“Superfluous”:
The Stories of Einstein’s Special Relativity

Draft Michelson Chapter

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Chapter 13

The Most Important Zero Ever: Albert Michelson

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, a complicated person notoriously stern and difficult (although he was an accomplished artist, musician, and tennis and billiards player). 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.

13.1 A Little Bit of 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 Fransisco and went to Washington, D.C. to see the President. Albert was nothing, if not persistent.

Albert Michelson was born in 1852 in Poland to Rosalie and Samuel Michelson, an itinerant merchant. Life under Prussia was untenable and so this small family decided to emigrate in a big way. Samuel's sister and her husband had previously decided that their fortunes lay in the gold rush in California. So Albert's parents followed them: with two babies in tow they left from Hamburg for New York and then San Fransisco. Not to chase gold, but to sell dry goods to the miners. It's what Samuel knew best.

Figure 13.1: Murphy's Camp in 1852 (Kenneth M. Castro)

They could have sailed around Cape Horn. Or, they could have traveled across the country in covered wagons. Those must have seemed too tame for this adventurous couple. From New York they boarded a steamer for Panama, then by canoe, mule train, and a brand new railway, made their way across the Isthmus of Panama to a clipper ship and then on to San Fransisco. It was a harrowing journey during which they lacked water, fought exotic insects, faced danger from outlaws, and avoided the desperately sick natives who were all around them. It made an impression on three year old Albert that he never forgot. In retrospect, covered wagons must have seemed like a better alternative.

The last leg of their journey was by stagecoach from the city to Murphy's Camp in the foothills of the Sierra Nevada mountains. After more than a year of dangerous travel, they settled alongside Samuel's brother-in-law and set up shop with the goods needed by any respectable prospector.

Their new home was bustling during those few years—tens of millions of dollars in gold was shipped from Murphy's Camp and that kind of activity came equipped with hard edges. The town resembled a bad cowboy movie: full of drunks, violence, and public hangings—and lots of cash. It thrived in its own way until it all burned to the ground in 1859 in less than an hour.

The town and the Michelsons rebuilt but by the time Albert was 12 years old in 1864, Rosalie decided that he needed a more formal education than available in Murphy's. She had tutored him, even insisting on violin lessons. But Albert was sent with his aunt and uncle to San Fransisco for high school where he so impressed the principal, that he was taken into his home and given special access to the school's science lab…and boxing lessons.

By this time Murphy's gold had dried up and the family moved to Virginia City, Nevada…where silver was all the rage and this new boom-town swelled to 30,000 inhabitants. The family moved into a large house over Samuel's new store where the business flourished. A whole-family enterprise was a possibility, but by this time Albert needed a different path. A scientific one.

13.1.1 The Navy

Today, in order to enter a U.S. military academy, an 18 year old needs a nomination by a state or federal elected representative. It's a highly competitive process requiring superior academics and typically, an athletic background. Albert's growing interest in science had led to a favorably received paper on optics and he wanted to pursue this subject. But how?

The U.S. Naval Academy at Annapolis, Maryland was then only 20 years old when Albert graduated from high school in San Fransisco and Samuel learned that Nevada's Congressman Thomas Fitch was accepting nominations for boys to the Academy. Albert applied, took the exams and tied with two other boys for first place. Fitch chose one of the other boys, who upon arrival failed and dropped out prompting Fitch to write to President Grant on Albert's behalf. In what was to become a characteristic Albert-move, at the age when U.S. kids are just getting their learner's permits, he took matters into his own hands and did what his family did: he got on the road. Hence, that teenage solo train ride across the country.

When he arrived in Washington, D.C. he presented himself at the White House, met with President Grant, and asked for a special posting to the Academy. The President was allotted 10 at-large appointments (now the Vice President can nominate five) and Grant had used up that total. Not to be outdone, Albert then took himself to Annapolis and sought an audience with the Commandant where he was examined, did well, but told that there were no openings.

As Albert's daughter described later, he was literally at Union Station boarding the train to return to San Francisco when a messenger from the President intercepted him to say the the President had decided to appoint 11 midshipmen that year (and later two more, for a total of 13). Michelson always joked that he was probably illegally a student at the Naval Academy. But it worked out. In 1869 at the age of 17, Albert joined the Navy.

