The Michelson-Morley Experiment

2

Albert Abraham Michelson *American physicist, 1852–1931*

Picture: Smithsonian Institution Dibner Library Public domain via Wikimedia Commons

Michelson arrived as a child in the United States in 1855. From 1869 to 1881 he served in the marines, eventually as an instructor in physics. He undertook his post-graduate study in Berlin and Paris. Starting in 1880, and collaborating later with E.W. Morley, Michelson developed precise experiments to investigate the effect of the Earth's velocity on the speed of light. In 1893 Michelson joined the University of Chicago, creating its acclaimed Department of Physics. In 1907 he was the first American to receive the Nobel prize for physics "for his optical precision instruments and the spectroscopic and metrological investigations carried out with their aid."

2.1 Earth's motion and the æther

In 1881 Michelson conducted an experiment in an attempt to measure a) the movement of the Earth relative to the material æther, and b) the effect of the movement of the Earth on the speed of light arising from the æther wind. In 1887 an improved experimental effort by Michelson with Morley[25] followed.

[25] Edward Williams Morley (1838–1923), Professor of Chemistry from 1869 to 1906 at what is now Case Western Reserve University.

J. Rafelski, *Relativity Matters*,
DOI 10.1007/978-3-319-51231-0_2

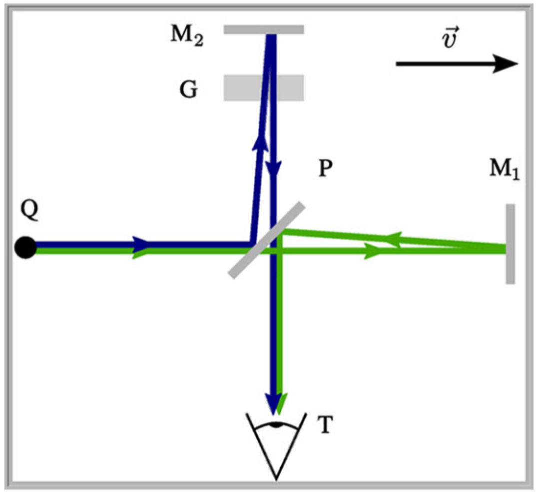


Fig. 2.1 The Michelson-Morley Interferometer. The light follows two partially overlapping paths: one QPM_2T shown in blue and the other QM_1PT shown in green. The glass plate G compensates the greater path length of the QM_1PT beam which is reflected on the silver coating placed on the upper side of the mirror P. The two beams could produce variable interference in the observer's T-device depending on the orientation with respect to $\vec{v}$

The Michelson-Morley (MM) apparatus consisted of a two-armed interferometer with the two light paths as depicted in Fig. 2.1. The apparatus is made to rotate around an axis. We assume a geometry such that at one time, an arm of the MM apparatus will be aligned parallel, and at another time, perpendicular, to the velocity of the Earth $\vec{v}$. While the light wave is traveling from Q, one of the mirrors (here either M_1 or the silver coated surface of P which reflects beam towards M_2) either approaches or recedes from the other. There should be a difference in the time it takes to travel from Q and T for the two optical paths. The interference fringe-shift in the detector T as the experiment is rotated should allow the observation of the velocity of the Michelson interferometer with respect to the material æther.

Michelson's objective was to push the precision of speed of light measurement to below the Earth's orbital speed of 30 km/s. Today we know that the peculiar velocity of the Earth with respect to the Cosmic Microwave Background is about 12 times greater than the orbital velocity. The three main components of Earth's velocity vector are illustrated qualitatively in Fig. 2.2: the smallest is orbital speed around the Sun; the orbital speed in the Galaxy is 10 times larger; and the velocity of our Galaxy with respect to the Cosmic Microwave Background (CMB) is yet about twice larger. The net velocity with respect to CMB[26] is 369 ± 1 km/s.

The detailed mathematical description of the light and mirror motion is inherent in our study of the light clock in Sect. 4.2, and we defer a detailed description of the optical paths to this discussion. Here we note that the optical paths were defined by mirrors attached to a common material body. Any changes of this body as it travels through the æther thus influences the outcome of the experiment as well.

[26]Particle Data Group (K.A. Olive, et al.), Chin. Phys. C **38**, 090001 (2014), see Table: Astrophysical Constants and Parameters.

