September 2018

# Lecture Notes for 8.225 / STS.042, "Physics in the 20th Century": Electrodynamics for Maxwell and Lorentz


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**Lecture Outline:**

1. Waves for Maxwell and Lorentz
2. The Michelson-Morley Experiment
3. Lorentz Contraction

# Introduction

Today we are going to continue examining electrodynamics the way that good mathematical physicists in the late 19th century did, to consider how they approached certain problems. This will make the contrast with young Albert Einstein's approach, to which we will turn in the next lecture, more clear.

To begin, we need to go back to a central conclusion that James Clerk Maxwell reached in the 1860s: all of space is filled with a physical, material substance (the "luminiferous ether"), and light was simply the "transverse undulation" of electric and magnetic fields within the ether. How did Maxwell arrive at this conclusion? Reviewing Maxwell's approach will make more clear how later physicists, such as the Dutch mathematical physicist Hendrik A. Lorentz, sought to work within Maxwell's program and extend it further. We will see that Lorentz had at least two distinct challenges in mind when he began working on the electrodynamics of moving bodies in the 1880s and 1890s.

# 1 Waves for Maxwell and Lorentz

## 1.1 Maxwell's "Transverse Undulations" in the Ether

We begin with a quick review of *wave physics*, and how Maxwell's equations for electricity and magnetism led him to think about light as waves of electric and magnetic fields. For the sake of brevity, we will write Maxwell's equations in their modern form, using the vector notation that a later Maxwellian — Oliver Heaviside — invented in the mid-1880s specifically to make Maxwell's equations easier to manipulate:[1]

$$\begin{aligned} \nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t}, \\ \nabla \times \mathbf{H} &= \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}, \\ \nabla \cdot \mathbf{D} &= 4\pi\rho, \\ \nabla \cdot \mathbf{B} &= 0. \end{aligned} \tag{1}$$

Here **E** and **B** are the electric and magnetic fields, and **D** and **H** are the electric displacement and magnetic field strength, respectively. The fields **D** and **H** quantify how a given material is affected by external electric and magnetic fields. In general, the fields **D** and **H** are related to **E** and **B** by the properties of the medium or material:

$$\mathbf{D} = \epsilon\,\mathbf{E} \ , \quad \mathbf{B} = \mu\,\mathbf{H}, \tag{2}$$

where $\epsilon$ is the "dielectric constant" and $\mu$ is the "magnetic permeability." To us, today, $\epsilon$ and $\mu$ quantify how readily the internal constituents within a material — including its electrons, ions, and/or clusters of such objects, such as electric and magnetic dipoles — can reorient themselves when an external electric or magnetic field is applied.[2] To Maxwell and his British colleagues, on the other hand, the parameters $(\epsilon, \mu)$ were related to the elastic properties of the underlying ether or other materials; that is, they were analogous to *spring constants*, indicating how quickly a given material could *dissipate* stresses or tensions that arose from the presence of electromagnetic fields.[3]

Maxwell calculated how quickly electric and magnetic disturbances would propagate within the ether — that is, in regions in which there were no external sources of charge or current (so that $\rho = \mathbf{J} = 0$). Being a highly trained Cambridge Wrangler, he had practiced how to use various mathematical identities among the differential operators, such as the following handy identity: for any vector **F**, one may write[4]

$$\nabla \times (\nabla \times \mathbf{F}) = \nabla\,(\nabla \cdot \mathbf{F}) - \nabla^2 \mathbf{F}. \tag{3}$$

He then found that within an otherwise empty region of space that contained only ether,

[1] See Bruce Hunt, *The Maxwellians* (Ithaca: Cornell University Press, 1991), 245-247.

[2] See, e.g., David Griffiths, *Introduction to Electrodynamics*, 4th ed. (New York: Cambridge University Press, 2017), chaps. 4 and 6.

[3] See esp. Jed Buchwald, *From Maxwell to Microphysics* (Chicago: University of Chicago Press, 1985); and Olivier Darrigol, *Electrodynamics from Ampère to Einstein* (New York: Oxford University Press, 2000).

