}\cdot d\vec{\ell} = \mu_\circ I + \mu_o \varepsilon_o \oint \frac{\partial \vec{E}}{\partial t}\cdot d\vec{s} \quad (4)$$

Electromagnetism (2)

- **Maxwell Equations:**

  - **Differential Form:**

Gauss's Law: $$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_\circ} \qquad (1)$$

Gauss's Law of magnetism: $$\vec{\nabla} \cdot \vec{B} = 0 \qquad (2)$$

Faraday's Law if Induction: $$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad (3)$$

Ampere's Law: $$\vec{\nabla} \times \vec{B} = \mu_\circ \vec{J} + \mu_o \varepsilon_o \frac{\partial \vec{E}}{\partial t} \qquad (4)$$

Electromagnetism (3)

- **Maxwell Equations:**

  - **Gaussian Units Form:**

Gauss's Law: $$\vec{\nabla}\cdot\vec{E} = 4\pi\rho \qquad (1)$$

Gauss's Law of magnetism: $$\vec{\nabla}\cdot\vec{B} = 0 \qquad (2)$$

Faraday's Law if Induction: $$\vec{\nabla}\times\vec{E} = -\frac{1}{c}\frac{\partial\vec{B}}{\partial t} \qquad (3)$$

Ampere's Law: $$\vec{\nabla}\times\vec{B} = \frac{4\pi}{c}\vec{J} + \frac{1}{c}\frac{\partial\vec{E}}{\partial t} \qquad (4)$$

Solution to Maxwell's Equations (1)

- **In free space (J=0, ρ=0):**
  - **Take 1, curl it, getting 2.**
  - **Substitute 3, identity 4, and 5**
  - **Obtain result**

$$1.\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$2.\nabla \times \left(\nabla \times \vec{E}\right) = -\frac{\partial\left(\nabla \times \vec{B}\right)}{\partial t}$$

$$3.\nabla \times \vec{B} = \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}$$

$$4.\nabla \times \left(\nabla \times \vec{E}\right) = \nabla\left(\nabla \cdot \vec{E}\right) - \nabla^2 \vec{E}$$

$$5.\nabla \cdot \vec{E} = 0$$

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

  - **Result is a wave equation, saying electric field can propagate at speed c where:**

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

Solution to Maxwell's Equations (2)

- **Similarly,** $\nabla^2 \vec{B} = \mu_0 \varepsilon_0 \dfrac{\partial^2 \vec{B}}{\partial t^2}$
- **Both** $\nabla^2 \vec{E} = \mu_0 \varepsilon_0 \dfrac{\partial^2 \vec{E}}{\partial t^2}$ **and** $\nabla^2 \vec{B} = \mu_0 \varepsilon_0 \dfrac{\partial^2 \vec{B}}{\partial t^2}$

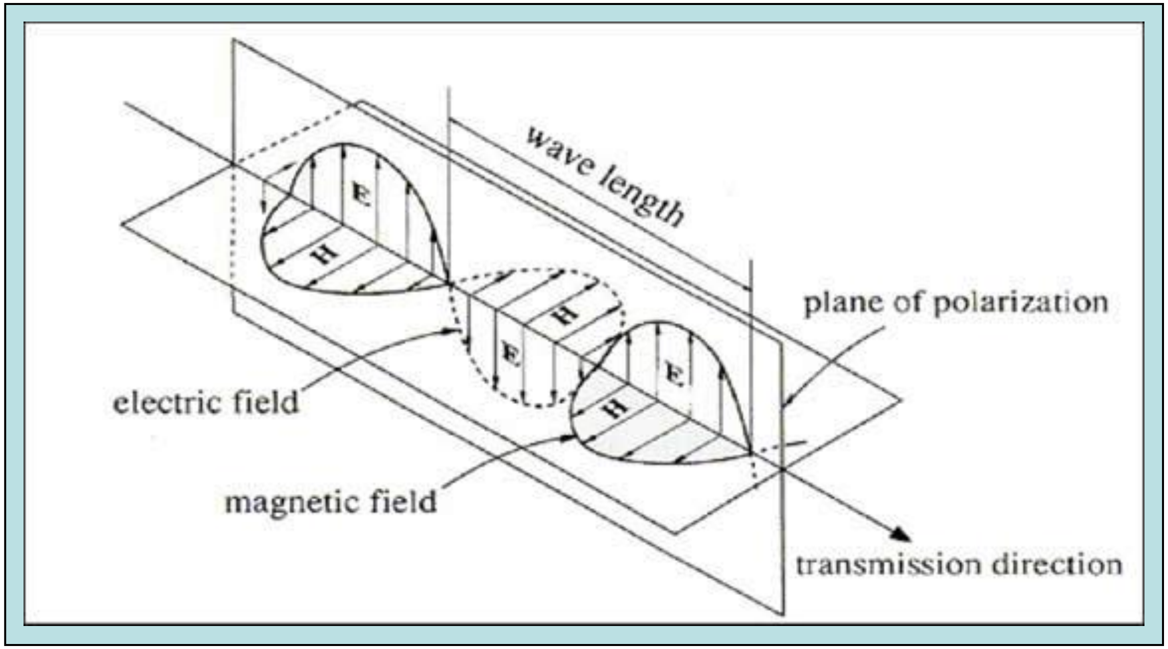
are equations of a wave traveling at the speed

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 299\,792\,458\ \mathrm{m/s}$$

- **Matches speed of light!**
  - **Based on this, Maxwell predicted that light is an electromagnetic wave.**

Consequences of Maxwell Equations

- **Electromagnetic waves travel at** $c = \dfrac{1}{\sqrt{\mu_0 \varepsilon_0}}$
- **Does not depend on speed of emitter!**



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Quantum Theory (1)

- Old Quantum Theory of Planck and Bohr
- Quantum Mechanics of Schrödinger
- Quantum Field Theory
  - Quantum Electrodynamics
  - Relativistic Field Theory
- Quantum Gravity $\Rightarrow$ General Relativity
- Quantum Optics $\Rightarrow$ Quantum Electronics (Lasers)
- Quantum Theory developed in parallel with Relativity

Timeline of Development of Quantum Theory

1900:
- Max Planck proposed theory about black-body radiation

1905:
- Albert Einstein wrote the paper, "*On a Heuristic Viewpoint Concerning the Production and Transformation of Light*"; proposed the idea of energy quanta dealing with the photoelectric effect.

1913:
- Neils Bohr proposed atomic structure theory

1918:
- Max Planck won Nobel prize in physics

1921:
- Einstein Won the Nobel Prize in Physics for his discovery and explanation of the law of the photoelectric effect.

1922:
- Neils Bohr won Nobel Prize in physics
- Stern-Gerlach Experiment (Verified the space quantization theory)

1924:
- Louis De Broglie published his doctoral thesis, "*Recherches sur la théorie des quanta*", which introduced his theory of electron waves.

1925:
- Heisenberg developed the Heisenberg Uncertainty principle
- Wolfgang Pauli developed the fourth quantum number- the spin number

1929:
Louis De Broglie won the Nobel Prize in Physics for hypothesis.

1932:
- Werner Heisenberg won Nobel Prize in physics

1933:
- Otto Stern measures the magnetic moment of the proton
- Schrodinger wins Nobel prize for his Schrodinger Equation

1936:
Publishes paper on Wave Mechanics and Schrödinger's Equation

1940:
Pauli proves Spin-Statistic Theorem

1943:
- Otto Stern receives Nobel prize in Physics

1944:
- Wolfgang Pauli won Nobel Prize in physics

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Erwin Schrödinger

- In 1926, at the University of Zurich, published a series of 4 papers
  - Wave Mechanics & Schrödinger's Equation
  - Solved Quantum Harmonic Oscillation, the Rigid rotor, diatomic molecules and rederived his equation
  - Compared his approaches to Heisenberg
  - Showed how to work with time

