The Experiment of Michelson and Morley

Experiment That Ruled Out Ether

Amit Roy

Light was assumed to propagate in a medium called ether which was all pervading and stationary. Earth's motion through ether was expected to have an effect on the velocity of light in the direction of the relative motion by the law of addition of velocities. Michelson–Morley experiment used an interferometric technique to detect this effect and got a null result, which was the first strong evidence against existence of ether and eventually had a natural explanation in special theory of relativity.

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The nature of light and its propagation through space and optical media has always fascinated humans and has engaged many brilliant minds in recorded history. Newton had given the corpuscular theory of light in order to account for its' propagation in straight lines, reflection, and refraction. He had to postulate an 'Aetheral (ether) medium' to explain diffraction in his *Opticks* in 1744. According to him, the vibrations of this ether was responsible for the production of both light and heat. Before Newton, Huygens had given the hypothesis of light being a longitudinal wave like sound, travelling through ether. This idea was rejected as it could not account for the two polarizations of light. Fresnel, on the other hand, introduced the wave theory of light, with light travelling as transverse waves in ether, since transverse waves can support two polarizations. Ether had to be omnipresent, filling all space, and since the Earth moves in its orbit around the Sun with an average speed of about 30 km/s, theories of ether drag were proposed. One was the complete dragging of ether by the Earth proposed by George Gabriel Stokes in 1844, and the other by Augustin-Jean Fresnel in 1830 of partial drag of the ether by Earth. Fresnel developed a formula to calculate the effect of dragging. The measurement of position of stars (stellar aberration)

Keywords
Propagation of light, ether, interferometer, vibration isolation, special theory of relativity.

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ruled out the possibility of strong ether drag. But, Fresnel's theory could be made compatible with the measurements. Armand Fizeau in 1851, performed the experiment on movement of light in water measuring the fringing of light due to motion of water, and the results were as predicted by Fresnel's formula. James Clark Maxwell had in 1878, suggested that it may be possible to measure the differences in velocity of light in two different directions due to the motion of Earth through ether, but discounted the possibility of measuring such tiny differences in a ground-based experiment.

This set the stage for Albert Abraham Michelson, who was deeply interested in the nature of light. By 1879, he had established his reputation as a master experimenter with his measurement of the velocity of light which was the most accurate measurement at that time (within 0.05% of the currently accepted value).

During his visit to Germany, Michelson decided to measure the relative motion between Ether and Earth. In 1881, he did his first experiment at the Physical Institute, Berlin, in Hermann von Helmholtz's laboratory with an apparatus built for this purpose, which he termed as an 'interferential refractor', later known as the 'Michelson interferometer'.

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Michelson argued that if he measured the time taken by light to travel a fixed distance in a direction parallel to the motion of the Earth and that for travelling the same distance in a perpendicular direction, he should observe a difference, since light moving in the stationary ether would have different velocities in the two directions. This time difference would give rise to a phase difference between the two rays of light, and their interference pattern (alternate dark and bright bands called fringes) would show shift in the position of fringes from that if the there was no relative motion between the Earth and ether. If the apparatus is rotated by 90 degrees, the fringes will shift by an equal amount in the opposite direction, and this difference would be measurable. He discussed the plans with Helmholz, who pointed out that the only difficulty would be in maintaining the temperature constant over the region of the apparatus during the measurement.