Albert was a popular and successful midshipman. There was that fight when he was challenged by a fellow cadet (eventually, Rear Admiral Bradley Fiske):

Fiske's memory of clashing with Michelson
The details of the fight were very carefully arranged; in fact the arranging of the details took more time than did the fight itself. That I had not the slightest chance became evident in about one minute; but I hammered away the best I could until the referees saw that I couldn't see out of either eye and declared that the fight was finished. I was put on the sick list by the surgeon for "contusions," and I stayed on the sick list for eight days.

Albert graduated in 1873 at or near the top in experimental and mathematical subjects—at the top in optics. . . and near the bottom in seamanship. He did his two year obligatory training at sea off the coast of South America and the Caribbean in a combined steam-sailing ship, the *Worcester* ending his sailing obligation in Norfolk as an Ensign. He decided to stay in the Navy and in 1875 was assigned physics instructor duties at the Academy under Lieutenant Commander William Sampson, the head of the Department of Natural and Experimental Philosophy who was to become a friend as well as benefactor. Mrs. Sampson's niece recently returned from finishing school in Paris and Margaret Heminway was introduced to him at a family event. She was the daughter of a wealthy and powerful lawyer and investor in New York City. In spite of their age and class differences, Albert and Margaret were married in 1877—a marriage "up" for Albert into a rarified atmosphere as compared to his immigrant upbringings. After more cruises, Albert and Margaret had their first son in 1878.

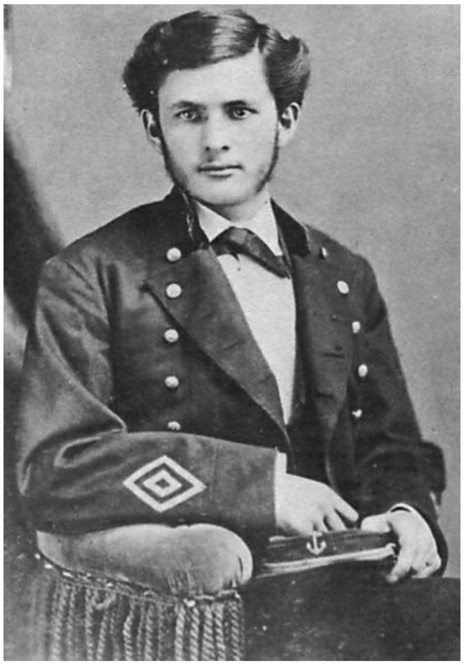

Figure 13.2: Albert Michelson as a cadet-officer.

13.1.2 Light

One of Albert's first tasks as an instructor was to create demonstrations for the midshipmen in their physics classes and he chose to take on a relatively new method for measuring the speed of light, now an experiment done by physics students in hallways around the world. Except he made it better and found a calling.

It's Really Fast

Is light an instantaneous disturbance? or did it travel at a finite velocity? Is it a wave? or is it a particle? Galileo (Chapter 6) imagined it to be have a finite speed and didn't concern himself with its nature but he actually tried to measure it without success. A few decades later in the middle of the 17th century, Ole Christensen Roemer, a Danish astronomer, had the brilliant idea to use one of Galileo's moons of Jupiter as a clock. Roemer's only conclusion was that light must have a finite speed and it took Dutch contemporary, Christiaan Huygens (Chapter 8) to determine that the speed must be around 200,000,000 m/s. (More details of these and other technique are in the **The Modern Bits of Michelson** section 13.2 below.) Robert Hooke, the grumpy instrument maker and Newton's lifetime foe dismissed the subject altogether saying that light's speed was so high that one might as well just conclude that is instantaneous.

The first terrestrial measurement of the speed of light waited until 1849 when Hippolyte Fizeau and Léon Foucault collaborated on a clever terrestrial technique to measure it. Both had started out with medical careers in mind, but Foucault couldn't stand the sight of blood and Fizeau was independently wealthy and changed direction out of an interest in astronomy. What brought them together originally was the goal of improving Daguerrotype photography, which after a decade, they did and applied it to the first detailed pictures of the sun's surface. They then developed ideas on how to measure the speed of light on the Earth, undoubtedly aware of the astronomical determinations of the past.