Schrödinger's Equation

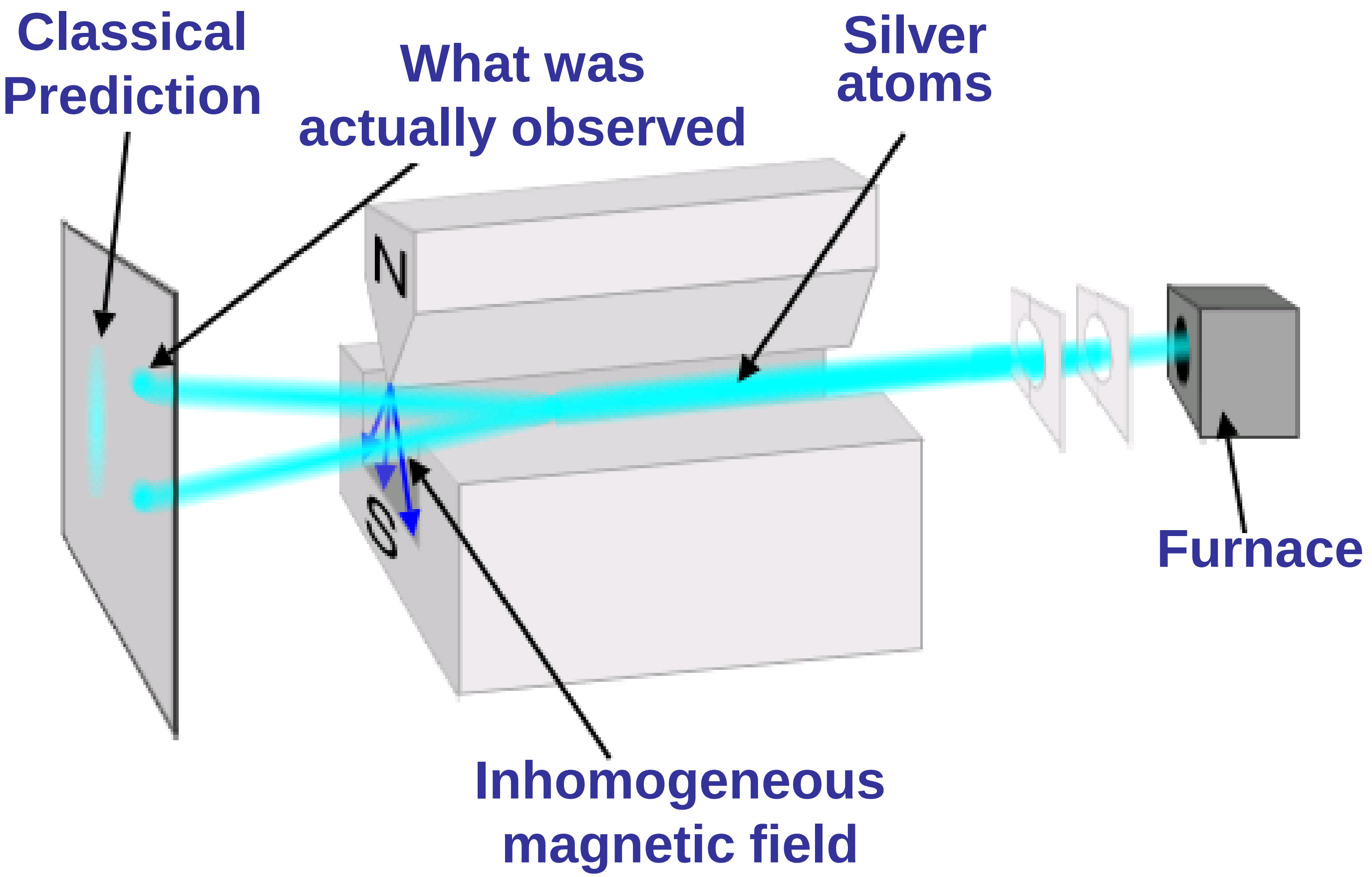
- While this appears to be a rather complicated equation, it is $H(t)\left|\psi(t)\right\rangle = i\hbar\frac{\partial}{\partial t}\left|\psi(t)\right\rangle$
- $\left|\psi(t)\right\rangle$ means at time *t*
- *i* is the square root of –1
- $\hbar$ Planck's constant divided by 2π
- $\partial/\partial t$ Derivative with respect to time
- ψ(*t*) = Wave Function
- H(t) = Quantum Hamiltonian

Otto Stern & Walter Gerlach

- Otto Stern and Walter Gerlach are famous for their Stern-Gerlach experiment, in which they shot a beam of silver atoms through a non-uniform magnetic field, showing that the atomic levels split into only 2 bands

- This verified the space quantization theory, and tested whether particles had intrinsic angular momentum

Stern-Gerlach Experiment



More on Otto Stern

- **Developed Molecular Ray Method**
- **Demonstrated the wave nature of atoms and molecules**
- **Measured atomic magnetic moments**
- **Corrected the proton’s magnetic moment**
- **Nobel Prize in Physics in 1943**

Werner Heisenberg

- Won Nobel Prize in 1932 in Physics "for the creation of quantum mechanics, the application of which has led to the discovery of all isotopic forms of hydrogen".
- Heisenberg pointed out that it is impossible to know both the exact position and the exact momentum of an object at the same time.
- This concept is called *Heisenberg Uncertainty principle.* Any electron that is subjected to photons will have its momentum and position affected.

Wolfgang Ernst Pauli

- Nobel Prize in Physics in 1945.
- The exclusion principle *(No two electrons exist in the same quantum state)* provided the reason for electrons in atoms being arranged in shells with the maximum number of electrons being 2, 8, 18, 32… etc, from the first to the nth shell.
- This principle explains why matter occupies space exclusively for itself and does not allow other material objects to pass through it and at the same time allowing lights and radiations to pass. It states that no two identical *fermions* may occupy the same quantum state *simultaneously*.

Max Planck and
Black Body Radiation

- Emission of light from hot objects (objects appear black before heating)
- How does the intensity of the electromagnetic radiation emitted by a black body depend on the frequency of the radiation and the temperature of the body?
- Interpolated between the laws of Wien and Rayleigh-Jeans
- Assumed that energy exists in individual units (discrete bundles)

Planck's Contributions

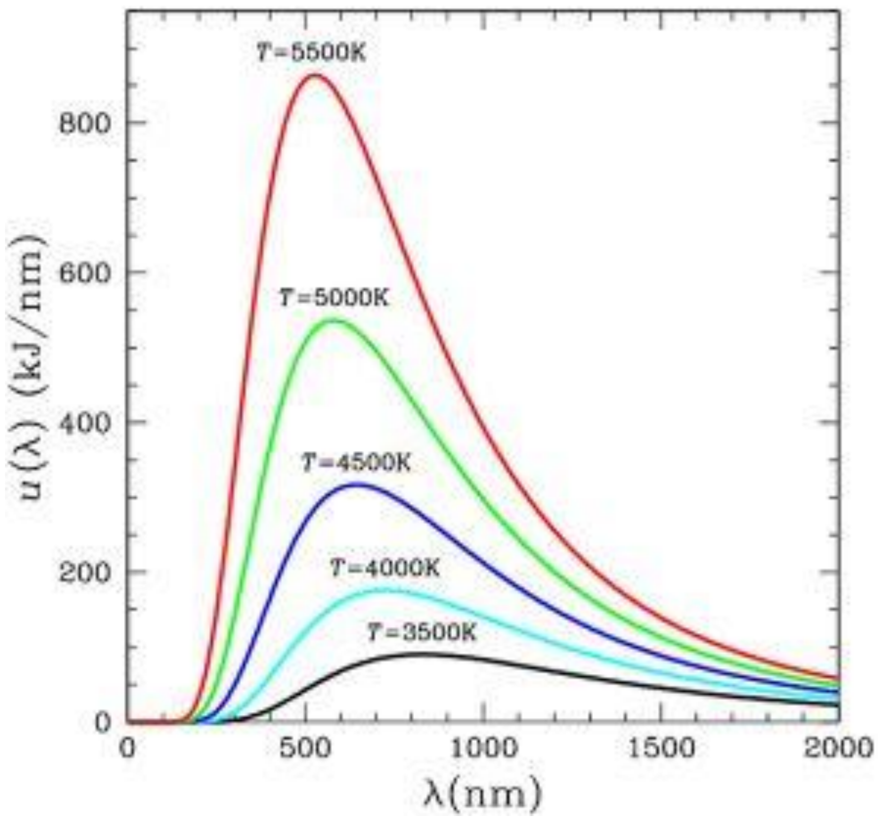
- **Formula predicts the spectral intensity of electromagnetic radiation at all wavelengths from a black body at temperature T**

$$I(\nu, T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

- ***h*** **is Planck's constant which is measured to be 6.63x 10-34 J.s**
- **Energy is always emitted or absorbed as a whole number multiple of h (2*hv*, 3*hv*…)**

Planck Distribution

- **Later simplified this to $E = h\nu$ in which E is energy, h is Planck's constant, and ν is frequency.**

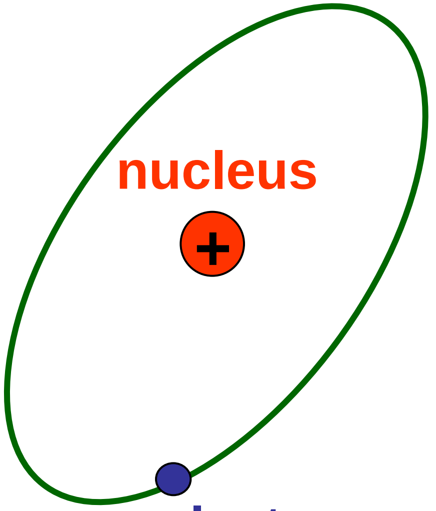


Neils Bohr

- **Introduced his concepts by borrowing ideas from quantum physics (Max Planck) in 1913.**
- **Presented a model of atomic structure that still stands true today.**
- **Started by assuming that electrons move in circular orbits around the nucleus.**
- **Determined that chemical properties of an element are determined by the number of electrons in its outer shell.**

More on Bohr

- Introduced the Idea that an electron can drop from a higher-energy level to a lower one, emitting a photon.
- Also determined that:
  - Electron exists a certain distance from the nucleus.
  - Electrons have circular orbits.
  - No energy is given off if an electron stays in one location.
- Received Nobel prize in 1922 for physics.



