

(relativity1)=

Lesson 15: Special Relativity, 1

▮ *Confusion about light.*

∴{admonition} What's Coming: Arguably one of the most important experiments in the last two centuries, and certainly the most important measurement ever of **zero**, starts in the Wild West of gold and silver mining – literally, the Wild West – and passes through Stockholm and the Nobel Prize. Let's talk about one of the more interesting physicists of all. Albert Michelson. ∴∴

(michelson)=

A Little Bit About Michelson

Faced with a difficult situation, he did what any mid-19th century 16 year old would do: he boarded the brand new Transcontinental Railroad at Oakland Land Wharf in San Francisco and went to Washington, D.C. to see the president. Albert was nothing, if not persistent.

Albert Michelson (1852 - 1931) was born in Poland and as a two year-old with his merchant-class family moved to the United States. The Michelsons were adventurous — facing hardship in Poland, they resolutely traveled to the wild west (a harrowing passage through lawless and diseased Panama) and became store-owners in various mining communities in California and Nevada, settling in the nearly untamed Murphy's Camp, California. A bad cowboy movie, lawless, gold-rush western town. His mother exported Albert to relatives in San Francisco where excelled in high school. College was in his future but his path was unusual: he applied in a competition to the relatively new United States Naval Academy at Annapolis, Maryland and was rejected. Hence, his audacious trip

to see President Grant who received him at the White House and eventually personally admitted him (above the prescribed number of cadets) to Annapolis as a midshipman in 1869. He graduated and did his two years at sea and returned to the Academy as an instructor. He always joked that he was probably illegally a student at the Naval Academy.

He fell into measuring the speed of light as a laboratory exercise for his students. This had only been measured on Earth 15 years earlier when Léon Foucault at the Paris Observatory created a clever apparatus involving a precisely measured rotating mirror to do so. Foucault found $c = 313,000,000$ m/s with a precision limited by the length of the light path in his instrument. It was Foucault's result that clued Maxwell into the fact that he'd found a model of light that worked.

This was the technique that Michelson adapted for his midshipmen students and by 1879, he'd improved on the results by a factor of 20 finding $c = 299,910,000 \pm 50,000$ m/s. (He never quit. In 1924 he improved this to $c = 299,796,000 \pm 4,000$ m/s with a light path stretching across the hills outside of the Hale Observatory near Pasadena.)

The rest of Michelson's life was consumed by making precision instruments to measure various features of light. He was the King of Optics – the master experimentalist in the measurement of precision optical phenomena leading to heroically precise techniques to measure c to very high precision. His expertise allowed for a leave of absence from the Navy and the opportunity to study in Germany for a while and to return to making increasingly better measurements of c . He was working on such a measurement using a mile-long evacuated tube when he died in 1931.

Michelson was notoriously stern and difficult (although he was an accomplished artist, musician, tennis player, and billiards player). He also led an interesting life. His first wife tried to have him committed and a maid sued him for abusive solicitation. He once had an argument about an experiment with a colleague in a hotel lobby that drew a crowd, maybe because they were loud and maybe because Michelson was still in his pajamas. He won the Nobel Prize in 1907, not for his most famous measurement of zero, but for his exquisitely precise instruments and the collection of scientific measurements that he made with them.

That Zero: "...it is absurd to imagine"

As a graduate student in 1880 in Hermann von Helmholtz's famous Berlin laboratory, against everyone's advice, Michelson decided to follow an off-hand comment of Maxwell's in a letter written the year before, during his last year of life. Maxwell imagined a way to measure the speed of the Earth relative to the fixed ether, but lamented that the precision required was beyond any terrestrial technique. This captured Michelson's attention and the speed of light went on the back-burner as he embarked on his most important – and personally disappointing – experiment.

What's Waving?

What's more ridiculous than a wave that has nothing to wave in?

From the time of Aristotle, it was assumed that empty space was not empty, but consisted of a strange substance archaically called "aether" and in the 19th century, "ether." The persistent belief in this substance was reinforced in the 19th century when Newton's demand that light consisted of particles was dethroned by (the young) Thomas Young's (unwelcome – he was drummed out of British science for disputing Newton) demonstration that light consisted of waves. This was the passage of light through two slits, showing that the emerging waves diffracted – only waves do that. We considered that in detail in a previous lesson.