Like anything that moves, determination of a speed requires measuring a distance and the time that it takes for an object to traverse that distance. As Galileo's failed attempt showed, it's the time-part that's hard and with Roemer's measurement setting the scale, ideas started to germinate. They agreed on the general approach: set a tool spinning very fast, send a light beam a long distance away, reflect it back and see how it interacts with the spinning tool. Before they could build such an instrument—which requires delicate engineering since whatever the tool is, it's spinning must be very fast and very precisely understood—they had a bitter falling-out and went their separate ways.

Fizeau made the first attempt in 1849 by chopping light up into bits and watching the bits return from an 8 km distance. By passing them through teeth in a rotating wheel, and tuning the rotation just right so that they returned through the next gap in the wheel. He found $c = 315,000,000$ m/s with a precision of about ±5%.[1] Meanwhile, that same year Foucault did it better by fabricating a rotating mirror with would reflect the returning beam to a different angle than that of the light source. His length was limited to 20 meters as the beam was broadened by its optical dispersion from his concave mirror. Nonetheless, his measurement was $c = 298,000,000$ m/s with a precision of less than a percent limited

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[1] The speed of light is universally referred to with the lower case c. Whether it's for "constant" or the Latin *celeritas* for "swift" is anyone's guess.

by the short length of the path over which the light traveled in the apparatus, the spreading of the beam after being reflected by the far mirror, and the tiny displacement from the original light direction that resulted (only 0.8 mm).

This was the technique that Michelson adopted for his midshipmen students and by 1878 he had a handful of ideas to better engineer the device. He lengthened the path length to 11 meters, he greatly improved the various focussing lenses required for the beams, swapped Foucault's concave far mirror for a finely ground plane mirror, and he delicately engineered the rotating mirror assembly by driving it with a regulated, hand-operated bellows to a constant speed of 130 turns per second. With this first measurement, he obtained $c = 300,140,000$ m/s with an uncertainty of about 0.2%. It cost him $10 in 1878 dollars.

In the same year that he and Margaret had a second child he obsessed about getting a new apparatus to work. With a lot of support from the Academy (he was, after all still in the Navy but with this unusual research assignment), $2000 (worth more than $50,000 today) from his father-in-law, and space at Annapolis along the waterfront, he was able to retain services from first-class instrument and optical manufacturers. Meanwhile, Congress had turned down a request of support and awarded $5000 to Simon Newcomb, a distinquished astronomer who actually suggested improvements in the young man's plans and supported him publicly. His new path-length was to be 609 meters and his rotating mirror assembly was a delicately controled 128 revolutions per second (he'd already broken an assembly at high speed when its balance was not perfect). He devised a tuning-fork with a small mirror attached. When it vibrated at its precise frequency, and the rotating mirror was in synch, stable images of the rotating mirror would show in the tuning fork's mirror. The time of day was regulated, as the heat would change dimensions of the apparatus. His result was $c = 299,910,000 \pm 50,000$ m/s, or a precision of $\pm 0.017\%$.

Measurement of the speed of light became a life-long passion and he was working on an audacious experiment in the hills of southern California when he died. His previous 1924 measurement of $c = 299,796,000 \pm 0.001\%$ m/s stood for three decades as most precise.

> May 14, 879, in the Virginia City Evening Chronicle:
>
> "THE VELOCITY OF LIGHT A YOUNG COMSTOCKER'S CONTRIBUTION TO THE WORLD OF SCIENCE
>
> Ensign A. A. Michelson, a son of S. Michelson, the dry goods merchant of this city, has aroused the attention of the scientific minds of the country by his remarkable discoveries in measuring the velocity of light." " The New York Times says: "It would seem that the scientific world of America is destined to be adorned with a new and brilliant name. Ensign A. A. Michelson, a graduate of the Annapolis Naval Academy, and not yet 27 years of age, has distinguished himself by studies in the science of optics which promise the discovery of a

> method for measuring the velocity of light with almost as much accuracy as the velocity of an ordinary projectile…""

Albert didn't want to go back to sea, which would have been his next Navy assignment. He was partially spared another sea voyage when Newcomb had enough influence to "borrow" Michelson from the Navy to work in his laboratory in Washington D.C.…where his job was to make his friendly competitor's, Congressionally funded, experiment work.