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Prince Louis-Victor de Broglie

- **Won the Nobel Prize in Physics in 1929.**
- **Broglie stated that all matter has a wave-like nature.**
- **Created a new field in physics, called wave mechanics, uniting the physics of light and matter.**

Broglie's Equation

$$\lambda = \frac{h}{p} = \frac{h}{mv}\sqrt{1 - \frac{v^2}{c^2}}$$

λ= the particle's wavelength

***h*= Planck's constant**

p= the particle's momentum

m= the particle's rest mass

v= the particle's velocity

c= the speed of light in a vacuum

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More on de Broglie

$$\lambda = \frac{h}{p} = \frac{h}{mv}\sqrt{1 - \frac{v^2}{c^2}}$$

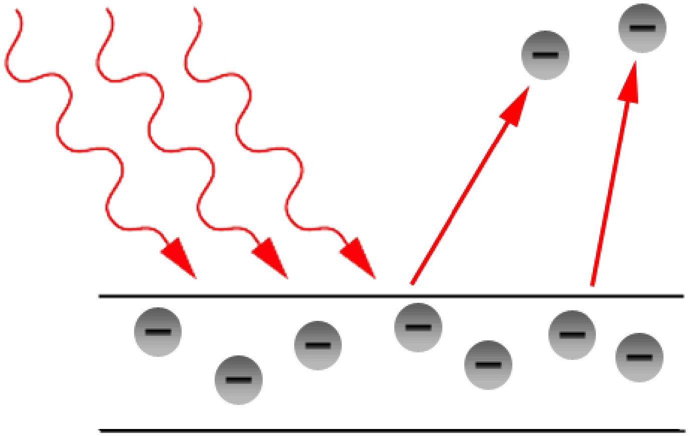
- **Equation used to describe the wave properties of matter, specifically, the wave nature of the electron.**
- **The de Broglie relation shows that the wavelength is inversely proportional to the momentum of a particle and that the frequency is directly proportional to the kinetic energy of the particle.**

Albert Einstein

- Won the Nobel Prize in Physics in 1905 for his work on Theory of Relativity.
- Won the Nobel Prize in Physics in 1921 for his discovery and explanation of photoelectric effect.
- Widely regarded as one of the greatest physicists of all time.
- Formulated the theory of relativity and made significant contributions to quantum mechanics and statistical mechanics.

The Photoelectric Effect

- **The photoelectric effect is the emission of electrons from matter upon the absorption of electromagnetic radiation, such as ultraviolet radiation or x-rays.**



The Photoelectric Effect

- The photoelectric effect can be modeled by the equation:

$$E_K = h\,\nu - W$$

E_K = maximal kinetic energy of an emitted electron.

h = Planck constant (6.626×10^{-34} J.s)

ν = frequency

W = work function (the energy required to free an electron from the material)

Summary

- **All of these men are interrelated in their discoveries; some proved the discoveries of others, others borrowed ideas and concepts.**

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Pre-Einstein Relativity

- Galilean transformation
- Newtonian Principle of Relativity

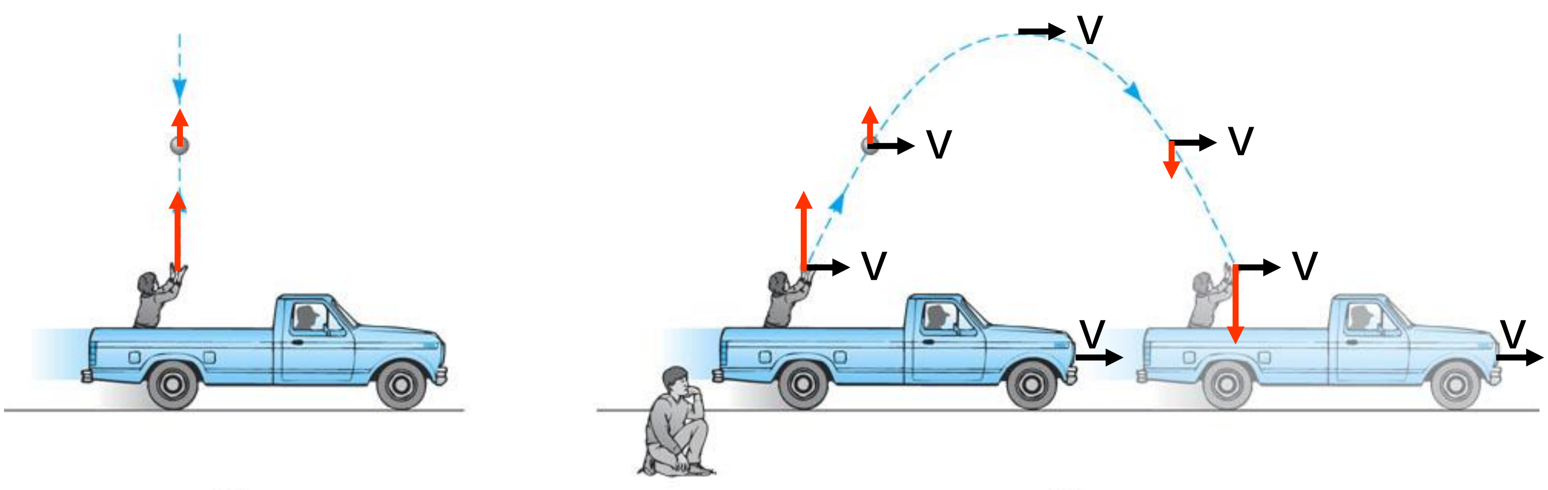
- **Newtonian-Galilean Theory of Relativity is known as "Classical Theory".**
- **Einstein's Special Theory of Relativity is known as "Modern Theory".**

The Principle of Newtonian Relativity

All laws of mechanics must be the same in all inertial frames of reference

Illustration

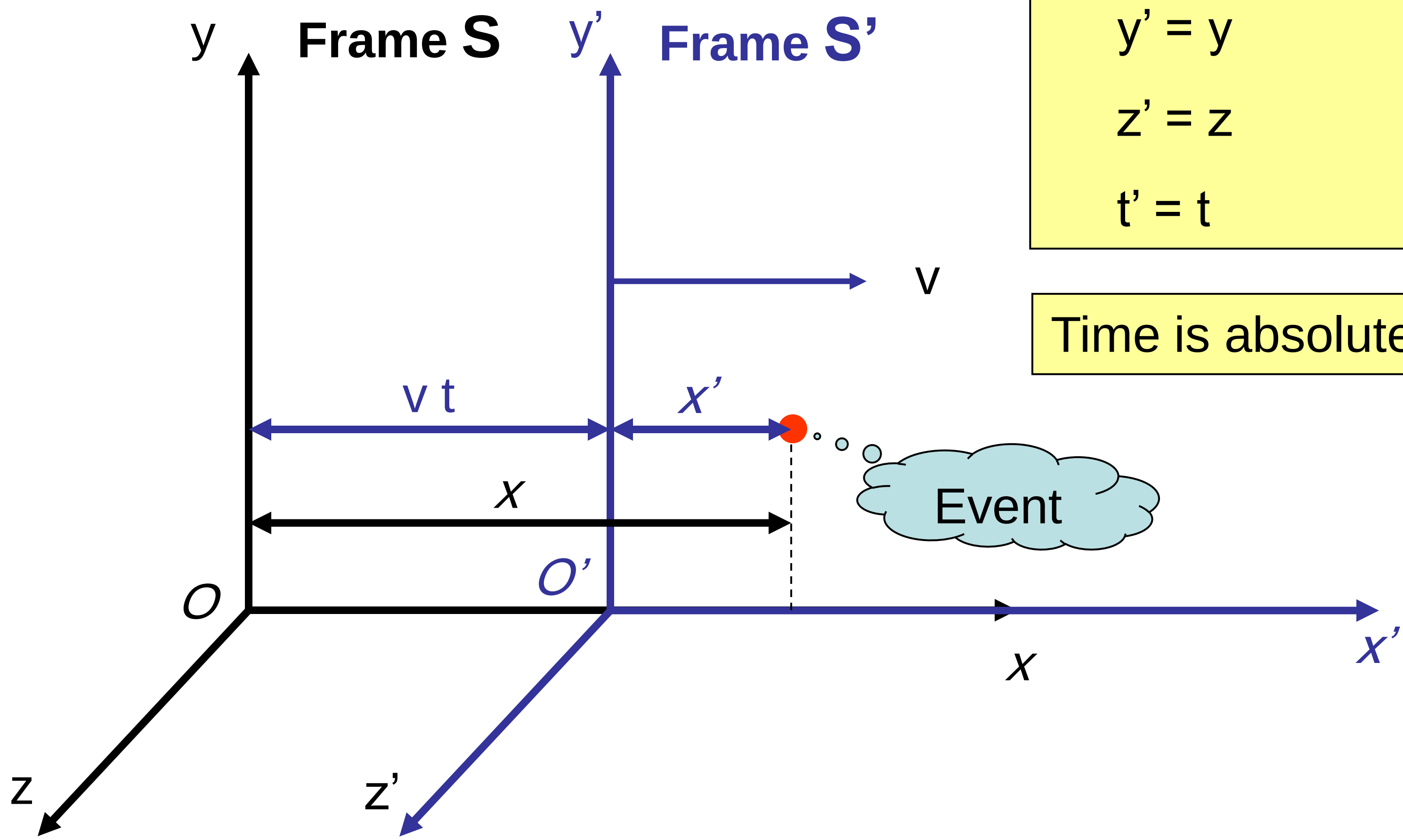
Experiment at rest **Experiment in moving frame**