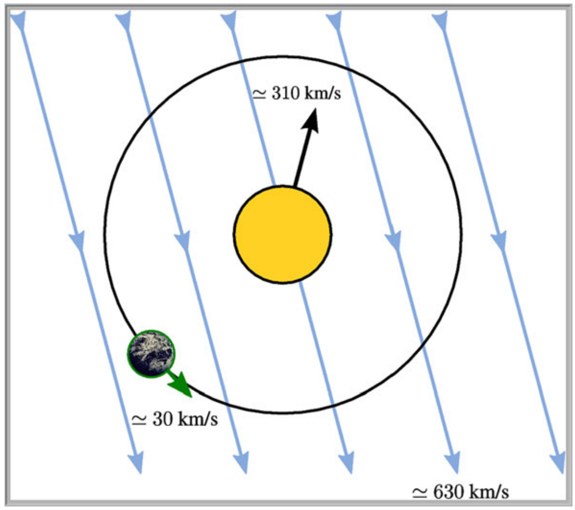


Fig. 2.2 The velocity vectors of the Earth around the Sun (speed 30.2 ± 0.2 km/s), Sun around the center of the Milky Way (speed $\simeq 310$ km/s) and Milky Way in the Universe (speed $\simeq 630$ km/s) define the net motion of 369 ± 1 km/s against the Cosmic Microwave Background

Michelson and Morley's experimental null result, a result of unprecedented precision at that time, at the level of 2.5×10^{-5} of the speed of light, was a sensation. Neither the motion of the apparatus nor any influence on the light speed was detected at the upper bound of an 8 km/s shift relative to a stationary material æther in which light propagates at the speed $c \simeq 300{,}000$ km/s.

The outcome of this pivotal experiment was a shift to the belief that the state of motion of an inertial observer is not observable by a local in space and time experiment.

2.2 Principle of relativity

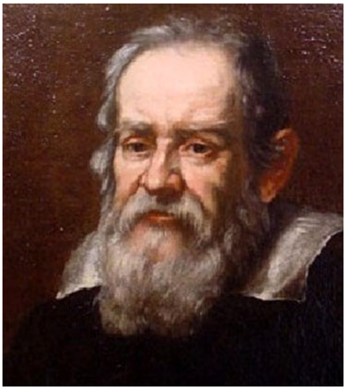
Inertial observers

Galileo put forward the principle that the laws of physics are the same in any inertial reference system that moves at a constant speed in a straight line, regardless of its particular speed or direction. Hence, there is no absolute motion, and thus no absolute rest and therefore no 'center' of the Universe.

This principle provided the basic framework for Newton's laws of motion, with the first law of motion we present as: *Every body perseveres in its state of rest or of uniform motion in a straight line, unless it is compelled to change that state by forces impressed upon it*. This is also presented in the form, "Unless acted upon by an external force, an object at rest tends to stay at rest and an object in motion tends to stay in motion with the same speed and in the same direction." This is also referred to as the **principle of inertial motion**, or simply **the principle of inertia**. An **inertial observer** is an observer for whom Newton's first law is true.

We will discuss rotating bodies in Part XI of this book, see in particular Sect. 29.2.

Galileo Galilei *Tuscan (Italian) Physicist, 1564–1642*



Public domain via Wikimedia Commons
From **Galileo Galilei** *portrait of 1636*
by J. Sustermans, Hayden Planetarium, NY

Called the **father of modern science** by Einstein, Galileo pioneered scientific reductionism, and insisted on the use of quantitative and repeatable experiments, allowing results to be analyzed with precision.

Galileo reduced the complexity of the real world by seeking to recognize key governing factors. He knew that many sub-dominant effects had yet to be included into each and every consideration, and that imprecision of measurement also hindered experimental agreement with models considered.

His adherence to experimental results and rejection of allegiance to all other authority in matters of science ushered in the development of the modern world.

The Vatican's ban on reprinting Galileo's works was partially lifted in 1718 and in full 100 years after his death.

Galilean transformation

Consider the conventional nonrelativistic relation between two inertial observers, A and A', with A' moving at velocity $\vec{v}$ relative to A. When inertial observer A measures the velocity $\vec{u}(t)$ of a body, this will differ at all times from the measurements made by observer A' by the relative velocity:

$$\vec{u}(t)' = \vec{u}(t) + \vec{v}\ . \tag{2.1}$$

Since the velocity of a body is the rate of change in time of the position vector, the Galilean transformations of the coordinates of a body from A to A' consistent with Eq. (2.1) must be:

$$\begin{gathered} t' = t\ , \\ x' = x + v_x t\ , \quad y' = y + v_y t\ , \quad z' = z + v_z t\ . \end{gathered} \tag{2.2}$$

Principle of relativity as used in this book

The Principle of Relativity requires the **physical equivalence of all inertial observers**: that is, two observers, who differ only in that one is moving at some fixed finite velocity relative to the other, are equivalent. This statement defines a class of inertial observers. From now on, an 'inertial observer' is any member of the class of all inertial observers. The laws of physics are the same for any inertial observer.