That probably wasn't ideal. He was fully aware that his engineering degree (because until recently the service academies offered one major—engineering) wasn't a qualifier for a faculty position, but no institution in the United States offered doctorates in physics.[2]

Again, not shy, he requested and received a year's leave of absence from the Navy and went to the top scientist in Germany, Hermann von Helmholtz at Humboldt University in Berlin. Off the four of them went to Berlin, Margaret, two children, and Albert.

Helmholtz was an expert in optics, having revolutionized ophthalmology with his invention of the ophthalmoscope and was extraordinarily multidimensional. His mathematical codification of the conservation of energy (see Chapter 12), development of the science of fluid dynamics, studies in acoustics, and both mathematical and experimental contributions to electromagnetism all marked his name in textbooks…in multiple fields. Not bad for a medical doctor.

Michelson had something on his mind and a plan for Berlin: the ether.

13.1.3 What's Waving?

As a graduate student in 1880 Albert studied mathematics and physics and worked in Helmholtz's famous Berlin laboratory. Against everyone's advice, he put the speed of light on the back-burner and embarked on his most important—and personally disappointing—experiment.

\subsubsection*{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, the "ether." The persistent belief in this substance gained new life in 1803 when Newton's demand that light consisted of particles was dethroned by Thomas Young's demonstration to the British Royal Society that light consisted of waves. Young demonstrated that the passage of light through two adjacent, narrow slits caused the emerging light beams to interfere with one another, a feat that only waves can do. Not particles. (This public result was…unwelcome. For disputing Newton, the young Young ((sorry)) was attacked with vengeance, and being a shy guy, turned his attentions elsewhere. Among other things (he was a practicing physician)

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[2] John's Hopkins University in Baltimore was about to offer Ph.D. degrees.

he became an amateur Egyptologist and did essential work toward deciphering the Rosetta Stone.[3] And he solved many other riddles in science and medicine.)

So waves it is. But waving in what, exactly?

Maxwell's (Chapter 11) subsequent unification of electricity, magnetism, and optics into a single model of waves of electric and magnetic field vectors and Heinrich Hertz's (as a student of Helmholtz) demonstration of their wave-like existence made it clear: light, electricity, and magnetism are waves and so surely electromagnetic radiation must propagate in a substance which supports that disturbance. The ether functioned for light as water reacts to a dropped pebble and air supports sound. 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, $c \approx 300,000,000$ m/s which Maxwell knew because of Foucault. 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 an image of walking with a lantern. No. The speed of light is a fixed value and everyone, including, and especially, Maxwell believed that light moved with that speed relative to the fixed ether. Light waves were fastened to that material.

Now this 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"or "Young's Modulus") of the material—steel is much stiffer than air and so the speed of sound in steel is more than 10 times that in air.

But light is fast! So turning that argument around, *the stiffness of the ether must incredibly be higher than even steel.* And yet a planet seems to plow through it in its orbit all the while

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[3] There's a story here. Young was first to decode some important facts about what symbols were phonetic and what were not and the numbering system. In 1819 he summarized his findings in an article for the Encyclopaedia Britannica. While unsigned, his authorship was apparently well-known. Later the person most associated with its solution was Jean-François Champollion, who wrote the first definitive book in which he credited Young with important discoveries.

delicately reflecting the propagating light images of itself that we see with 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 much stiffer than steel?

No matter. A detail. There had to be an ether in order for their to be a wave of light. Over a century, the ether's job description seemed to grow into two assignments:

1. The ether is the material that undulates with the propagation of light waves.
2. Newton (Chapter 9) insisted that generalized space was a "thing," a structure measured by an absolute coordinate system (his Absolute Space). Constant and accelerated motions—could be measured in reference to this Mother Of All Coordinate Systems. The ether seemed to be that perfect construct: it and only it could function as that absolutely at-rest structure that anchors and even defines space.

The question was: how do we detect the ether? Many people had tried in the middle of the 1800's, by measuring the speed of light in the direction of the Earth's motion and comparing that to astrophysical determinations of the Earth's speed. These were unsuccessfully imprecise and so not reliable.

Michelson set out to determine it using a novel technique of his own invention. It took another year's leave of absence from the Navy to make his first publishable result.