Same result. Ball rises and ends up in the thrower's hand. Ball in the air the same length of time.

Experiment looks different from ground observer (parabolic trajectory, speed as a function of time) and observer on the truck. However, they both agree on the validity of Newton's laws.

Galilean Transformation



$$x' = x - v\,t$$

$$y' = y$$

$$z' = z$$

$$t' = t$$

Time is absolute

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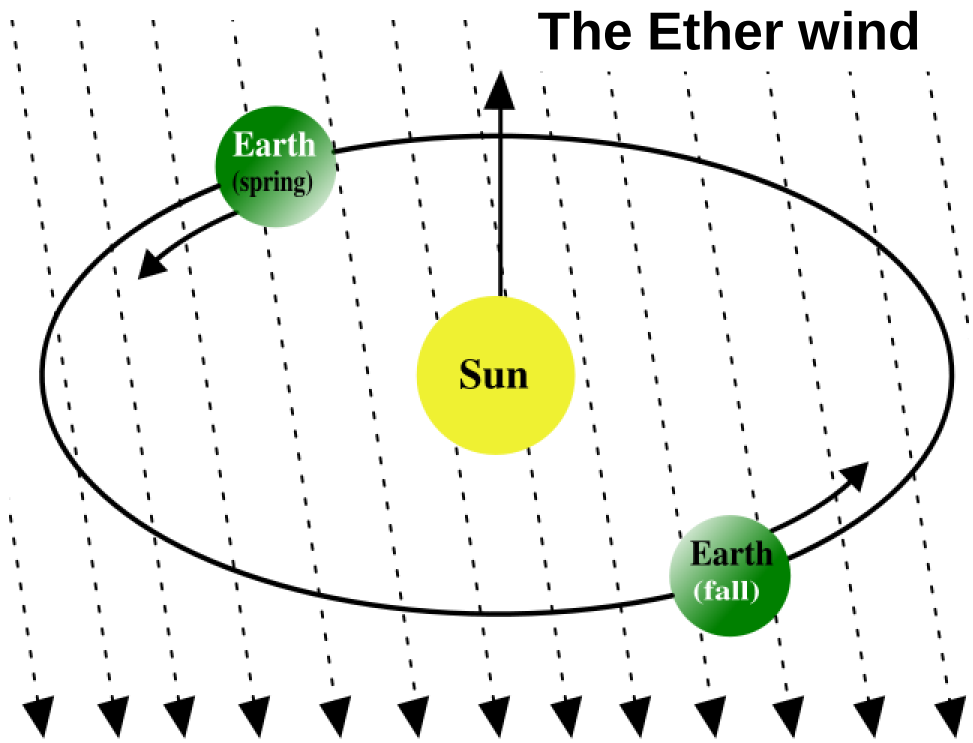
Follow up on Maxwell Findings

- Light is a wave
- Waves require a medium through which to propagate.
- The medium is called “Ether” (from the Greek word Aither, meaning upper air).
- Maxwell equations assume that light obeys the Newtonian-Galilean transformation.

The Ether Hypothesis

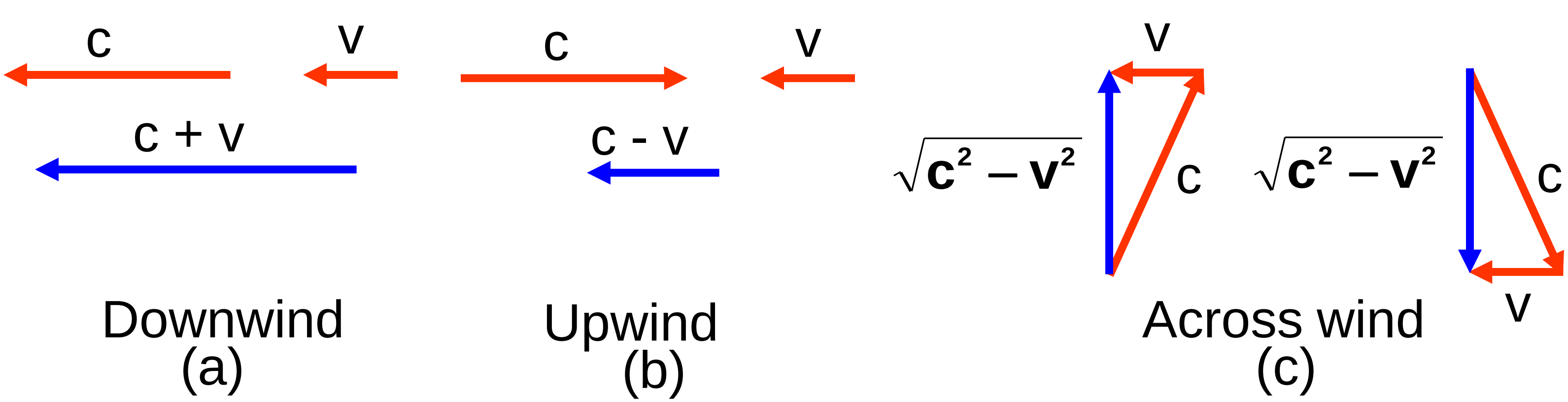


The Ether: it was hypothesized that the Earth moves through a "medium" of Ether that fills the Universe and carries light in an absolute frame at rest relative to Ether

The Ether Hypothesis

If the velocity of the ether wind relative to earth is v and the velocity of light relative to ether is c, then the speed of light relative to earth is:

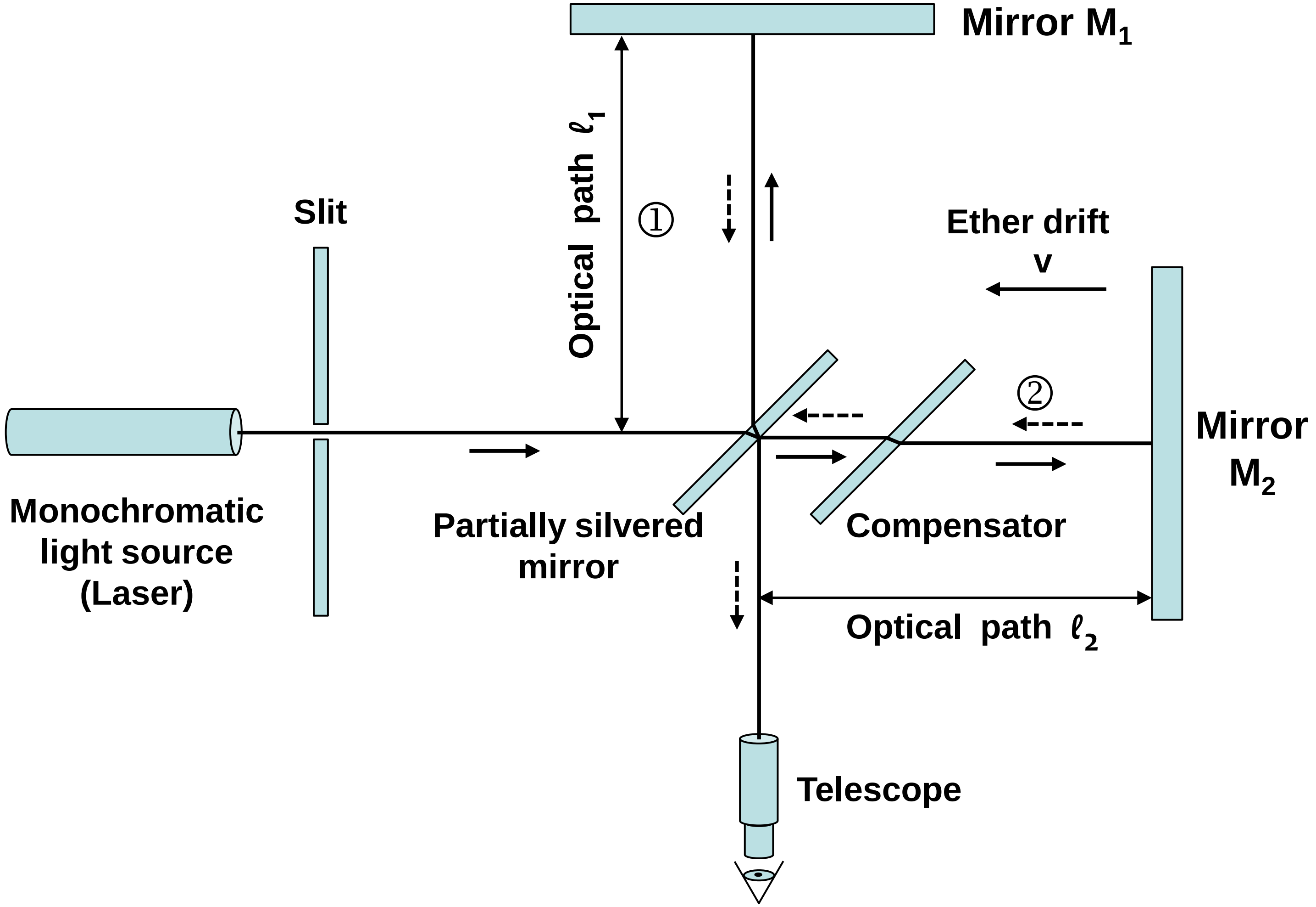
(a) c + v in the downwind direction, (b) c – v in the upwind direction, and (c) (c2 –v2)$^{1/2}$ in the direction perpendicular to the wind.