Maxwell's subsequent unification of electricity, magnetism, and optics into a single model of waves of electric and magnetic field vectors and Hertz's demonstration of their existence made it clear: light, electricity, and magnetism are waves and so it has to propagate in a substance which supports that disturbance. The ether was to light as water is to a dropped pebble and air is to sound. And nobody imagined otherwise. Sir Oliver Lodge was passionate (and relentless) on the subject, even after it was clear he was wrong:

... it is absurd to imagine one piece of matter acting mechanically on another at a distance, whether that distance be large or small, without some intervening mechanism or connecting link...

But Maxwell Said c !

There was a serious fundamental problem. The solution to Maxwell's equations is indisputably a wave and furthermore, the speed of that wave is a single number, $c = 300,000$ km/s. *But with respect to what?* Maxwell's model didn't include the freedom for it to be c plus whatever the speed of an emitter might be...like walking with a lantern. No. The speed of light is a fixed value and everyone, including, and especially, Maxwell believed that the ether provided a fixed reference and that the speed of light – and the light waves themselves – were fastened to that material.

The ether was a very strange beast. If you were to do an experiment (that you should not do) involving a railroad track and a hammer, you would find that sound travels faster in a solid than in air. If your (former) friend bangs on a railroad track a 100 yards away, and if you put your ear to the track, you'll hear it through the metal before you hear it through the air. Now, get off the track. That's dangerous.

In fact the speed of a wave in a medium is dependent on the square root of the "stiffness" (called the "bulk modulus") of the material – steel is a million times stiffer than air, so the speed of sound in steel would be 1000 times faster.

Now light is the fastest thing there is! So turning that argument around, *the stiffness of the ether must be incredibly higher than even steel*. And yet, the ether needs to be easily plowed through by the planets that presumably swim around in their orbits through it while they delicately reflect their light back to our telescopes. How can a substance offer no resistance to a planet's motion (or even a car, or a person, or a bird) and yet be incredibly stiffer than steel?

No matter. A detail. Its actual existence, while required, seems circumstantial. There had to be an ether in order for there to be a wave of light. It seemed to have two functions:

1. As I remarked above, Maxwell created his four equations for electricity and magnetism, out of which popped the mathematical representation of a transverse wave, the speed of that wave, " c " was required by him to be the speed of light relative to the ether.
2. Newton insisted that space was a "thing," a property of the universe and that there is an absolute coordinate system (Absolute Space) against which all

motions – constant velocity and accelerated motions – could be measured. The ether seemed to be that perfect construct: it and only it would function as that absolutely at-rest structure that anchors space.

The question is how do we detect the ether? Michelson set out to determine our speed as we move through it.

Moving Through The Ether

A naval analogy, as described by Michelson to his children.

Suppose you and your friend are standing by a river and ready to race. The river is *still* as shown in the figure and you each plan to pilot your motor boat a distance L , starting at point A and ending at point A . One of you goes across the river (AB to BA), and the other of you to the right and then left (AC to CA). Who wins if both boats can move through the water at the same speed?

Obviously, both of you are traveling at the same speed, over the same distance and if the water is perfectly still (no current), your race from AB , BA compared with AC , CA would result in a tie. That's too easy.

Now suppose that the river has a strong current to the left. I take the right-left trip and in the first leg, AC I must go against the current while the return CA is helped by the current. By contrast, you take the trip AB but you can't go directly across the river since your boat would be carried downstream, so you must aim your boat to the right at *just* the right angle to drift to B as you plow through the water at your regular speed. Then your return has to be the same thing.

Who wins?

Well, it turns out that the round trip across the river will be quicker than the trip to the right and to the left.

Now suppose we make the following substitutions in our nautical race:

- boat → light beams
- river → the ether "wind" as the Earth passes through it
- bank → the Earth

From the position of the Earth, the ether moves past to the left as the Earth moves in its orbit, here to the right. So on Earth we should detect a constant "ether wind." Or a current to the left. Here is Michelson's instrument riding on the Earth and together they move through the fixed ether:

Michelson's Interferometer

How did he do this? The instrument he invented and spent his life perfecting is called the Michelson Interferometer and it's a standard tool in today's laboratories in optics and even astronomy.