13.1.4 Germany

Always imaginative, during the last year of his life, Maxwell suggested in a letter that it might be possible to measure the speed of the Earth relative to the (fixed) ether. However, he worked out that the precision of any measurement using the Earth needed to be incredibly difficult:

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

To Maxwell, this was an impossibility. To Michelson this was a challenge. After all, precision optics seemed to be his game.

Moving Through The Ether

What was Maxwell's idea? A naval analogy that he later described to his children gives a good feeling for Michelson's complicated apparatus.

Suppose Bob and Doris and are ready to race in a river. They each plan to pilot their identical motor boats the same distances starting at a the same point on the south shore and ending up back at that same location. Bob goes across the river north to the opposite shore, and then returns south to the starting point. Doris pilots her boat to the east and then back to the starting point, returning to the west. In this race, the river is still—no current. Who wins if both boats can move through the water at the same speed?

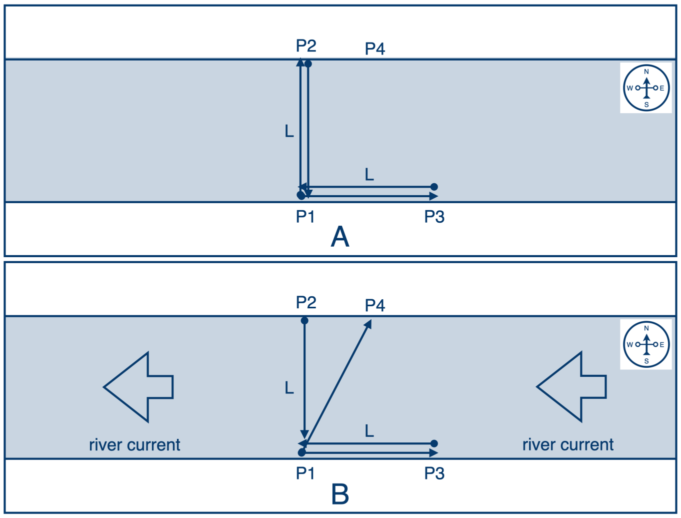

Figure 13.3: A. The race in a still river with no current. B. The race in a river with a current from east to west.

Obviously, since they're both traveling at the same speed, over the same distance and if the water is perfectly calm, their round trip race would result in a tie. That's too easy.

Now suppose that the river has a strong current from east to west. Same boats, same relative speeds through the water, and the same trips, north then south for Bob and east and return west for Doris. Both travel the same distance relative to the shore. Who wins now?

Since the river is flowing to the west, Doris has to fight the current to go the required distance to the east, but on her return, the current helps. Meanwhile, in order to get directly across the river, Bob has to aim to the east of his intended point so that the current pulls him back to the north shore directly opposite his starting position. Coming back, he must do the same sort of maneuver.

Now who wins? Bob or Doris?

It turns out that the round trip across the river and back will be quicker than the trip to the right and to the left. (See Appendix 13 for the calculation.) So Bob wins.

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

- instead of boats→ we'll use light beams
- instead of a river→ we'll imagine an ether "current" as the Earth passes through it

- instead of the fixed bank→ we'll imagine the fixed Earth

From the position of the Earth, the ether moves past to right to left as the Earth moves in its orbit around the sun, to the right. ("North" and "south" are hard to envision in the whole-Earth picture, huh,) So on Earth we should detect a constant "ether current" to the left. Like the river. A river of light-supported ether just like the water supported Bob and Doris' boats.

Michelson's Interferometer

The instrument Michelson invented and spent decades of his life perfecting is called the *Michelson Interferometer* and it's a standard tool in today's optics laboratories and even in astronomy.

The principle of the Michelson Interferometer takes advantage of the innate property that all waves possess. When material bodies collide, they bounce off of one another. They don't pass through like ghosts. But waves are much friendlier. When two waves approach one another, they pass through and make a new wave, one that might have higher peaks (or lower) and one that might be periodic with different timing than either of the original two. If they are precisely the same and interfere in such a way that their upward (or downward) peaks are coincident in time, the resulting wave pattern will look just like the originals, but the peaks will be twice as high. If on the other hand, their nodes are just out of phase so that when one wave goes up, the other is going down, they will exactly cancel. Start out with two waves, and end up with no wave. (That's the principle behind your noise-cancelling headphones.)