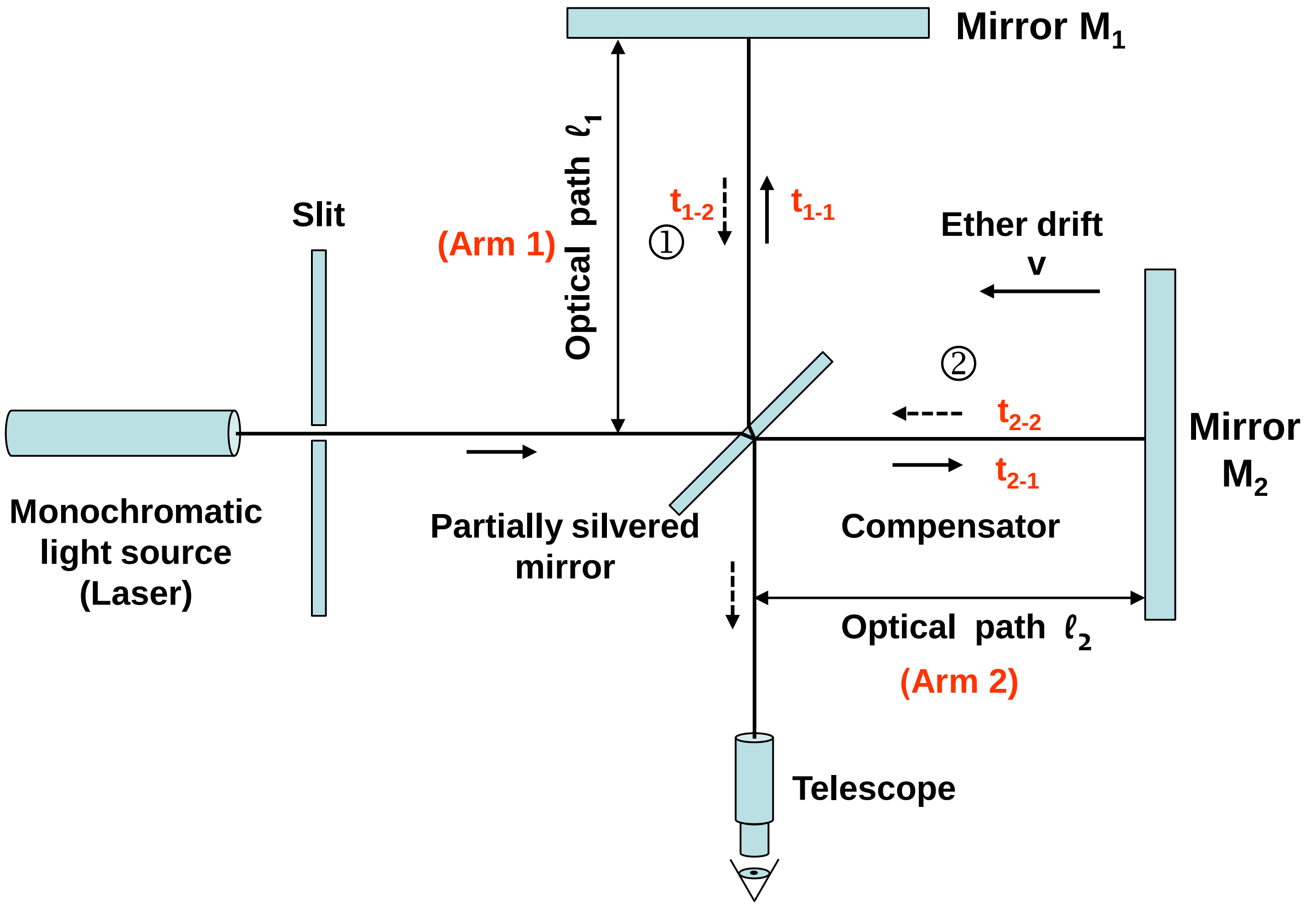
The Ether Hypothesis
Michelson-Morley Experiment

- **The experiment was designed to measure small changes in the speed of light. It was performed by Albert A. Michelson (1852-1931, Nobel) and Edward W. Morley (1838-1923).**
- **They used an optical instrument called an *interferometer* that Michelson invented.**
- **The experiment was designed to detect the presence of Ether.**
- **The outcome of the experiment was negative, thus contradicting the Ether hypothesis.**
- **A.A. Michelson and E.W. Morley, *American J. of Science*, 34, 333 (1887).**

The Ether Hypothesis
Michelson-Morley Experiment



The Ether Hypothesis
Michelson-Morley Experiment



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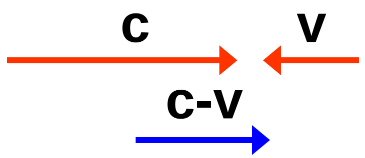
The Ether Hypothesis
Michelson-Morley Experiment

Calculate the path difference between Arms 1 and Arm 2

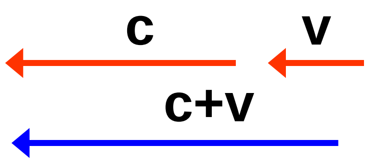
Arm 2:

$t_{2\text{-}1}$ = time needed for the beam approaching mirror 2



$$\boxed{t_{2-1} = \frac{\ell_2}{c - v}}$$

$t_{2\text{-}2}$ = time needed for the beam when reflected from mirror 2



$$\boxed{t_{2-2} = \frac{\ell_2}{c + v}}$$

t_2 = total time for optical path 2

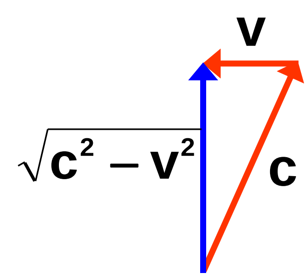
$$\boxed{t_2 = \frac{\ell_2}{c - v} + \frac{\ell_2}{c + v} = \frac{2\ell_2 c}{c^2 - v^2} = \frac{2\ell_2}{c\left(1 - \frac{v^2}{c^2}\right)} = \frac{2\ell_2}{c}\left(1 - \frac{v^2}{c^2}\right)^{-1}}$$

The Ether Hypothesis
Michelson-Morley Experiment

Calculate the path difference between Arms 1 and Arm 2

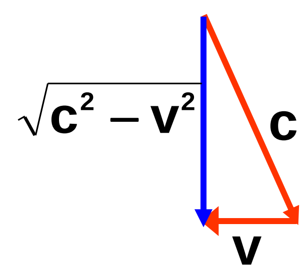
Arm 1:

$t_{1\text{-}1}$ = time needed for the beam approaching mirror 1



$$\boxed{t_{1-1} = \frac{\ell_1}{\sqrt{c^2 - v^2}}}$$

$t_{1\text{-}2}$ = time needed for the beam when reflected from mirror 1



$$\boxed{t_{1-2} = \frac{\ell_1}{\sqrt{c^2 - v^2}}}$$

t_1 = total time for optical path 1

$$\boxed{t_1 = \frac{\ell_1}{\sqrt{c^2 - v^2}} + \frac{\ell_1}{\sqrt{c^2 - v^2}} = \frac{2\ell_1}{\sqrt{c^2 - v^2}} = \frac{2\ell_2}{c\left(1 - \frac{v^2}{c^2}\right)^{\frac{1}{2}}} = \frac{2\ell_1}{c}\left(1 - \frac{v^2}{c^2}\right)^{-\frac{1}{2}}}$$