⚠ Pencils Out!  **⚠**

Here's the idea:

Suppose we have two identical trains that leave the station on identically constructed tracks at precisely the same speeds. Each train has 4 cars, each car is exactly the same length, and the spacing between the cars is exactly the same. Our little trip is kind of boring. It consists of the following set of loops created so that the tracks and so the trains pass one another at the top. We're at point O and there's a light source on the other side of the trains from us.

On the left, this figure shows the trains just starting out on their trips. On the right they have reached the mid-point and are just beginning to pass one another. Notice that the fronts line up with blue going right and red going left.

Let's look at successive times. From A to B to C, we have snapshots of the train positions from early to later times. In each case, the gaps between the cars line up and from O we can see the light.

Now, let's mess with them and make the right-hand track just a tiny bit longer than the left-hand track. Same trains. Same speeds. Now the left-hand blue train reaches A slightly before the right-hand red train, right? So the gaps are out of phase and you don't see the light except only occasionally. From top to bottom, we can see that the gaps never will line up.

Suppose (and I don't know how to build this), the right-hand track is not getting longer, but moving away toward the right, away from the other one by stretching the track. Can you see that this too would make the gaps not line up, except only occasionally?

That's the principle behind the Michelson Interferometer. Instead of trains, he used light. Instead of gaps, the peaks and valleys of the light waves either would be in phase and get bigger in synch – like seeing through the gaps between the cars – or they would not and interfere and you'd see the peaks diminished or even gone.

Michelson invented and built (on Earth!) a first version of an instrument that sent a beam of light in one direction, like AC on the river and at the same time a second beam of light in a perpendicular direction, like AB on the river. Then with mirrors he brought them together back at A to see who wins. What determines winning?

Well, light is a wave and when two waves encounter one another, they mix and interfere. Where the two waves are in-synch, the result is a new wave that's big at the position of the original common peaks. Where they're out of synch? Well, then you get a quiet result – no wave (think of your noise-cancelling headphones). If they're somewhere in-between, then there's a peak, but it's not where the peak is for either of the two initial waves. So calibrate your instrument carefully for both beams in-synch and then turn it loose on the ether and see what happens.

Here we have two waves that overlap and because they are completely in phase, their overlap (the orange) is at the same place as the two initial peaks.

Now let's suppose that the two initial waves are out of time with one another, as if one arrived before the other.

Notice that the two orange curves in the two figures are slightly offset. Here's a superposition of the two figures for the first cycle. I've started the dashed initial curve for the out-of-phase scenario at the same point as the common, in-phase scenario.

Michelson expected to see the "fringe shift" of the light-orange curve, lagging the in-phase curve as one leg of his interferometer went against the ether or along with the ether.

With The Phone Guy's Help

With financial assistance from Alexander Graham Bell and a German optical company, in 1881 Michelson built an exquisitely precise interferometer which combined waves in exactly this way.

Here's a cartoon illustrating how this worked, the device that's riding on the moving Earth:

His first prototype had arms about a meter long.

He knew how accurate his device needed to be because the effect of the two light beams would be of the order of

$$\text{effect} \propto \frac{v_{\text{Earth}}^2}{c^2} \approx 0.000000000002! \quad (1)$$

This required a ridiculous level of precision, which Maxwell had calculated and decided it to be impossible. His first instrument was not up to it as even traffic outside of the lab building was sufficiently disruptive to ruin his measurements. He subsequently moved it to a basement in a lab at rural Potsdam in suburban Berlin where the measurement was better, but unsatisfying. After more than six months of painstaking work, he published his results and wrote to his benefactor:

Heidelberg, Baden, Germany

April 17th, 1881

My dear Mr. Bell,

The experiments concerning the relative motion of the earth with respect to the ether have just been brought to a successful termination. The result was however negative...

At this season of the year the supposed motion of the solar system coincides approximately with the motion of the earth around the sun, so that the effect to be observe [observed] was at its maximum, and accordingly if the ether were at rest, the motion of the earth through it should produce a displacement of the interference fringes, of at least one tenth the distance between the fringes; a quantity easily measurable. The actual displacement was about one one hundredth, and this, assignable to the errors of experiment.

Thus the question is solved in the negative, showing that the ether in the vicinity of the earth is moving with the earth; a result in direct variance with the generally received theory of aberration...

N.B. Thanks for your pamphlet on the photophone.

The speed of the ether relative to the Earth is zero. It was the first failure that Michelson had endured in his so-far, distinguished career as the young King of Optics.