Most important is to understand how the Principle of Relativity modifies previous understanding. At the time of the heliocentric Universe, the Sun is at the center, and at rest. Now:

a) The Principle of Relativity in any context forbids a preferred point of origin; all places in the Universe are equivalent.
b) In the context of special relativity, any and all laws of physics do not refer to a preferred frame of reference; Einstein declines the possibility[27] of an "absolute rest-frame."

While the laws of physics according to the Principle of Relativity do not refer to any preferred frame of reference, a further condition is needed in order to define non-inertial, *i.e.* accelerated motion, and this must introduce a preferred observer, adopted to be the Mach's cosmological rest-frame, Sect. 29.2.

A survey of professional web pages which address the Principle of Relativity reveals quite a few different ways to argue. As an example of one such argument, where the summarized claims are in italics[28] (here the sequence is changed):

All experiments run the same in all inertial frames of reference.
(#2 in original list) This statement paraphrases our discussion above.

No experiment can reveal the absolute motion of the observer.
(#3 in original list) However, any experiment that explores the vastness of the Universe can reveal motion with respect to Mach's cosmological rest-frame.

Absolute motion cannot appear in any law of physics.
(#1 in original list) This claim is a restatement of a stronger claim listed here previous to it, *i.e.* (3), since in our view laws of physics follow from experimental reality.

Body motion

The theory of special relativity is usually presented in the limit that all forces causing acceleration of a material body are arbitrarily weak (what weak means will be explained in Sect. 29.3). SR is, as Einstein put it in the title of his 1905 paper, a description of "moving bodies". Interpretation of SR phenomena requires that we know if and when a

---

[27] In his 1905 paper Einstein speaks of the "unsuccessful attempts to discover any motion of the Earth relative to the 'light medium'…" and carries on to conjecture that the laws of physics possess "no properties corresponding to the idea of absolute rest." He finishes raising this conjecture to the level of a principle he calls "Principle of Relativity".

[28] J.D. Norton at: http://www.pitt.edu/~jdnorton/teaching/HPS_0410/chapters/Special_relativity_principles/, retrieved June 2016.

body is accelerated. One can loosely equate the above statements with Mach's principle which uses the rest-frame of all mass in the Universe to define a reference inertial observer.

An inertial observer must forever remain inertial. In SR when acceleration is involved there is no relativity: we cannot describe the properties of an accelerated body by pretending that it is an inertial observer who is accelerated. This is true irrespective of the magnitude of the acting force, see for example Sect. 12.3 and the following exercise V–4 on page 161 concerning how this distinction works in regards to time dilation.

The speed of light

Within the corpuscular view of light, a moving emitter is 'throwing' the light-particles. Therefore, the Galilean view of light velocity follows from Eq. (2.1); the source and light velocities add vectorially. On the other hand, we know that the speed of sound is a property of the medium in which sound propagates (air, water, etc.), and is not dependent on the motion of the emitter. However, the motion of material, such as air, can change the speed of sound:

$$c_s' = c_s + v, \tag{2.3}$$

where v is the 'wind' speed, and not the velocity of the source.

The speed of Maxwell waves representing light was at first understood in analogy to the speed of sound. Maxwell considered a medium, a material æther, necessary for his waves to propagate. Since the speed of light was the property of the material medium, only a modification of the state of the material æther, and in particular 'æther wind', could modify the observed velocity of light.

The first insight about the universal nature of the speed of light comes from Maxwell's study of the speed of electro-magnetic wave propagation. The form of Maxwell's equations made c independent of the velocity of the wave source, and independent of the wavelength of the wave.

There remains, however, the possibility that c depends on the state of the æther. The opinion in the late 19th century was that Maxwell's equations were valid only with respect to the æther at rest. Given the large magnitude of the speed of light, it was thought that it would take elaborate experimentation to discover the limits of validity of Maxwell's equations inherent in the motion of the æther.

Since the material æther was seen to be at rest in some specific reference frame, one could proceed to measure Earth's velocity vector with respect to material æther. Furthermore, observation of changes in the speed of light could tell us about the properties of the material æther. Such experiments were naturally of great interest.

However, before we continue, let us remember that, paraphrasing Einstein's words, there cannot be an æther velocity, and that only relative velocities play a role in SR. We will learn (see Chap. 27) that Maxwell's equations can be cast into a form valid for any inertial observer and as long as this form is valid, there is always a universal speed of light, valid for all inertial observers in all reference frames

$$\boxed{c' = c\,.} \tag{2.4}$$

Equation (2.4), the universality of the speed of light, is arguably the key input into Einstein's formulation of SR.

2.3 Cosmic microwave background frame of reference

Seeing the universality of the speed of light one can wonder if this is compatible with the changing Universe, since scales of distance expand as the Universe ages. By comparing the wavelength of the quantum of light, a photon, emitted by a distant atom, to the expected wavelength emitted by an atom in laboratory, we can tell how long this photon has traveled before being observed. This effect is the cosmological redshift.