The Ether Hypothesis
Michelson-Morley Experiment

The time difference between the horizontal round trip (slide 56) and the vertical round trip (slide 57) is:

$$\Delta t = t_2 - t_1 = \frac{2\ell_2}{c}\left(1-\frac{v^2}{c^2}\right)^{-1} - \frac{2\ell_1}{c}\left(1-\frac{v^2}{c^2}\right)^{-\frac{1}{2}}$$

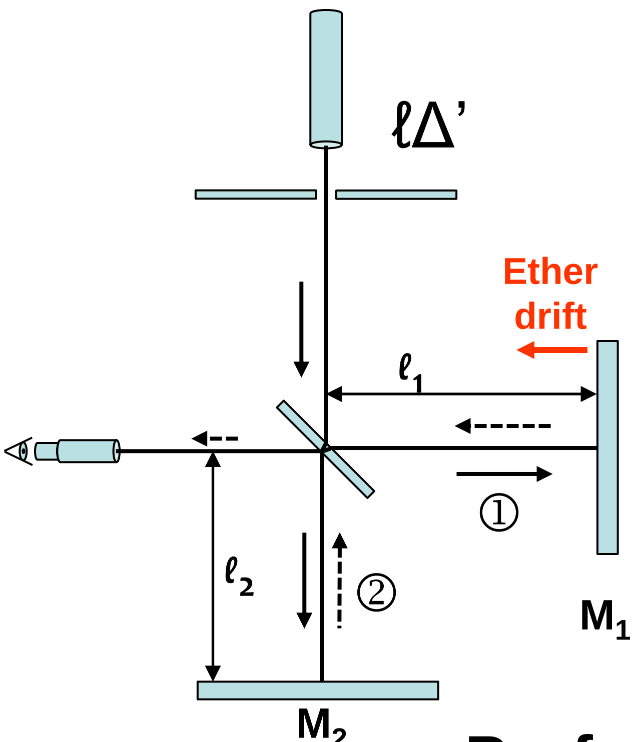
The path difference $\Delta\ell$ between the two interfering beams is:

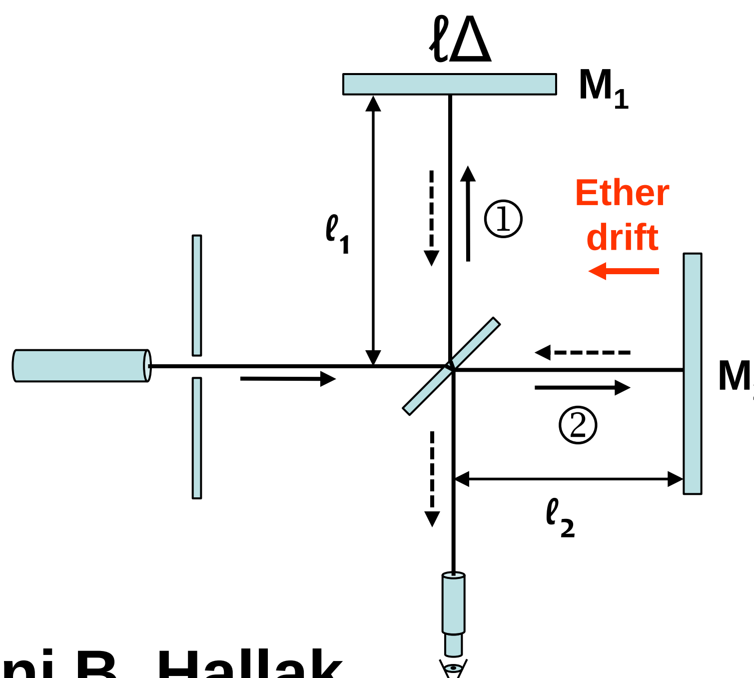
$$\Delta\ell = c\Delta t = 2\ell_2\left(1-\frac{v^2}{c^2}\right)^{-1} - 2\ell_1\left(1-\frac{v^2}{c^2}\right)^{-\frac{1}{2}}$$

The Ether Hypothesis
Michelson-Morley Experiment

When the entire experimental setup is rotated through 90º, the roles of the longitudinal and traverse paths are interchanged. In such a case, the path difference (Δℓ') becomes:

$$\Delta\ell' = c\Delta t' = 2\ell_2\left(1-\frac{v^2}{c^2}\right)^{-\frac{1}{2}} - 2\ell_1\left(1-\frac{v^2}{c^2}\right)^{-1}$$





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The Ether Hypothesis
Michelson-Morley Experiment

Let us calculate the change in the path difference when the rotation through 90^o takes place.

$$\Delta\ell - \Delta\ell' = 2\ell_2\left(1-\frac{v^2}{c^2}\right)^{-1} - 2\ell_1\left(1-\frac{v^2}{c^2}\right)^{-\frac{1}{2}} - 2\ell_2\left(1-\frac{v^2}{c^2}\right)^{-\frac{1}{2}} + 2\ell_1\left(1-\frac{v^2}{c^2}\right)^{-1}$$

$$\Delta\ell - \Delta\ell' = 2(\ell_1 + \ell_2)\left[\left(1-\frac{v^2}{c^2}\right)^{-1} - \left(1-\frac{v^2}{c^2}\right)^{-\frac{1}{2}}\right]$$

v can be taken as the speed of the earth around the sun. i.e. $v = 3.0 \times 10^4$ m/s, $c = 3.0 \times 10^8$ m/s. $\Rightarrow v^2/c^2 << 1$. Therefore, we can simplify the above expression by using the following binomial expansion after dropping all terms higher than second order.

$$(1-x)^n \approx 1 - nx \qquad \text{for } x << 1$$

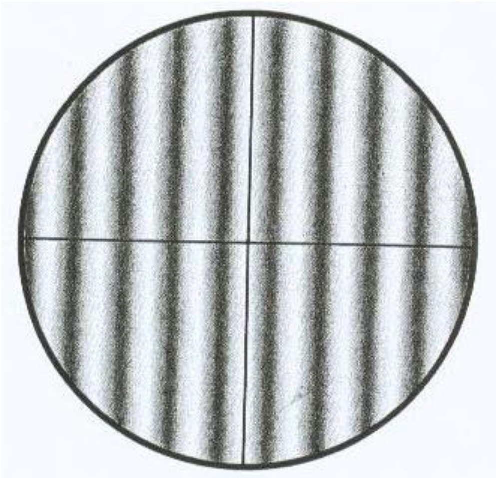
In our case, $x = v^2/c^2$, and we find that:

The Ether Hypothesis
Michelson-Morley Experiment

$$\Delta\ell - \Delta\ell' = 2\left(\ell_1 + \ell_2\right)\left[\left(1 - (-1)\frac{v^2}{c^2}\right) - \left(1 - \left(-\frac{1}{2}\right)\frac{v^2}{c^2}\right)\right]$$

$$\Delta\ell - \Delta\ell' = \left(\ell_1 + \ell_2\right)\left(\frac{v^2}{c^2}\right)$$

$\Delta N \longrightarrow$

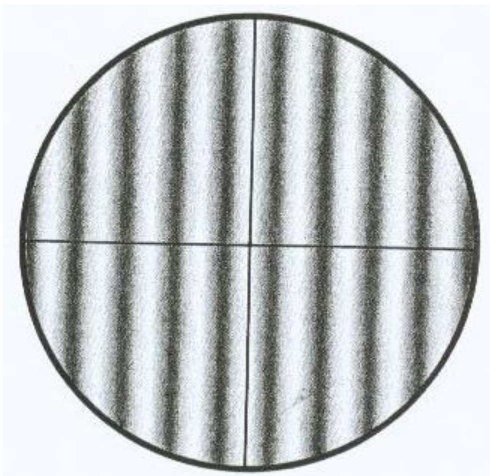


If the above path difference changes by one wavelength (λ) in the course of the rotation, then there should be a shift of one fringe in the cross wire of the telescope shown. Hence the rotation through 90^o results in a shift of ΔN fringes that is expected to be:

$$\Delta N = \frac{\Delta\ell - \Delta\ell'}{\lambda} = \frac{\left(\ell_1 + \ell_2\right)}{\lambda}\left(\frac{v^2}{c^2}\right)$$

The Ether Hypothesis
Michelson-Morley Experiment

$\Delta N \longrightarrow$



$$\Delta N = \frac{1}{\lambda}(\ell_1 + \ell_2)\left(\frac{v^2}{c^2}\right)$$

No Ether

c is constant

Galilean Transformation is not valid

No fringe shift was observed when the interferometer was rotated by 90º.