[4] On the training of Cambridge Wranglers, see esp. Andrew Warwick, *Masters of Theory: Cambridge and the Rise of Mathematical Physics* (Chicago: University of Chicago Press, 2003).

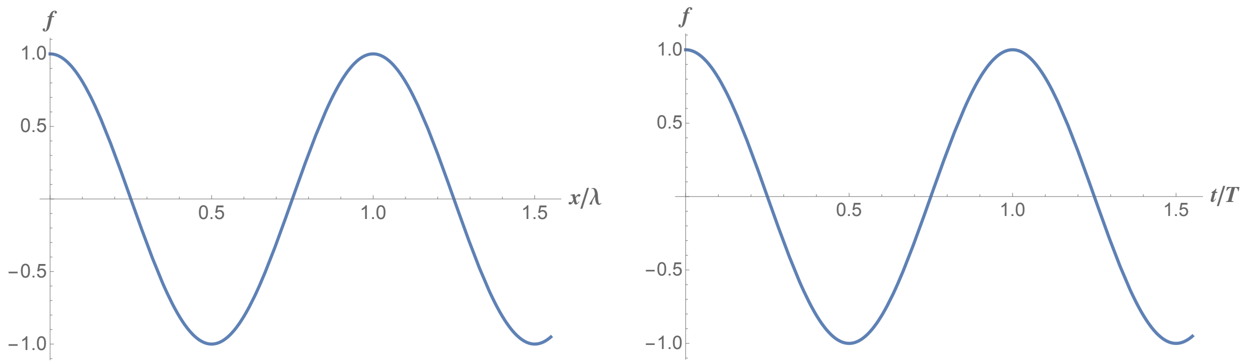


Figure 1: The function $f(t,x)$ of Eq. (6) is a solution to Eq. (5) in one spatial dimension. Shown here is $f(t,x)$ with $A=0$, $B=1$. At a given moment in time, the function $f(t,x)$ oscillates in space with a characteristic wavelength $\lambda$ (*left*); at a given location in space, the function $f(t,x)$ oscillates over time with a characteristic period $T$ (*right*).

the electric and magnetic fields would each obey an equation of the same form:

$$\left[\nabla^2 - \epsilon_0\mu_0 \frac{\partial^2}{\partial t^2}\right] \mathbf{E} = 0\,, \quad \left[\nabla^2 - \epsilon_0\mu_0 \frac{\partial^2}{\partial t^2}\right] \mathbf{B} = 0, \tag{4}$$

where $\epsilon_0$ and $\mu_0$ (to Maxwell) were the corresponding "spring constants" of the ether itself.

Why did Maxwell interpret this result in terms of the propagation of *light*? Because (as he knew from his Cambridge Tripos training) this is the general form of a *wave equation*, which generically takes the form:

$$\left[\nabla^2 - \frac{1}{v^2}\frac{\partial^2}{\partial t^2}\right] f(t,\mathbf{x}) = 0, \tag{5}$$

where $v$ is the speed of the traveling wave. Why is Eq. (5) known as a "wave equation"? For simplicity, let us consider motion in a single direction of space, so that $\mathbf{x} \rightarrow x$. Then we see that solutions of Eq. (5) may be written in the form

$$f(t,x) = A\sin(kx + \omega t) + B\cos(kx + \omega t), \tag{6}$$

where $A$ and $B$ are constants, and we have introduced the *wavenumber* ($k$) and the angular *frequency* ($\omega$) as:

$$k \equiv \frac{2\pi}{\lambda}\;,\;\; \omega \equiv \frac{2\pi}{T}, \tag{7}$$

in terms of the *wavelength* ($\lambda$) and the *period* ($T$). From Eq. (6), we see that solutions to the wave equation of Eq. (5) simply *oscillate* in space and time. Moreover, the quantities $\lambda$ and $T$ are related to the speed of the wave, $v$, which appears in Eq. (5):

$$v = \frac{\lambda}{T} = \frac{\omega}{k}. \tag{8}$$

When Maxwell applied the quantitative values for $\epsilon_0$ and $\mu_0$ that had been inferred from various electromagnetic experiments, he found that

$$\epsilon_0\mu_0 \simeq \frac{1}{c^2}, \tag{9}$$

where $c \simeq 3 \times 10^5$ km/s was the speed of light that researchers had independently inferred from various astronomical phenomena. *That* is what convinced Maxwell that light consisted of "transverse undulations" of electric and magnetic fields in the luminiferous ether: the fields $\mathbf{E}$ and $\mathbf{B}$ obeyed the simple wave equation of Eq. (4), with the speed of the waves given by $v = 1/\sqrt{\epsilon_0\,\mu_0} = c$.[5]