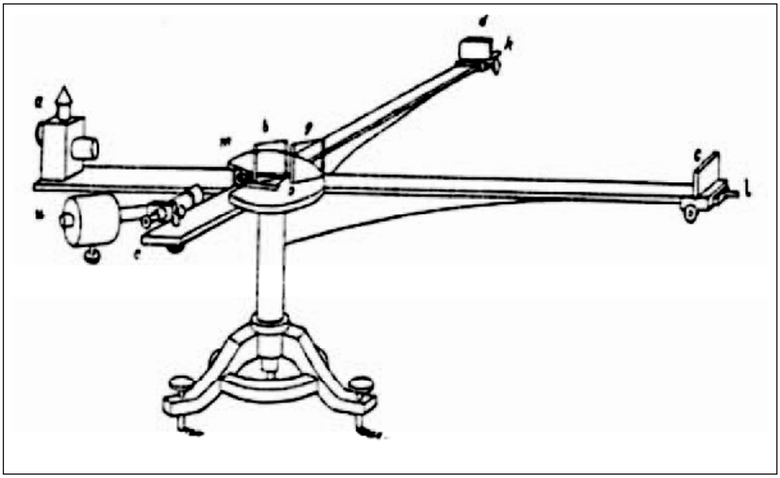

Figure 1. Michelson's interferometer that he used in the experiment at Potsdam in 1881[1].

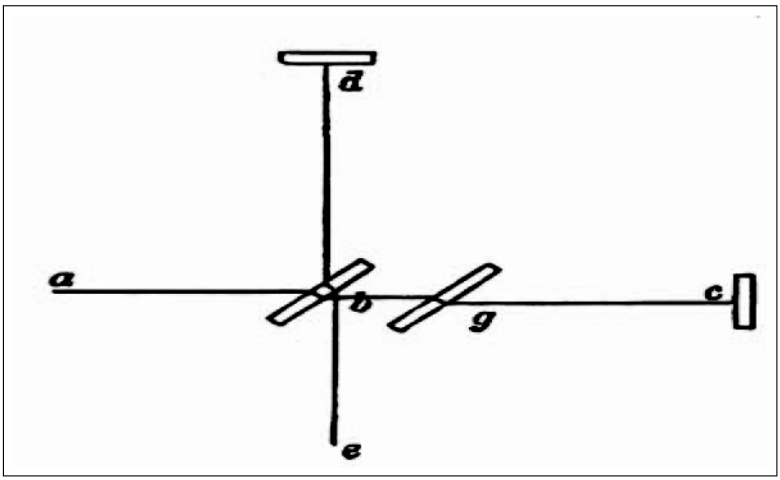

Figure 2. Schematic drawing showing the arrangement of source of light and mirrors in the Michelson interferometer [1].

Michelson got the instrument shown in *Figure* 1, built by a German instrument company Schimdt and Haensch. The schematic of the arrangement is shown in *Figure* 2 [1].

The two arms – ***bd*** and ***bc*** – over a meter in length, were made of brass and were covered by long paper boxes to guard against changes in temperature. The source of light ***a*** was a lantern with a collimator (a screen with a circular hole) whose flame was placed at the focus of a lens, so that a parallel beam of light emerged. The mirrors at ***c*** and ***d*** could be moved with fine screws to position

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them at equal distances from the half-silvered mirror at ***b***. The compensating plate of glass ***g*** cut from the same piece of glass as that for ***b***, was inserted between ***b*** and ***c*** to equalize the optical path.

The light coming from the source ***a*** will be split at the partial transparent mirror ***b*** into a reflected ray towards ***d*** and a transmitted ray towards ***c***. These two light rays will be reflected at the mirrors ***d*** and ***c*** respectively, meeting together at ***b***, and transmitted to the eyepiece of the telescope ***e***, where the fringes may be observed to see if the waves are in interference. The mirror ***b*** could be moved in fine steps with a micrometer screw ***m*** in the direction ***eb*** to the position where the fringes appeared sharpest. The path travelled by the two light rays in perpendicular directions were first equalised. The mirrors ***c*** and ***d*** were first moved up as close as possible to the plate ***b*** and the distances ***bc*** and ***bd*** made nearly equal. Then the position of plate ***b*** was adjusted to make the two images of the source coincide at the eyepiece ***e***. Then a sodium flame placed at source a produced interference bands which were sharpened by further adjustments of the position of plate ***b***, ensuring that the two optical paths were equal. On switching to the white light source, the micrometer screw had to be adjusted a little to get the coloured fringes with a black central band to appear. The displacement of the fringes was measured, noting the positions of the dark central band on the eyepiece (*Box* 1).