Numerical Example

In the Michelson-Morley experiment, ($\ell_1 + \ell_2$) was 22 m and the wavelength of light used was 6000 Å. They assumed that ether is fixed relative to the sun so that the earth and the interferometer move through the ether at a velocity v = 3 x 10^4 m/s which is the orbital speed of earth around the sun. Calculate the fringe shift they expect to observe.

λ **= 6000 x 10^{-10} m = 6 x 10^{-7} m**

$$\left(\frac{v}{c}\right) = \frac{3\times10^4}{3\times10^8} = 10^{-4}$$

$$\Delta N = \left(\frac{\ell_1+\ell_2}{\lambda}\right)\left(\frac{v}{c}\right)^2 = \left(\frac{22}{6\times10^{-7}}\right)\left(10^{-4}\right)^2 = 0.37$$

The experiment was sensitive enough to detect a shift as small as 0.01 .

Big problems at the turn of the century

- Michelson and Morley showed that the Galilean Transformation disagree with Maxwell Equations.
- Maxwell Equation are not be wrong.
- Galilean Transformation did not hold for the laws of Newtonian Mechanics.
- Einstein proposed a solution through his Theory of Special Relativity.

Inertial & Non-inertial Reference Frames

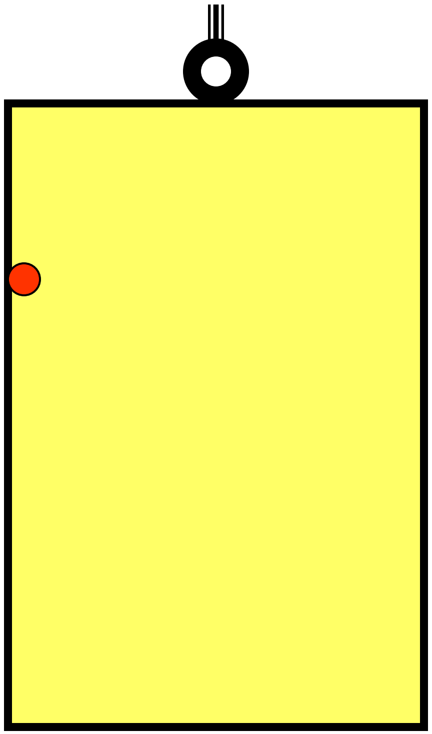
For an Inertial Reference Frame

- No accelerations are observed in the absence of external forces.
- Newton's Laws hold in all inertial reference frames.

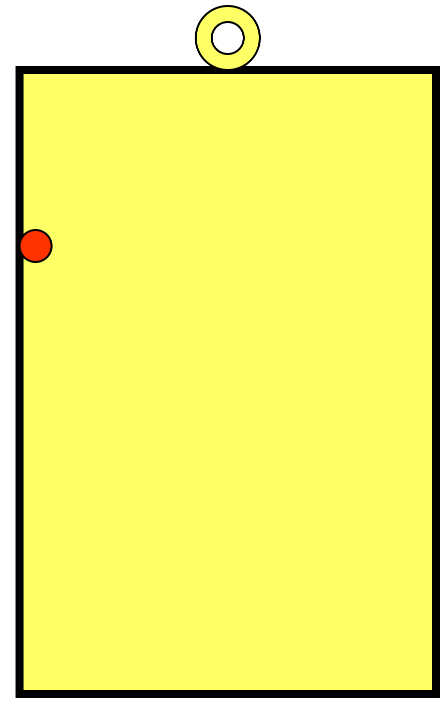
For an Noninertial Reference Frame

- Accelerating with respect to an inertial reference frame.
- In such a frame, bodies have accelerations in the absence of applied forces.

Free-Falling and Floating Freely



Elevator at rest relative to Earth



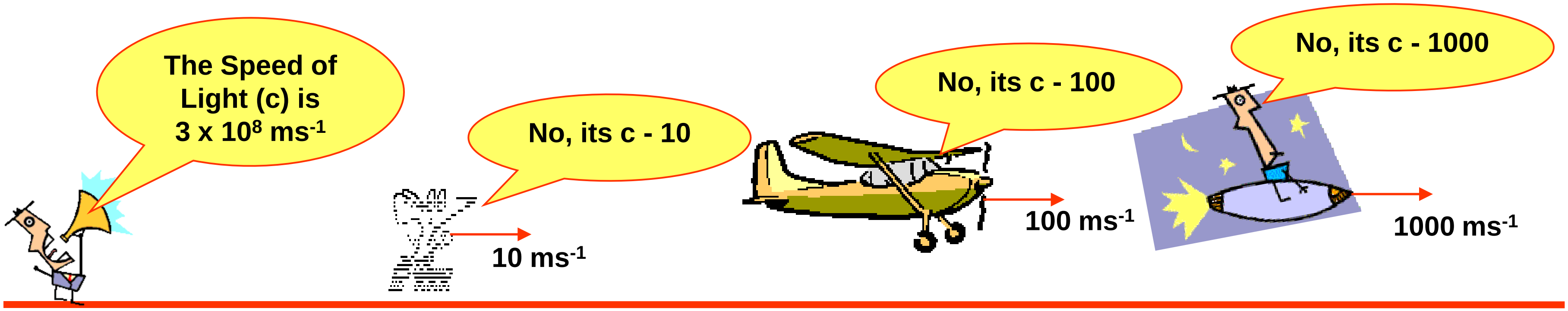
Elevator in a free-fall (free-float)

Einstein's Principle of Relativity

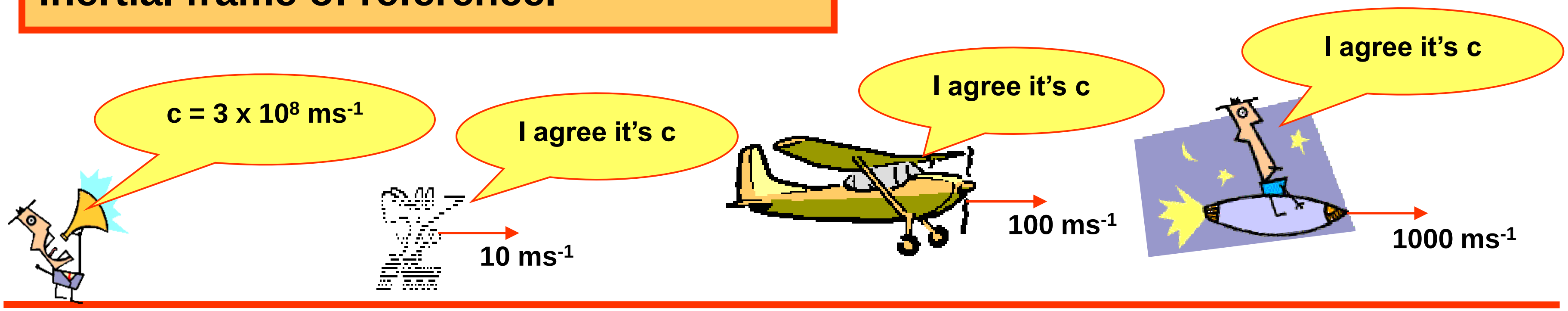
- **Resolves the contradiction between Galilean relativity and the fact that the speed of light is the same for all observers.**
- **Postulates**
  - **The *Principle of Relativity*: All the laws of physics are the same in all inertial frames.**
  - **The *constancy of the speed of light*: the speed of light in a vacuum has the same value in all inertial reference frames, regardless of the velocity of the observer or the velocity of the source emitting the light.**

The constancy of the speed of light

Under Galileo and Newton, the speed of light would vary depending the inertial frame of reference.



Whilst under Maxwell, the speed of light is constant no matter what the inertial frame of reference.



The Principle of Relativity

- This is a sweeping generalization of the principle of Galilean relativity, which refers only to the laws of mechanics.
- The results of *any kind* of experiment performed in a laboratory at rest must be the same as when performed in a laboratory moving at a constant speed past the first one.
- No preferred inertial reference frame exists.
- It is impossible to detect absolute motion.