## 1.2 H. A. Lorentz: Generalize for Moving Sources or Receivers

Maxwell's deep insight, which united optics with electricity and magnetism, had been accomplished by assuming that both the source of light and the receiver of the light were at rest with respect to the ether. Beginning in the 1880s, the great Dutch mathematical physicist Hendrik A. Lorentz tried to generalize these results to the case in which either the emitter or receiver of light was *in motion* relative to the ether. Hence Lorentz and his contemporaries were concerned with the general problem of "the electrodynamics of moving bodies." Lorentz had both mathematical and experimental motivations for his work. We will first consider the mathematical side.

Lorentz knew how to relate the coordinates of different frames of reference which were moving with a constant speed $v$ with respect to each other: these were simply the coordinate transformations that Galileo had first formulated in the early 1600s, and that Newton had codified in the late 1600s:

$$x' = x + vt \ \ , \ \ t' = t. \tag{10}$$

(Reference frames that move with a constant speed are called "inertial frames of reference.") Note, in particular, that there was no change for the *time* coordinate: for Galileo and Newton (and their followers right through the end of the nineteenth century), time was simply time, and all observers should agree on the rate at which time passes.[6] (Newton had famously written in the opening passages of his great *Principia Mathematica* in 1687 that "Absolute, true, and mathematical time, of itself, and from its own nature, flows equably without relation to anything external, and by another name is called duration."[7] In short: time is absolute.)

[5]See, e.g., Darrigol, *Electrodynamics from Ampère to Einstein*, 151-53, 162.

[6]See, e.g., Alberto A. Martínez, *Kinematics: The Lost Origins of Einstein's Relativity* (Baltimore: Johns Hopkins University Press, 2009).

[7]Isaac Newton, *The Principia: Mathematical Principles of Natural Philosophy*, trans. I. Bernard Cohen and Anne Whitman (Berkeley: University of California Press, 1999), 408.

When Lorentz used this Galilean coordinate transformation and looked at what the resulting equation for the **E** and **B** fields would look like in the moving frame, he found (restricting to a single spatial dimension for simplicity):

$$\left[\frac{\partial^2}{\partial x'^2} - \frac{1}{c^2}\left(\frac{\partial}{\partial t'} - v\frac{\partial}{\partial x'}\right)^2\right]\mathbf{E}'(t', x') = 0, \tag{11}$$

and a similar equation for $\mathbf{B}'(t', x')$. But Eq. (11) does not look like the simple form of a wave equation; in particular, solutions to Eq. (11) would not be simple sines and cosines, akin to the wave behavior we found in Eq. (6).[8]

So what? Lorentz knew that we (on the *moving* Earth) often do observe light behaving as sines and cosines. So if the ether is real, and the Earth is really moving through it, how could it be that we observe optical phenomena behaving as if the **E** and **B** fields obeyed Eq. (4) rather than Eq. (11)?

This presented Lorentz with an important mathematical challenge within the Maxwellian tradition: how to bring the new equations for $\mathbf{E}'(t', x')$ and $\mathbf{B}'(t', x')$, which would hold in a moving reference frame, into the familiar form that had worked so well when describing optical experiments.