So if an experimenter has a device that can detect that the result of a collision of two waves is a *distorted* wave, then they know that the waves arrived out of phase. One of them led the other. Bob.

One way to make waves be out of phase with one another is to have them travel different distances, bounce them from mirrors and recombine. Or, to create a reference wave and compare it to a wave that travels with and against the ether's motion across the moving Earth. That is, create a "Bob" light path perpendicular to the Earth's motion and compare it to a "Doris" light path that went first against, and then with the ether's current. Bob is the reference and Doris is the question: Does the Bob wave get there first and so interfere noticeably with the Doris wave?

That was the plan, but the engineering and instrumentation was formidable and while Humboldt University was prepared to give Michelson a laboratory in the basement, there was very little funding for the equipment.

13.1.5 With The Phone Guy's Help

Simon Newcomb comes to the rescue again. He seemed to know everyone and so naturally he contacted Alexander Graham Bell who came through with sufficient financial support that Michelson could collaborate with a German optical company. So in 1881 Michelson built an exquisitely precise interferometer prototype which combined waves in exactly as the river analogy required. Figure 13.4 is a sketch of how the apparatus works.

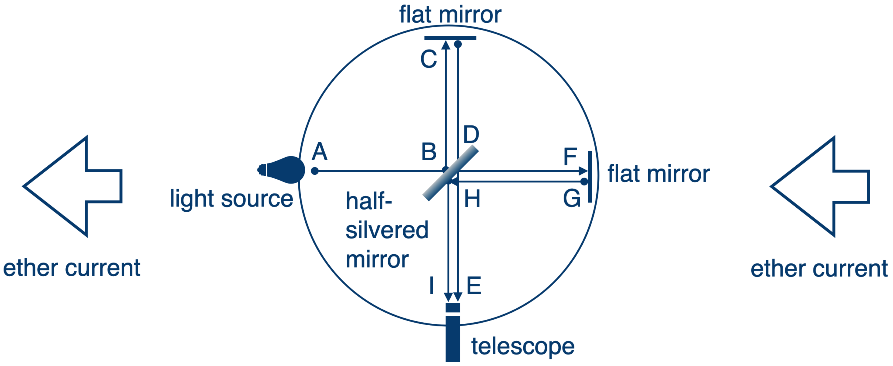

Figure 13.4: A sketch of the Michelson Interferometer.

Light from the source, S, is separated by mirror that lets half of the light through and reflects half.[4] The reflected piece goes up on path BC, is reflected from mirror at C, and returns on path CDE all the way to the bottom. Meanwhile, the light that passed through the half-silvered mirror continues to the right along path DF and is reflected from mirror at F and returns along GH to where it's reflected down along path HI. The two beams are then combined at the bottom. If they were out of phase, then fringes will appear and their spacing is indicative of how out of phase they are. When the apparatus is rotated then there should be a shift in the pattern of the interference—the fringes—as the arms change places relative to the presumed ether current.

The apparatus rides on the Earth, which in everyone's view, moved through the ether like in Figure 13.5.

His first prototype instrument had arms about a meter long but was sensitive to traffic outside of the lab building which was disruptive enough to ruin his measurements. So, he made the measurements at night. That was still unstable and so he subsequently moved it to a new lab at rural Potsdam, and then a second lab in that same facility. This was in suburban Berlin where the measurement was better, but. . . even stomping on the ground 100 meters away would cause the interference patterns to disappear! Figure 13.6 is a perspective

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[4] This is called a "half-silvered" mirror or "wave-splitter." Think of a teleprompter.