The Constancy of the Speed of Light

- **Confirmed experimentally in many ways.**
  - **A direct demonstration involves measuring the speed of photons emitted by particles traveling near the speed of light.**
  - **Confirms the speed of light to five significant figures.**
- **Explains the null result of the Michelson-Morley experiment.**
- **Relative motion is unimportant when measuring the speed of light.**
  - **We must alter our common-sense notions of space and time.**

Consequences of Special Relativity

- **Restricting the discussion to concepts of length, time, and simultaneity**
- **In relativistic mechanics**
  - **There is no such thing as absolute length.**
  - **There is no such thing as absolute time.**
  - **Events at different locations that are observed to occur simultaneously in one frame are not observed to be simultaneous in another frame moving uniformly past the first. Simultaneity is not absolute also.**

Re-evaluation of Time

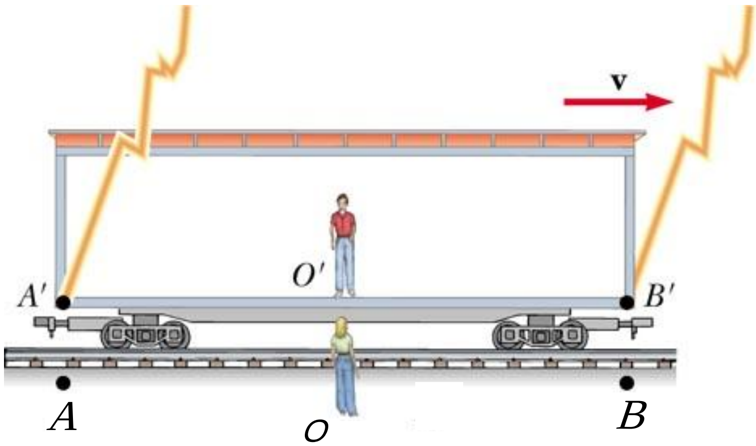
- **In Newtonian physics we previously assumed that *t = t'.***
  - **Thus with "synchronized" clocks, events in S and S' can be considered simultaneous.**

- **Einstein realized that each system must have its own observers with their own clocks and meter sticks.**
  - **Thus events considered simultaneous in S may not be in S'.**

Simultaneity

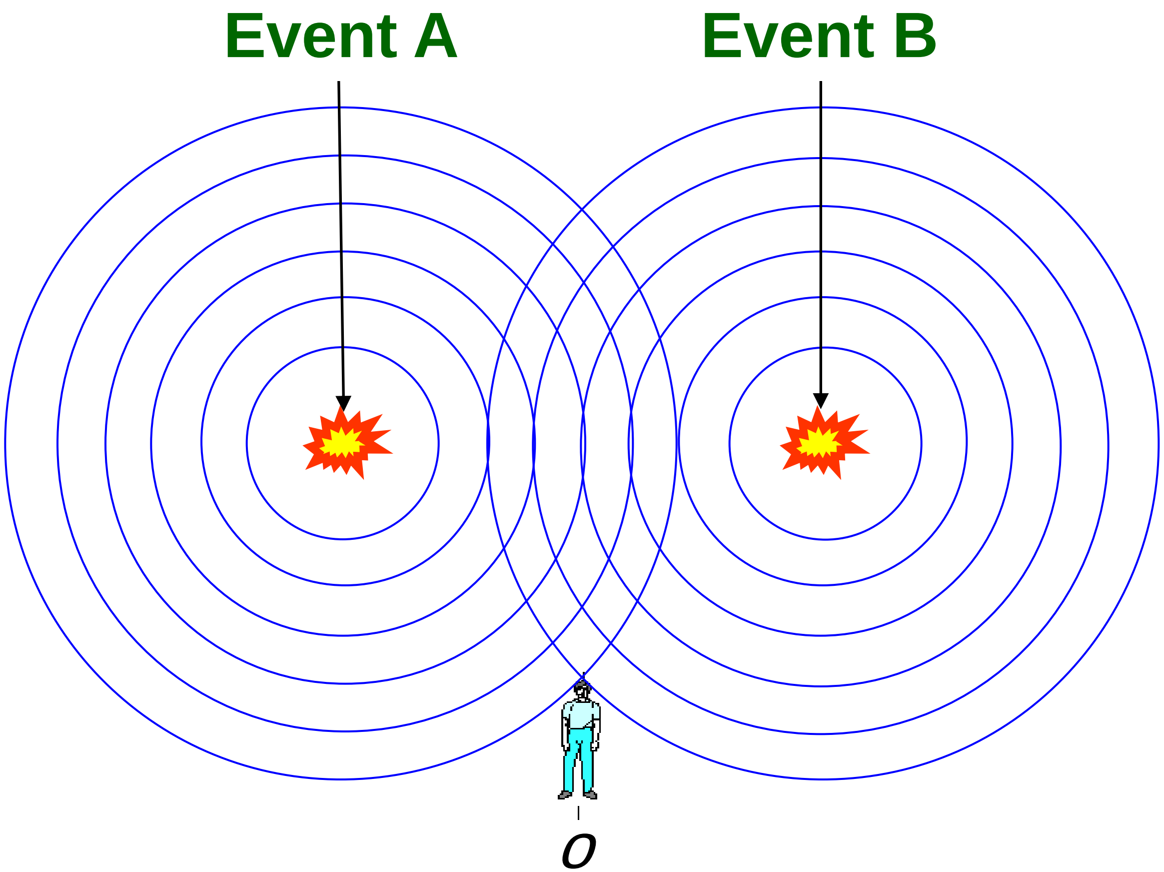
- **In Special Relativity, Einstein abandoned the assumption of simultaneity.**
- **Thought experiment to show this.**
  - **A boxcar moves with uniform velocity.**
  - **Two lightning bolts strike the ends.**
  - **The lightning bolts leave marks (A' and B') on the car and (A and B) on the ground.**
  - **Two observers are present: O' in the boxcar and O on the ground.**

Simultaneity – Thought Experiment Set-up



- **Observer *O* is midway between the points of lightning strikes on the ground, A and B**
- **Observer *O'* is midway between the points of lightning strikes on the boxcar, A' and B'**

Stationary Frame

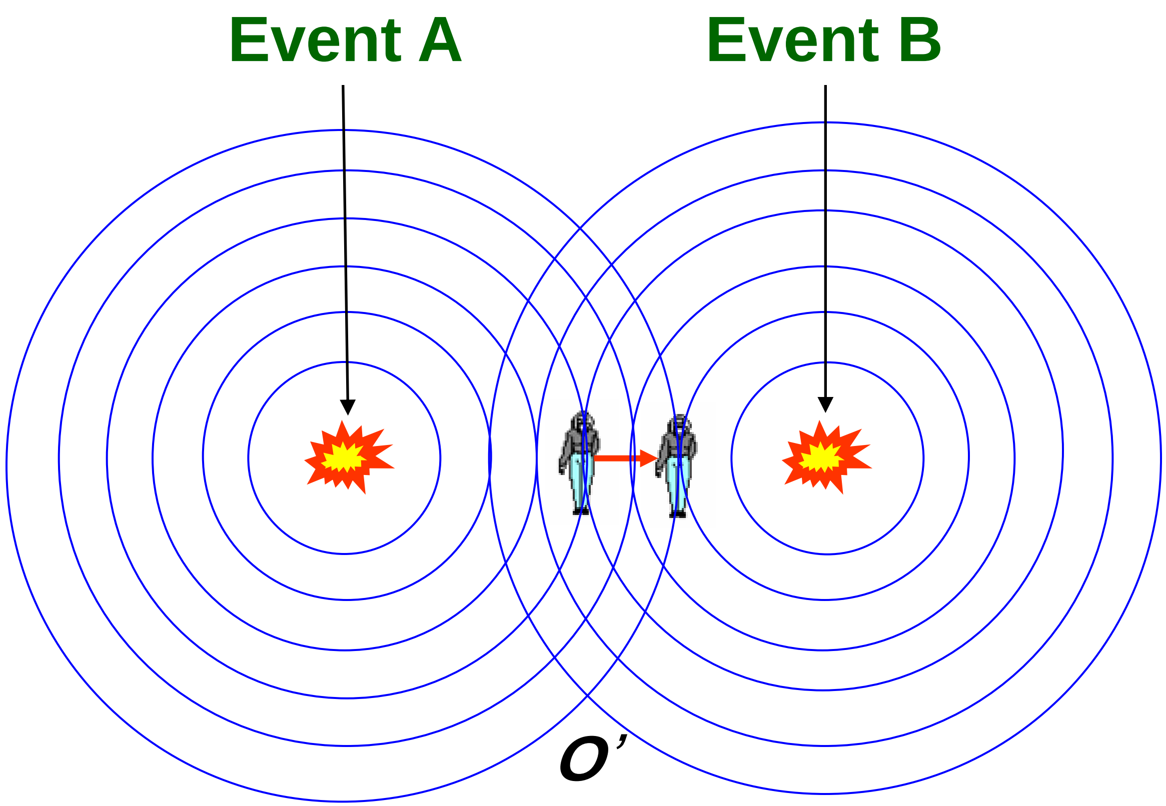


The boy at rest is equidistant from events A and B.

The boy “sees” both flashes go off simultaneously

Prof. Awni B. Hallak

Moving Frame



The girl, moving to the right with speed *v*, observes events A and B in different order:

The girl "sees" event B, then A.

Prof. Awni B. Hallak

Simultaneity–Thought Experiment, Summary

- **Two events that are simultaneous in one reference frame are in general not simultaneous in a second reference frame moving relative to the first**
- **That is, simultaneity is not an absolute concept, but rather one that depends on the state of motion of the observer**
  - **In the thought experiment, both observers are correct, because there is no preferred inertial reference frame**