Lorentz was a very talented mathematical physicist, and he realized that if he introduced a new set of hypothetical rules for coordinate transformations — distinct from the familiar Galilean transformation — he could put the wave equation for $\mathbf{E}(t', x')$ and $\mathbf{B}(t', x')$ in the same form as for the stationary case in Eq. (4). In particular, if the new time coordinate, $t'$, became a function of $x$, $t$, and $v$, just as $x'$ transformed as a function of $x$, $t$, and $v$, then Lorentz could preserve the form of the wave equation. He called the new coordinate $t' = t'(x, t, v)$ the "local time," and considered it little more than a mathematical *trick*: in the end, Lorentz concluded, $t'$ would always be referred back to the genuine, absolute time $t$ of the ether rest frame.

This was Lorentz's *mathematical* response to the quandary of the electrodynamics of moving bodies: to alter the Galilean coordinate-transformation rules in order to save the form of a particularly important set of equations. We'll see in the next section that Lorentz also had an *experimental* reason for adopting the new transformation rule as well.

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[8]See, e.g., Darrigol, *Electrodynamics from Ampère to Einstein*, 327-28; and Arthur I. Miller, *Albert Einstein's Special Theory of Relativity: Emergence (1905) and Early Interpretation (1905-1911)*, 2nd ed. (New York: Springer, 1998), 18-37.

# 2 The Michelson-Morley Experiment

Like all good mathematical physicists of the era, Lorentz knew that light propagated in the ether: the ether was the medium in which light waves traveled. Hence there was a natural question which occupied the efforts of many physicists in the late 19th century: could one detect the Earth's motion *through* this all-pervasive ether? Clearly the Earth moved around the Sun, and it seemed extremely unlikely that the ether would be moving exactly along with the Earth — so there must be some relative motion between the stationary ether and the moving Earth. Add on top of this the fact that the ether supported light in its travels, and some researchers sought to use the behavior of light to measure the Earth's motion through the ether. This was the experimental context in which Lorentz sought to extend Maxwell's study of light and ether.

## 2.1 The Interferometer

The most sensitive experiment performed to test for the Earth's motion through the ether was devised and conducted by the American experimental physicist Albert Michelson in the 1880s. Michelson was working at what is now known as Case Western Reserve University in Cleveland, Ohio, and was already a renowned expert in optics; in fact, he was the first US-based physicist to win the Nobel Prize in Physics, which he received in 1907. At the time, his research was among the very few efforts in the US that European-based physicists paid any attention to; the scientific community in the US otherwise still seemed like a backwater compared to the leading centers in Western Europe.[9]

Michelson's most significant contribution was to use the *interference of light* to test for the Earth's motion through the ether. To understand his new instrument, the *interferometer*, it will help us to first consider two swimmers in a river. Imagine that each swimmer can only swim at a constant speed $c$ with respect to the water; meanwhile, the river flows with respect to the shore with a constant speed $v$. One swimmer swims directly against the current for a length $L$, and then for her return trip she swims directly with the current. The other swimmer swims across the river a length $L$ and then back. The question: *who will win the race?*

For each leg of each swimmer's journey, we know that

$$\text{time} = \frac{\text{distance}}{\text{speed}}. \tag{12}$$

For the first leg of her journey, the first swimmer has a speed relative to the shore of $(c-v)$,

[9]See Daniel J. Kevles, *The Physicists: The History of a Scientific Community in Modern America*, 3rd ed. (Cambridge: Harvard University Press, 1995), 27-29.