The interferometer was placed on a stone pier in the basement of the institute in Berlin in such a way that the arms of the instrument pointed to the north and east, the east pointing arm coinciding with the direction of motion of the Earth. The entire instrument could rotate around an axis perpendicular to the two arms. Michelson set about measuring the fringe shift when the instrument was rotated by 90 degrees so that the parallel and perpendicular arms interchanged their directions. He had estimated the fringes to shift by about 0.16 of the distance between fringes for the arm length of about 1.2 meter, which he thought was possible to measure with his instrument. However, he found the in-

Box 1. White *vs.* Monochromatic Light

Bright and dark alternate patterns called fringes were observed in Young's two-slit experiment due to interference of the light waves. They are best observed when monochromatic light is used which has high coherence length (defined as the length over which the light can interfere) resulting in a uniform fringe pattern. With white light, the observation of fringes require strict equality of the optical paths the two light rays would take, due to its low coherence length. However, white light was chosen by early experimenters as it produced a distinctive coloured fringe pattern having a central sharply defined black fringe which could be used as zero reference for all readings. Changes in a uniform fringe pattern were hard to record, specially in the early days of measurements. A partially monochromatic light (from a sodium lamp) was used only for initially setting up the equipment before switching over to white light.

terferometer to be extremely sensitive to vibrations. He could not take any readings during the day and was forced to work only at night. Even then, the fringes could not be observed continuously over a reasonable time to obtain reliable data.

Obviously, he had to look for another place and the apparatus was accordingly moved, through the good offices of Helmholtz and H C Vogel, to a cellar in the Astrophysicalisches Observatorium in Potsdam, where Vogel was the Director. Here, it was possible to measure the fringes as the place was usually quiet enough. However, the instrument was so sensitive that Michelson wrote, "Stamping of the pavement, about 100 meters from the observatory, made the fringes disappear entirely!" [1].

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Michelson also worried about the effect of temperature changes on the fringes as was voiced by Helmholtz. For brass arms of about 1m length, calculations showed that if one arm should have a temperature only one-hundredth of a degree higher than the other, the resulting difference in their lengths would make the fringes experience a displacement thrice as great as that which would result from the rotation. But, since the changes of temperature were independent of the direction of the arms, these changes were not too great, specially in the cellar of the building and hence their effect could be ignored. Mechanical distortions of the arms during rotation also affected the measurements which Michelson

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had to take into account. Time and again, some mechanical noise or sudden air currents would make the fringes shift by undefined amounts and these sets of measurements had to be discarded.

He measured the position of the fringes in the eyepiece in units of twelfths of the distance between the fringes rotating the instrument in steps of 45 degrees for five full revolutions in one series of measurement. At the end of each series, the support was turned 90 degrees, and the axis was carefully adjusted to the vertical by means of the foot screws and a spirit level. Four series of data were recorded and from the analysis of the observed positions of the fringes, Michelson found that the displacement of the interference bands were consistent with zero within the limits of the errors of the experiment. He concluded that "the result of the hypothesis of a stationary ether is thus shown to be incorrect, and the necessary conclusion follows that the hypothesis is erroneous."

However, M A Potier and later H A Lorentz pointed out that Michelson did not take into account the effect of the motion of Earth on the path of the ray at right angles to the motion. This effect would reduce the expected amount of fringe displacement by half (*Box* 2). Since this value now was barely outside the limits of the experiment, the conclusion of the experiment was questionable.

After returning to USA, Michelson took up a faculty position in 1883, at the Case School of Applied Science in Cleveland, and teamed up with Edward Williams Morley, a professor of Chemistry at Western Reserve College, Cleveland, to reduce the measurement errors and repeat the measurements with a new instrument. Their major challenge was to reduce the effects of external vibrations on the interferometer and mechanical distortion of the setup during rotation.