The cosmic microwave background radiation (CMB) are the ashes of the Big-Bang in the form of radiation dating back to the hot Universe era during which atoms were formed. This radiation, discovered in 1964,[29] fills the entire present day universe with a thermal $T_{\mathrm{CMB}} = 2.7255(6)\,\mathrm{K}$ microwave (cm-size wavelength) black body spectrum. In essence we can say that we see everywhere the primordial CMB photons which were already present when atoms were formed.

Cooling of the Universe due to the expansion allowed for ion-electron binding at about 372,000 years after the Big-Bang, and the Universe became transparent to radiation. Ongoing Universe expansion means that the ambient temperature today is much lower. The relatively low T_{CMB} is thus due to a 1000-fold cosmological redshift by the expansion of the Universe. CMB photons were originally formed at energies corresponding to temperatures $T \simeq 2{,}970\,\mathrm{K}$ when ions and electrons filling the early Universe recombined. In the absence of free electrons the Universe became transparent to radiation.

In the above considerations we implicitly made the assumption that the laws of physics and thus also atomic emission lines were the same eons ago as they are today.[30] Attempts to find time variation of natural constants continue. The limit on relative variation of the

[29] Arno Penzias and Robert Woodrow Wilson were awarded the Nobel Prize for Physics 1978 for the discovery of CMB. CMB radiation was predicted in 1946, albeit at $\mathrm{T} = 50\,\mathrm{K}$, by Georg Gamov (1904–1968), a Russian-American theoretical physicist, student of A. Friedman of cosmological FLRW model fame, best known for the explanation of nuclear alpha decay via quantum tunneling, and his work on star evolution and the early Universe, also the author of "Mr. Tompkins' adventures" series of popular-scientific books.

[30] H. Fritzsch *The Fundamental Constants: a Mystery of Physics*, World Scientific Publishing Company, Singapore (2009); J.-Ph. Uzan, "Varying Constants, Gravitation and Cosmology," *Living Rev. Relativity* **14**, 2 (2011); X. Calmet, M. Keller "Cosmological Evolution of Fundamental Constants: From Theory to Experiment" *Mod. Phys. Lett. A* **30**, 1540028 (2015).

fine-structure constant is

$$\alpha \equiv \frac{e^2}{4\pi\epsilon_0\hbar c} = \frac{1}{137.035399074(44)}\,, \qquad \frac{1}{\alpha}\frac{d\alpha}{dt} = \frac{(0.20 \pm 0.20) \times 10^{-16}}{\text{yr}}\,, \tag{2.5}$$

and for the proton to electron mass ratio

$$\mu \equiv \frac{m_p}{m_e} = 1836.15267245(75)\,, \qquad \frac{1}{\mu}\frac{d\mu}{dt} = \frac{-(0.5 \pm 1.6) \times 10^{-16}}{\text{yr}}\,, \tag{2.6}$$

both obtained assuming a constant rate of change during the lifespan of the Universe.[31] This shows that we can proceed assuming that natural constants are constant, and consider properties of the early Universe using the physics laws determined today. We believe accepting Occam's Razor argument introduced in conversation I-1 on page 17 that this applies also to the universal speed of light c.[32]

The CMB radiation background provides a 'natural' frame of reference which can be universally recognized. A moving observer sees a Doppler-deformed, see Chap. 13, CMB radiation spectrum. This means one can recognize relative motion in the Universe with respect to the CMB rest-frame of reference. We keep in mind the equivalence of all observers inertial with respect to the CMB rest-frame, and that our knowledge of which observer is at rest with respect to CMB does not violate the principle of relativity: equally well we could imagine measuring velocities with respect to any other inertial 'beacon-observer' in the Universe. The CMB is just a very convenient 'beacon' we can refer to.

[31] N. Huntemann, B. Lipphardt, Chr. Tamm, V. Gerginov, S. Weyers, E. Peik, "Improved limit on a temporal variation of m_p/m_e from comparisons of Yb+ and Cs atomic clocks," *Phys. Rev. Lett.* **113**, 210802 (2014).

[32] Regarding the question if time variation of c could in principle be observable, see: M.J. Duff, "Comment on time-variation of fundamental constants" http://lanl.arxiv.org/pdf/hep-th/0208093v4 (November 2016).

Springer
http://www.springer.com/978-3-319-51230-3

Relativity Matters
From Einstein's EMC2 to Laser Particle Acceleration and Quark-Gluon Plasma
Rafelski, J.
2017, XXV, 468 p. 85 illus., 63 illus. in color., Softcover
ISBN: 978-3-319-51230-3