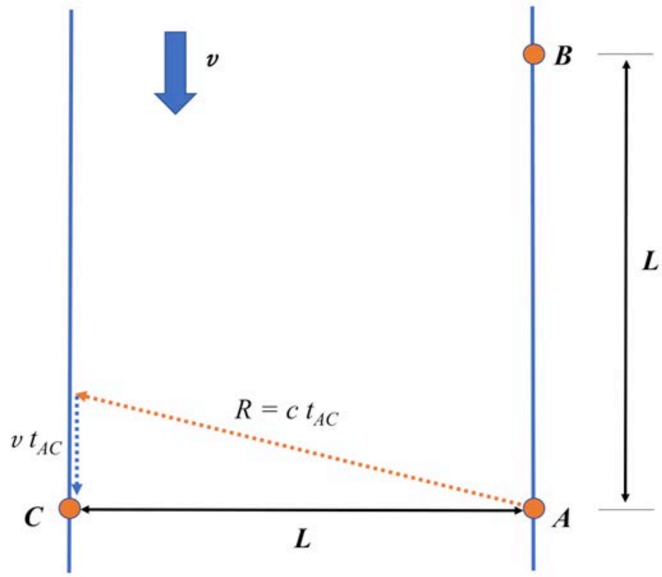


Figure 2: An analogy for the Michelson-Morley interferometer: two swimmers race in a river with current $v$. They each swim at speed $c$ with respect to the water. The first wimmer starts at point $A$ and swims a distance $L$ to point $B$, then swims back to $A$. The second swimmer starts at point $A$ and swims a distance $L$ across the river to point $C$, then swims back.

because she is fighting the river's current. So her time to swim the length $L$ from location $A$ to location $B$ is

$$t_{AB} = \frac{L}{(c - v)}. \tag{13}$$

For her return trip from $B$ to $A$, her speed as measured from the shore is $(c + v)$ — she picks up the speed of the river. So her time to swim from $B$ back to $A$ is

$$t_{BA} = \frac{L}{(c + v)}. \tag{14}$$

The total time for her lap is then

$$t_{ABA} = \frac{L}{(c - v)} + \frac{L}{(c + v)} = \frac{2L}{c} \frac{1}{\left[1 - \left(\frac{v^2}{c^2}\right)\right]}. \tag{15}$$

The second swimmer must set off at a diagonal to offset the effects of the river's current. Since the river is a distance $L$ across, she will swim along the diagonal $R$ in time $t_{AC}$. During that time, the river's current will push her straight down a length $vt_{AC}$. We may then analyze her path in terms of a right triangle, and use the Pythagorean theorem:

$$R^2 = (vt_{AC})^2 + L^2. \tag{16}$$

But remember that she swims at speed $c$ with respect to the water, so $R = ct_{AC}$. Substituting

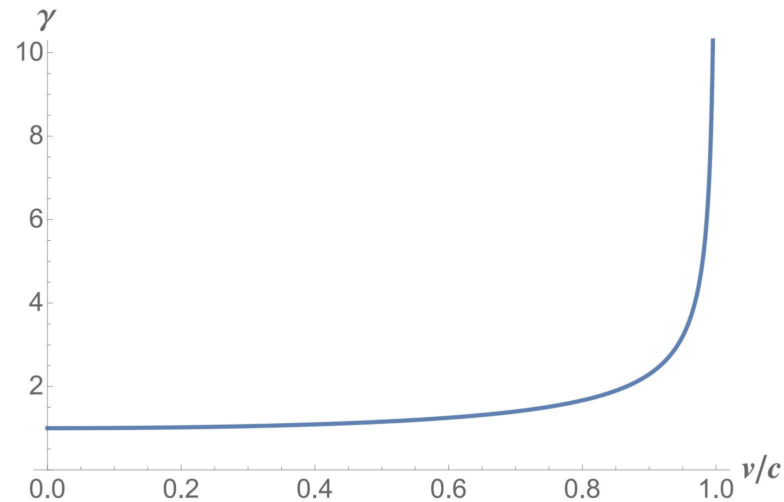


Figure 3: The function $\gamma$ of Eq. (19). For $v \ll c$, $\gamma \simeq 1$, but $\gamma \gg 1$ as $v \to c$.

into Eq. (16), we then have

$$\begin{aligned} (ct_{AC})^2 &= (vt_{AC})^2 + L^2 \\ \longrightarrow t_{AC} &= \frac{L}{c} \frac{1}{\sqrt{1 - \left(\frac{v^2}{c^2}\right)}}. \end{aligned} \tag{17}$$

Her return trip is symmetrical, so we find $t_{CA} = t_{AC}$, and hence

$$t_{ACA} = t_{AC} + t_{CA} = \frac{2L}{c} \frac{1}{\sqrt{1 - \left(\frac{v^2}{c^2}\right)}}. \tag{18}$$

Let us define

$$\gamma \equiv \frac{1}{\sqrt{1 - \left(\frac{v^2}{c^2}\right)}}. \tag{19}$$

We note that $\gamma \geq 1$ for all $0 \leq v \leq c$.