They constructed an interferometer which was larger and more sensitive than the original Potsdam interferometer [2]. Morley designed a vibration isolation support by mounting the interferometer on a massive sandstone slab floating on a pool of mercury. The path traversed by the light rays was increased to nearly 11 m

Box 2. Fringe Shift on Rotation

Let V= velocity of light (in Michelson's time constancy of velocity of light was not postulated, we usually denote it by c), v = velocity of the Earth in its orbit, D = distance ***ab*** or ***ac***, in *Figure* A(i).
Turning to *Figure* A(ii), the time taken by light to pass from ***a*** to ***c*** is $T = D/(V - v)$, and the time light takes to return from ***c*** to $\boldsymbol{a}_1$, is $T_1 = D/(V + v)$. Adding these two, $T + T_1 = 2DV/(V^2 - v^2)$. The distance travelled in this time, $\boldsymbol{aca}_1 = 2DV^2/(V^2 - v^2) = 2D(1 + v^2/V^2)$, up to 2nd order.
The length of the other path $\boldsymbol{aba}_1 = 2(D^2 + v^2(D/V)^2)^{1/2} = 2D(1 + v^2/2V^2)$, up to 2nd order.
Therefore, the difference, $\boldsymbol{aca}_1 - \boldsymbol{aba}_1 = Dv^2/V^2$.
If, the whole apparatus is turned through 90°, the difference will be in the opposite direction. Then, the total displacement of the interference fringes should be $2Dv^2/V^2$.
Using $v \sim 30$ km/s, $V \sim 3 \times 10^8$ m/s, the expected displacement = $2D \times 10^{-8}$.
In the 1881 experiment [1], the displacement was estimated to be $4Dv^2/V^2$, a factor of two higher.
In the first experiment, $D = 1.2$ m $\sim 2 \times 10^6$ wavelengths of yellow light and hence the displacement to be expected was 0.04 of the distance between interference fringes. In the second experiment of 1887, $D = 11$ m $\sim 2 \times 10^7$ wavelengths of yellow light, hence the displacement expected was 0.4 fringe distance. Michelson and Morley estimated that their interferometer was capable of measuring a shift of about 0.01 fringe.

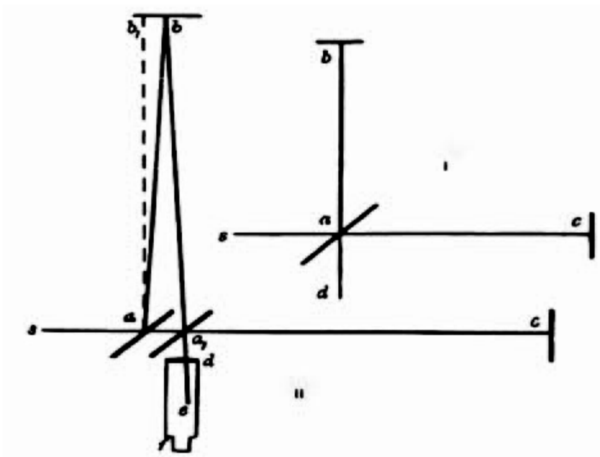

Figure A. Schematic drawing of Michelson–Morley experiment of 1887 taking into account the effect of motion of Earth on the light rays in the direction perpendicular to the motion [2].

(ten times larger than in 1881) by arranging mirrors for multiple reflections. The increased path length increased the expected displacement of the fringes by a factor of ten over that in the first experiment.

Following the criticism of Potier and Lorentz, Michelson took into account the effect of the motion of Earth on the light rays travelling in the direction perpendicular to the motion and recalculated the expected displacement of the fringes due to Earth's motion. *Figure* A(i) corresponds to the case when the apparatus is at rest with respect to the ether and *Figure* A(ii) represents the apparatus moving along direction ***sc*** coincident with the motion of Earth in its orbit.

In *Figure* A(i), the two rays of light – ***ab*** and ***ac*** – get reflected in the mirrors ***b*** and ***c*** and interfere along ***ad*** if the paths ***ab*** and ***ac*** are equal. In *Figure* A(ii), the direction ***ab*** will no longer be perpendicular to the mirror at ***b*** and will be reflected in the direction $\boldsymbol{ba}_1$ but would still go to the focus of the telescope if the objective was large enough. The angle $\boldsymbol{aba}_1$ is twice the aberration angle, ***a***. The transmitted ray goes along ***ac***, is returned along $\boldsymbol{ca}_1$, and is reflected at $\boldsymbol{a}_1$, making the angle $\boldsymbol{ca}_1$ equal to $90 - a$, therefore still coinciding with the first ray, although they do not meet at exactly the same point $\boldsymbol{a}_1$. The difference in the two paths $\boldsymbol{aba}_1$, and $\boldsymbol{aca}_1$ would be responsible for shift of the fringes. Michelson and Morley were now confident that even after this correction was incorporated, the expected fringe shift would be measurable with the new instrument (*Box* 2).