The Fallout of Michelson's Null Result

There was very little reaction to Michelson's Potsdam experiment. Hendrik Lorentz – another "king," (whom we'll meet in a later lesson) this time of electromagnetic, pointed out a numerical mistake in Michelson's analysis but it didn't change the result: still zero.

Hendrik Lorentz was the undisputed expert in the mathematics and physics of Maxwell's electromagnetism and extended it in a crucial way. Maxwell's equations describe the electric and magnetic fields due to extended charge distributions – "stuff" that you could hold in your hand.

Lorentz, however, was a firm believer in the atomistic picture and that the atoms included "electrons" which when they oscillated, radiated electromagnetic waves. (Notice, this was before our electron was discovered so Lorentz's "electrons" were not what we think of as electrons today...they were just hypothetical charged components of an atom.) In 1887 he worked out the equations for the motions of his "electrons" and today we call these the Lorentz Force equations. His theory required that the motions of the electrons be related to the stationary coordinate system defined by the ether and so he was interested in Michelson's 1881 Potsdam results since they were inconsistent with his theory. Indeed, he criticized Michelson's conclusions in which he postulated that the ether was dragged by the Earth, and so no speed would be detected in his apparatus.

In order to study the results, Lorentz built a model and calculated what the electric field would be like for a moving charge...like in the materials of Michelson's instrument...and what he found was that materials would actually shrink in size along the direction of the motion relative to the ether. *An actual mechanical change of size*. In our river analogy, my trip up and downstream would take longer than across but it could be brought to coincidence with your across-trip if my distance L was shorter by

The Irish physicist George FitzGerald originally thought of this, but without a model to illustrate the shrinkage. While this is not the actual case, that square root factor will be a big part of our lives for the next few lessons!

Getting Serious: The Michelson-Morley Experiment

When Michelson's time in Germany (and Paris) was done, the future was uncertain and so he was delighted to discover that colleagues had interceded on his behalf to offer him a faculty position at the brand new Case School of Applied Science in Cleveland, Ohio. (This is now the very fine Case Western Reserve University.) With sufficient startup funds and laboratory space, Michelson readily accepted the position, resigned from the Navy, and in 1881 re-established his light-speed measurement work in Cleveland. There he teamed with Case chemistry professor Edward Morley (1838-1923) to do it better.

{numref}MM_Case shows an engineering drawing of the apparatus that they constructed.

Outside vibrations had been a problem in Berlin and while reduced in Potsdam, they were still a problem. What they did was build the new apparatus on a huge, heavy sandstone slab that floated in a pool of mercury—a dangerous environment. This isolated it vibrationally and allowed the experimenters to keep the whole instrument in constant rotation, slowly, so that the directions of the arms are constantly, uniformly changing. That would eliminate any potential bias. Furthermore with high quality mirrors the light paths were essentially increased back and forth to 36 meters in effective length which greatly improved the precision.

So on six days in July they did their experiment walking around the circle looking into the eyepiece all the while in 30 minute shifts each. Here are their results:

In August, 1887, Michelson wrote to John William Strutt, 3rd Baron Rayleigh – future Nobel Laureate and another king of physics:

The Experiments on relative motion of earth and ether have been completed and the result is decidedly negative. The expected deviation of the interference fringes from the zero should have been 0.40 of a fringe — the maximum displacement was 0.02 and the average much less than 0.01 — and then not in the right place.

As displacement is proportional to squares of the relative velocities it follows that if the ether does slip past [the earth] the relative velocity is less than one sixth of the earth's velocity.

The result is unequivocally zero. For Michelson it was a failure. Either the ether moves with the Earth or there is no ether. Or something else, like Lorentz's hypothesis. Neither Michelson nor anyone could imagine that the ether didn't exist.

Michelson and Chicago

His work with Morley exhausted him and he literally had an emotional breakdown that required hospitalization. As I noted, his loving wife actually sought to have him committed (which, imagine that, created considerable tension to their relationship) and he spent months recovering in a New York institution with serious emotional and mental incapacitation. Case actually replaced him on the faculty (!) as it was presumed that he'd

never recover nor do science again. Fortunately, he recovered after a couple of months and returned to try to piece together his career and his marriage. The former recovered, but the latter was troubled until it ended 13 years later. Michelson moved himself into his own quarters in their large Cleveland house and by many accounts, his personality changed after these two betrayals becoming cynical about his relationships going forward. By the way, he was reinstated on the faculty...but told by the Board of Trustees that his salary would have to be cut in order to help pay for his (unnecessary) replacement.