So who wins the race? Written in terms of $\gamma$, we have found

$$t_{ABA} = \left(\frac{2L}{c}\right) \gamma^2 \ , \ t_{ACA} = \left(\frac{2L}{c}\right) \gamma. \tag{20}$$

We just saw that for $v \neq 0$, $\gamma > 1$, and hence if there is a current in the river, then swimmer 1 takes a *longer time* to return to the starting point than does swimmer 2. So swimmer 2, who set off across the river along the diagonal, wins the race. Moreover, we see that the difference in their times is

$$\begin{aligned} \Delta t = t_{ABA} - t_{ACA} &= \left(\frac{2L}{c}\right) \gamma(\gamma - 1) \\ &= \left(\frac{L}{c}\right) \left(\frac{v}{c}\right)^2 + \mathcal{O}\left[\left(\frac{v}{c}\right)^4\right]. \end{aligned} \tag{21}$$

The race is close: the difference in the two swimmers' lap times is *second order* in the ratio $(v/c)$; hence this race is sensitive to "second-order" effects in $(v/c)$.

Albert Michelson realized that this thought experiment involving swimmers in a river with a current flowing should hold true for light as measured on a moving Earth as well. Like the swimmers, light will travel at a constant speed through the stationary ether, at speed $c$. But if the Earth is moving through the ether, there should be an "ether wind" that we would feel on our moving platform — like the wind you feel on your face when you ride a bicycle through calm air. When you're at rest with respect to the air, you don't feel any wind, but as soon as you begin to move with respect to the air, you feel the wind on your face. Michelson built his *interferometer* to measure this ether wind on Earth. One of the arms of the interferometer would be aligned with the Earth's motion, and hence light beams traveling along that route would be like the first swimmer, swimming directly against the river's current, and then directly with it for the return trip. The second arm of the interferometer would be perpendicular to this ether wind; light rays traveling along that arm would be akin to the swimmer who set off across the river.

Just like the swimmers, light that set off along the second arm (perpendicular to the ether wind) should therefore return to the starting point *before* light from the first arm did. If the light waves that followed these distinct paths took different amounts of time to return to the starting point, then they would arrive *out of phase* with each other: crests of one light wave would not line up with crests of the second light wave. Hence there should be *interference* of the two waves — a pattern that would be readily observable as a series of bright and dark patches on a screen. The specific interference pattern would depend on the magnitude of the time delay between the two light waves, and hence on the Earth's motion through the ether, $v$. Thus, reasoned Michelson, he should be able to measure precisely the Earth's speed through the stationary ether.

He built a modest-sized instrument (with each arm about 1 meter long) and found no interference pattern. But we saw in Eq. (21) that the time difference (and hence the details of the expected interference pattern) scaled with $L$, the length of the arms. So in 1887, Michelson built a much larger device, together with his assistant, Edward Morley. Their new instrument had arms 11 meters long. They set the entire apparatus floating on a huge vat of mercury to dampen vibrations from the street, and they took careful measurements over several months: swapping the direction in which the arms pointed, looking for seasonal effects, and so on.[10]

[10]Gerald Holton, "Einstein, Michelson, and the 'crucial' experiment," in Holton, *Thematic Origins of Scientific Thought: Kepler to Einstein*, rev. ed. (Cambridge: Harvard University Press, 1988), 279-370; see also Darrigol, *Electrodynamics from Ampère to Einstein*, 316-19.