A photograph of the experimental setup is shown in *Figure* 3 [3] and the vertical section of the mounting system in *Figure* 4 [2]. The stone slab ***a*** measured about 1.5 meter square and 0.3 meter thick resting on an annular wooden float ***bb***. The wooden float rested on mercury contained in the cast-iron trough ***cc***, of such dimensions as to leave a clearance of about one centimeter around the float. A pin ***d***, guided by arms ***gggg***, fits into a socket ***e*** attached to the float to it concentric with the trough without bearing any part of the weight of the stone. This allowed the whole interferometer with its support to rotate freely.

To increase the path length travelled by the two light rays, four optically plane mirrors made of of speculum alloy (2/3 Cu and 1/3 Sn) were placed at each corner of the stone. Near the center of the stone was a plane-parallel glass, which split the light from a

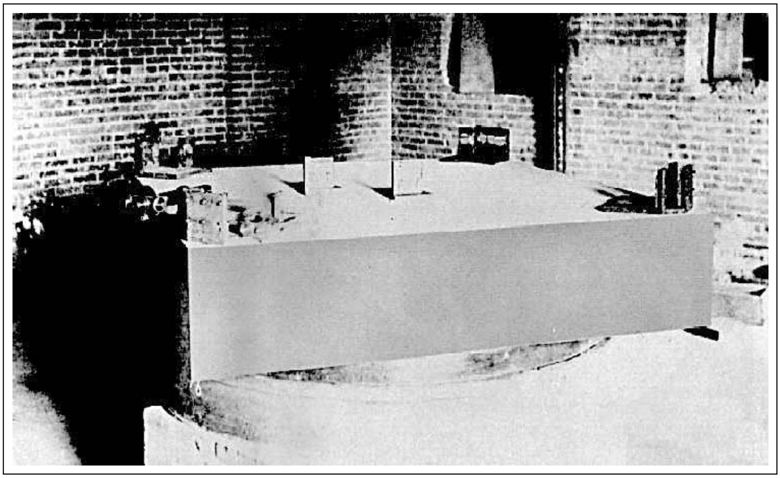

Figure 3. Michelson and Morley's interferometric setup, mounted on a stone slab that floats in an annular trough of mercury. (https://commons.wikimedia.org/wiki/File:Michelson_Morley_experiment_1887.jpg)

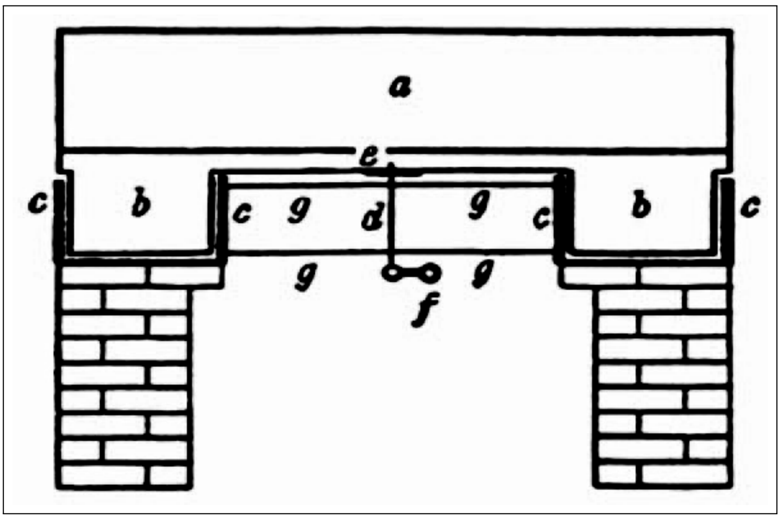

Figure 4. Sketch of the front view of the mounting system for the Michelson–Morley experiment [2].

lamp in two perpendicular directions to the mirrors in the corners. Another identical glass plate was placed in the path of one of the rays to compensate for the passage of the other through the same thickness of glass. The whole of the optical portion of the apparatus was kept covered with a wooden cover to prevent air currents and rapid changes of temperature [2].