By 1888 Michelson was unhappy at Case. There was the on-again, off-again, strange replacement of Michelson's position. Furthermore, there was a huge fire on campus in 1886 that destroyed Michelson's laboratory forcing him to move into Morley's lab and he could not get funds to rebuild his own space. The family had been through two more disasters in 1887 in Cleveland. A cook actually robbed them of their jewelry and other valuables (which were recovered in another town). And, in 1887 that maid accused Michelson of sexual assault actually leading to his arrest at home with headlines in the paper! Blackmail had been demanded and Michelson, Morley, a lawyer, and the Cleveland police actually set up a sting operation to get the perpetrator to expose her plot exonerating Michelson.

The lack of an ether would seem to pale compared to these events, but it didn't.

When a Clark University was started in Worcester, Massachusetts, in 1889 Michelson jumped at the chance to restart his program as the first Chair of Physics with finally adequate financial and technical support. In retrospect, Case had made a terrible mistake. Off they went to the New England countryside. It wasn't a match made in heaven for any of the faculty recruited to Clark. By 1892, Michelson and almost all of the Clark faculty resigned in unison because of an unbearable meddling by the university president who was on an entirely different course from the founder and financial benefactor, Jonas Clark. It was a mess. Today, Clark University is a thriving institution. But another one bearing the distinction of losing Michelson. To the new University of Chicago in 1892.

Michelson divorced and then remarried in Chicago and he and his new wife had three more children. His first wife created a wall between her and their children that Michelson was unable, or unwilling to break through and he had no contact with them for decades.

His time at Chicago was productive and pleasant. His students enjoyed him. He played tennis regularly and had a productive and well-staffed laboratory and was able to watch his new family grow up. He was in demand around the country and the world and took on new and engaging experiments with enthusiasm and his characteristic talent for precision optics. The projects he took on included:

- The measurement of the radius of a star – initially the red giant, Betelgeuse using interferometry – essentially capturing light with two telescopes and letting them interfere. In effect this increases the resolving power (or effective size) of any single telescope by a considerable factor. This is a standard technique especially in radio astronomy today.
- He was commissioned to create a standard of length to augment or replace the precious, single physical meter bar in Paris. This he did by counting wavelengths of sodium vapor light so a standard meter could be reproduced anywhere in the world.
- He continued his speed of light measurements and was engaged in a long-baseline experiment in California when he passed away.
- He created and perfected the creation of very precise diffraction gratings with an engineered instrument in the basement of the physics building. They were the best in the world and required weeks of patient, delicate fabrication.

Oh. And he won the Nobel Prize in 1907, the first American to do so. The prize was not for the ether experiment, as Special Relativity was still only a year or so old and Einstein was still unknown. Michelson's award reads: "for his optical precision instruments and the spectroscopic and metrological investigations carried out with their aid."

Michelson died at the age of 79 in Pasadena, California where he was engaged in a multiple experiments to improve the precision of the determination of the speed of light. He and his wife had retired from the University of Chicago and moved the previous year so he could focus on the culmination of nearly a half century of steadily improving this measurement. He had had multiple operations for prostate and intestinal disease with multiple infections (before the time of antibiotics). This final experiment involved the construction of an evacuated tube about a mile long in the mountains of Irvine Ranch near Santa Ana, California. With multiple reflections, the path length was effectively more than 5 miles. Their biggest hurdle were the tiny geophysical shifts in the mountain range. He worked right to the end, from bed, often dictating instructions and publication

drafts.

Today the determination of the speed of light is exquisitely precise using lasers: but the technique is still essentially the same one that Michelson pioneered while he was in the Navy. Likewise, his original notion of measuring the size of a star using two small, but widely spaced optical receivers and letting the interfering pattern determine the angular size of the star is now the standard technique of radio astronomy for huge radio telescopes around the world. Finally, the Michelson Interferometer is a standard bench instrument in optics labs everywhere and is the principle that was deployed in the LIGO experiment that has recently discovered Gravitational Radiation and has initiated a whole new branch of astronomy by studying the collisions of neutron stars and black holes.