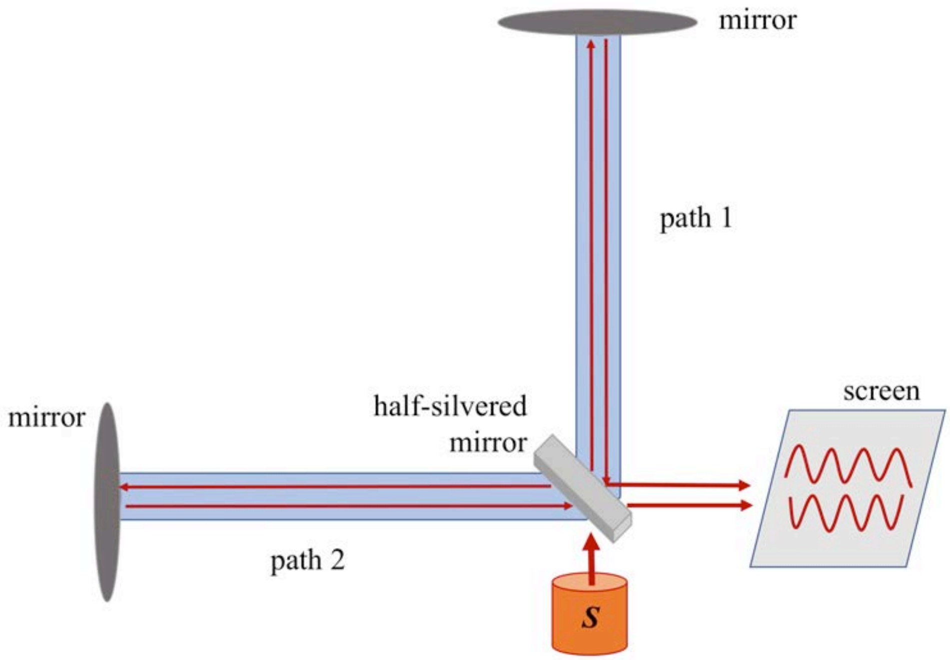


Figure 4: Schematic of the Michelson interferometer. Light from a monochromatic source ($S$) encounters a half-silvered mirror. Half of the light passes through and travels a length $L$ along path 1 before being reflected by a mirror; half of that returning wave is reflected by the half-silvered mirror and reaches the screen. In the meantime, half of the original beam is reflected by the half-silvered mirror and travels down the other arm of the interferometer for a length $L$ along path 2, before being reflected by a mirror; half of that returning wave is transmitted by the half-silvered mirror and reaches the screen. If the light waves from each path take different amounts of time before reaching the screen, they will be out of phase with each other, revealing a characteristic interference pattern on the screen.

To Michelson's shock and lifelong disappointment, he never measured any interference pattern. His results were consistent with the race always being a tie, with $\Delta t = 0$, time and time again. This was a huge puzzle: light was clearly a wave in the ether; the Earth was clearly in motion through the ether; and Michelson had built the most sensitive instrument ever with which to try to measure the effects of the Earth's motion through the ether. He considered himself a failure, right up to his death in 1927. (May we all win the Nobel Prize but remain unsatisfied...)

# 3 Lorentz Contraction

The "null result" which Michelson and Morley found time and time again bothered many of the leading European theorists, much as it bothered Michelson. Hendrik Lorentz, in particular, labored to make sense of the experimental result. He concluded that there must be a *physical contraction* of the entire apparatus along the direction of motion — and that this contraction should exactly offset what should have been a longer travel time for one of the light waves. If the arm of the interferometer that was moving directly into the ether wind became *shortened*, then the light waves that traveled along that path would have a shorter distance to travel, and hence they would arrive back at the starting point at the *same time* as the light waves in the other arm; the race would become a tie, and no interference fringes should be observed.

The main idea, which Lorentz first published in 1892 and to which he returned throughout the 1890s and early 1900s, was that the physical material making up the apparatus actually shrunk (along the direction of motion) due to the resistance of the ether. Lorentz cautiously noted in his papers and in correspondence from the time that it was "not inconceivable," and "not far-fetched to suppose" such a physical deformation due to the ether.[11]

For one thing, the effect would be small — remember, Lorentz was trying to account for a *second-order* effect, proportional to $(v/c)^2$. To get an estimate for the expected size of such an effect, Lorentz approximated $v$ (for the Earth's motion through the ether) based on the Earth's speed through the Solar System as it orbits the Sun: $v \simeq 2\pi r/T \sim 10^{11}\,\mathrm{m}/(10^7\,\mathrm{sec}) = 10^4\,\mathrm{m/sec}$. Given the speed of light $c = 3 \times 10^8\,\mathrm{m/sec}$, this yielded

$$\left(\frac{v}{c}\right)^2 \sim 10^{-8}, \tag{22}$$

meaning that the effect would be about one part in a hundred million!