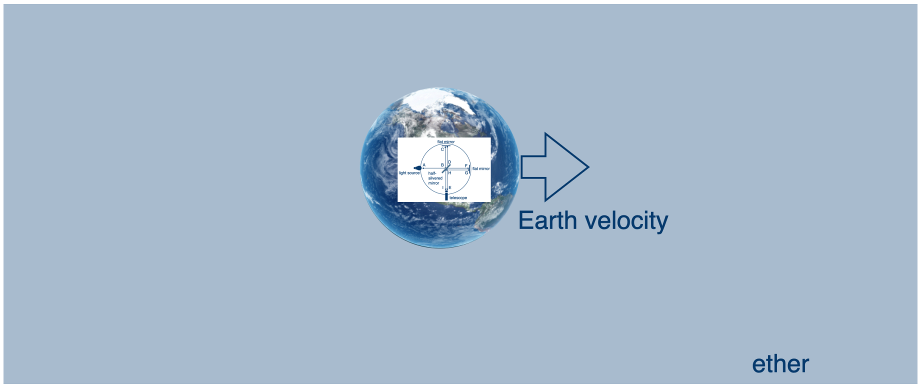

Figure 13.5: A of the interferometer riding on the Earth as it moves through the ether.

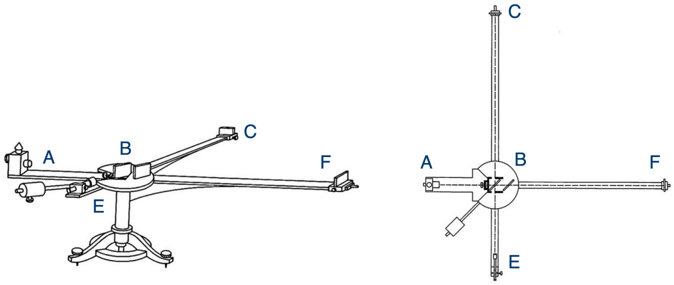

Figure 13.6: On the left is a perspective engineering drawing of Michelson's prototype. On the right, a plan view. The labels correspond to the points highlighted in Figure 13.6

engineering drawing from Michelson's Potsdam apparatus.

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 oserve [sic] 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 seemed to be zero. In the last page of his first publication he referred to a possible ether model due to Stokes a few decades before in which the ether would be strongest in the inner parts of an atom, and weaker outside. That might mimic his null result. But that was grasping at straws. He believed it to be a failure, the first in his so-far, distinguished career as the young King of Optics.

13.1.6 Getting Serious: The Michelson-Morley Experiment

The work in Potsdam was exhausting and discouraging and so he and Margaret and (now three) young children explored the German countryside with Albert watercoloring and studying. They spent some time in Heidelberg where he worked in another lab and improved his ability to produce half-silvered mirrors. After a pleasant summer, they went to Paris (Margaret's stomping ground from her youth) and Albert spent time in the École Polytechnique where the legacy of Foucault lived on. The next fall and winter Albert repeatedly failed to show his skeptical French colleagues that his interferometer worked! Eventually, he succeeded with relief…which was short-lived. One of them showed him that he'd made an arithmetic mistake in his ether publication's analysis which served to reduce the fringe shift. About that same time, Hendrik Antoon Lorentz (1853-1928, Chapter 14) found the same mistake. That raised the stakes as Lorentz was the first to begin to think seriously about what a null result might mean.

When Michelson's time in Europe was complete, his 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 a salary of \$2000 per year and \$7500 for equipment, and his graduate education under Helmholtz, he readily accepted the position, resigned from the Navy, and in 1881 re-established his light-speed measurement work in Cleveland. A structure was erected for his lab and he reassembled as much of his Annapolis equipment as he could find. As his daughter pointed out, "Michelson's experiments had a way of costing far more than had been originally expected." He ran out of money and was assisted by... Newcomb, again. His result of $299,853,000 \pm 60,000$ meters per second stood as the standard for four decades.

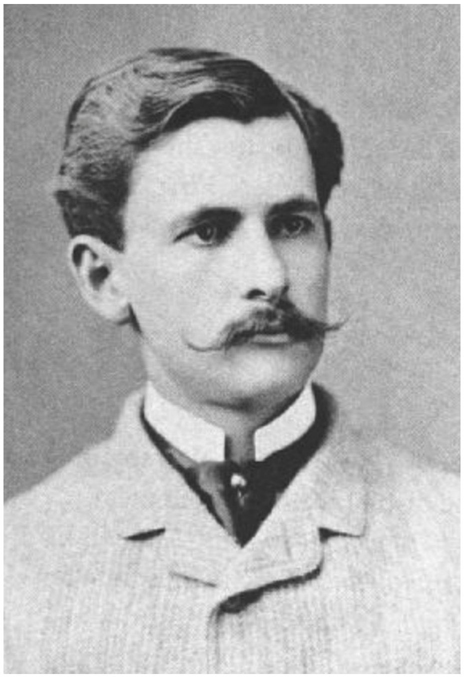

Figure 13.7: Michelson in 1887, around the time of the Michelson-Morley experiment.