The procedure to get the interferometer ready for observations was the same as followed in the 1881 experiment. The two perpendicular optical paths were equalised first using a sodium lamp. Then an argand lamp[1] was used as a source of white light. The apparatus was revolved very slowly (one turn in six minutes) and the positions of the interference fringes were noted at 16 positions in one revolution. The readings were taken while the apparatus was in motion as the results were much more uniform and consistent than when the stone was brought to rest for every observation. Measurements were taken till the apparatus had completed six revolutions. The observations were repeated at noon and evening for a few days to check for any diurnal variation. The displacement was expected to show a sinusoidal variation as the apparatus rotated through 360 degrees.

[1] Invented by Aime Argand in 1780, giving light equivalent of 6–10 candles.

The experiment yielded a maximum displacement of less than one-twentieth, rather close to one-fortieth of the expected fringe shift, and hence ruled out any relative motion between the Earth and ether. Cautious experimenters that they were, Michelson and Morley added that "but since the displacement is proportional to the square of the velocity, the relative velocity of the Earth and the ether is probably less than one sixth the Earth's orbital velocity, and certainly less than one-fourth" [2]. The null result obtained by Michelson and Morley is regarded as the first strong evidence against the existence of the ether.

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G F FitzGerald and H A Lorentz offered an explanation of the null result using the ad hoc hypothesis of Lorentz–Fitzgerald contraction in which, the apparatus moving relative to the ether contracted in length in the direction of travel. The amount of contraction was worked out to be just the right amount needed to compensate for the fringe shift expected. Einstein showed that the Lorentz–Fitzgerald contraction formula were a consequence of the special theory of relativity without referring to ether at all. Einstein had known about the null results of Michelson–Morley experiment as a student, and it might have influenced his thinking about having no fixed inertial reference frame. However, his formulation of special theory of relativity was probably based on purely theoretical postulates of relativity and constancy of velocity of light, and not on the experimental results.

Over the years, many experiments were performed refining the sensitivity of the Michelson–Morley experiment using new instruments. Recent experiments using optical resonators to measure anisotropy in the speed of light have since reduced the possible value to a number very close to zero, about 10^{-17} [4].

Michelson's interferometer finds application in many fields of study, and he himself showed in 1890 that it could be used to measure the diameter of a star. Michelson went on to receive the Nobel Prize in Physics in 1907 with the citation, *for his optical precision instruments and the spectroscopic and metrological investigations carried out with their aid.* Recently, the same interferometric principle has been employed by LIGO to observe gravitational waves, throwing open a new window to observe the cosmos.

Suggested Reading

[1] **Albert A Michelson, The Relative Motion of the Earth and the Luminiferous Ether, *American Journal of Science*, Vol.22, pp.120–129, 1881.**

[2] **Albert A Michelson, Edward W Morley, On the Relative Motion of the Earth and the Luminiferous Ether, *American Journal of Science*, Vol.34, pp.333–345, 1887.**

[3] **https://commons.wikimedia.org/wiki/File:Michelson_Morley_experiment_1887.jpg.**

[4] **Eisele, Ch., Nevsky, A Yu., S Schillerv, Laboratory Test of the Isotropy of Light Propagation at the 10–17 Level, *Physical Review Letters*, Vol.103, No.9, p.090401; 2009. S Herrmann; A Senger, K Möhle, M Nagel, E V Kovalchuk, A Peters, 2009. Rotating Optical Cavity Experiment Testing Lorentz Invariance at the 10–17 level, *Physical Review*, Vol.D 80, No.100, p.105011.**

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