[11] See, e.g., Darrigol, *Electrodynamics from Ampeère to Einstein*, 327-28. The Irish mathematical physicist George F. FitzGerald had made a similar suggestion in 1889, though Lorentz appears not to have known about FitzGerald's short paper at the time.

Moreover, Lorentz reasoned by analogy that one could see all kinds of physical deformations when bodies traveled through viscous, resistive media, such as a beach ball being dragged at high speed under water: the beach ball would become squeezed along the direction of motion. If the ether was a physical, elastic medium, then hydrodynamical analogies like this should hold — leading to an expectation that the arm of the interferometer really should become shorter along the direction of motion.

Lorentz therefore suggested his hypothesis of *length contraction*: perhaps the length of objects shrunk by a small amount along their directions of motion through the ether, to be

$$L' = \frac{L}{\gamma}, \tag{23}$$

where $\gamma$ was the factor defined in Eq. (19). In that case, then the time for the first swimmer's lap would be adjusted. Instead of $t_{ABA}$ of Eq. (15), her return-trip time would be

$$\begin{aligned} t'_{ABA} &= \frac{2L'}{c}\gamma^2 \\ &= \frac{2}{c}\left(\frac{L}{\gamma}\right)\gamma^2 \\ &= \frac{2L}{c}\gamma \\ &= t_{ACA}, \end{aligned} \tag{24}$$

and hence $\Delta t = 0$ — the race would be a tie, after all, and no interference fringes would be detected within Michelson's interferometer.

Moreover, as we saw earlier, Lorentz had already figured out from his mathematical analysis that in order to retain the proper *mathematical* form for the wave equation for light, he would need to change *both* his spatial coordinates and his time coordinate, to introduce "local time." In place of the usual Galilean transformation of Eq. (10), Lorentz found what we now call the "Lorentz transformations":

$$\begin{aligned} x' &= \gamma(x + vt), \\ t' &= \gamma\left(t + \frac{vx}{c^2}\right), \\ y' &= y, \\ z' &= z, \end{aligned} \tag{25}$$

for motion along the $x$ direction at speed $v$. By making *both* $x'$ and $t'$ for the moving frame involve the rest frame's coordinates $x$ and $t$, Lorentz could keep the form of the wave equation unchanged:

$$\left[\frac{\partial^2}{\partial x'^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t'^2}\right]\mathbf{E}'(t', x') = 0, \tag{26}$$

and likewise for $\mathbf{B}'(t', x')$. In both reference frames — on the moving Earth and with respect to the stationary ether — light would simply move as a wave of speed $c$ *with respect to the ether.*[12]

Thus Lorentz addressed two puzzles — mathematical and experimental — regarding the electrodynamics of moving bodies. Based on the idea of the ether as a physical, elastic, resistive medium, he concluded that there should arise a *physical contraction* of material along the direction of motion through the ether, which would be accommodated by adopting a new coordinate transformation between the frames of reference. With these postulates, the null result of the Michelson-Morley experiment could be explained: one arm of the interferometer shrank by exactly the right amount to cancel out the time delay in travel times for the two light waves.

More generally, Lorentz's approach was to postulate a *physical force* to explain things like different clock rates and measured lengths for observers moving through the ether. That is, he began with *dynamics* (the study of forces) in order to account for *kinematics* (the motion of objects through space and time).

An unknown patent clerk working in Bern, Switzerland — far away from the main centers of physics at the time — re-derived the Lorentz transformation rules for $x'$ and $t'$ in 1905, but from a wholly different set of starting assumptions. As we will see in the next lecture, to the young Albert Einstein, the challenge of "the electrodynamics of moving bodies" suggested quite different types of responses.

[12]See, e.g., Darrigol, *Electrodynamics from Ampère to Einstein*, 327-28; and Miller, *Albert Einstein's Special Theory of Relativity*, 18-37.