In 1884 while on a trip to Montreal to attend a scientific conference, he met Edward Morley (1838-1923) on the train—a senior Western Reserve University chemistry professor who was good with his hands in a lab. They struck up a friendship and on their return determined to work together. Michelson had the pleasure of hearing his results discussed in lectures at the conference and Simon Newcomb made sure to introduce him to all of the attendees of note. As a result he found himself becoming friends with John William Strutt, 3rd Baron Rayleigh—future Nobel Laureate and another king of physics who invited him to Baltimore for a marathon 20 lectures on physics at Johns Hopkins to be delivered by Sir William Thomson, the future Lord Kelvin. One of his emphases was the elastic properties that the ether must have for the planets to move it aside as they pass. Thomson paid no attention to Maxwell's electromagnetic theory as Hertz was still three years away from his experimental confirmation in Helmholtz' lab.

Michelson and Morley resolved to do that experiment together and to use an interferometer as the device in Main Hall on the Case campus.

But it didn't happen. Morley wrote:

> "I can only guess at the stresses which brought about his illness. Overwork—and the ruthless discipline with which he drove himself to a task he felt must be done with such perfection that it could never again be called into question."

Michelson wasn't sleeping, nor eating. He'd been a tennis champion on campus, but now only worked. Eventually he collapsed and on September 19, 1885 at the age of only 33, Margaret had him committed to a nerve specialist in New York. Again, from Morley:

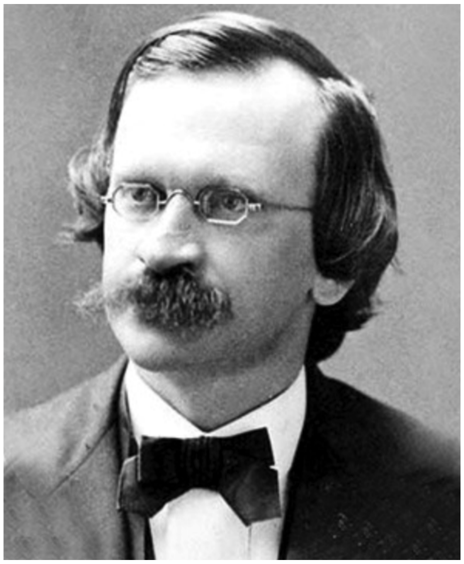

Figure 13.8: Edward Morley

> ... Mr. Michelson of the Case School left week ago yesterday. He shows some symptoms which point to softening of the brain; he goes for a year's rest, but it is very doubtful whether he will ever be able to do any more work. He had begun some experiments in my laboratory, which he asked me to finish, and which I consented to carry on.

What happened next is astonishing. He recovered in two months and wrote to Morley to inquire as to the experiment and learned that Case University had hired his replacement.

His doctor wrote:

> ... his [Michelson's] wife has urged me to shut him up in an asylum which I promptly refused to do. Mr. Michelson is one of the brightest men of this country if not of the world in his chosen study. He is an accomplished man, very popular with those who know him... Professor Michelson's most temperamental fault is a tendency to emotional acting, but I cannot say that it is unduly expressed, or that he ever acts without proper and adequate stimulus...

Fortunately, he recovered by December 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.

While healthy and ready to resume his research, the indignities from Case weren't yet over. The Trustees indicated that they would be happy for him to return to the faculty, but he'd have to take a considerable cut in his salary since they had hired his replacement for a whole year. Michelson had to pay for his own stand-in!

It gets worse, before it gets better. Sometime between midnight and 2AM on October 27, 1886 Main Hall on campus exploded. Michelson was able to salvage much of their apparatus and he and Morley reconstructed in Morley's Western Reserve chemistry lab. And that's when it got serious. They set out to reduce as many of the systematic uncertainties that the Potsdam experiment encountered and succeeded.

They tried to damp the vibrations that plagued the Potsdam measurement by building 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.

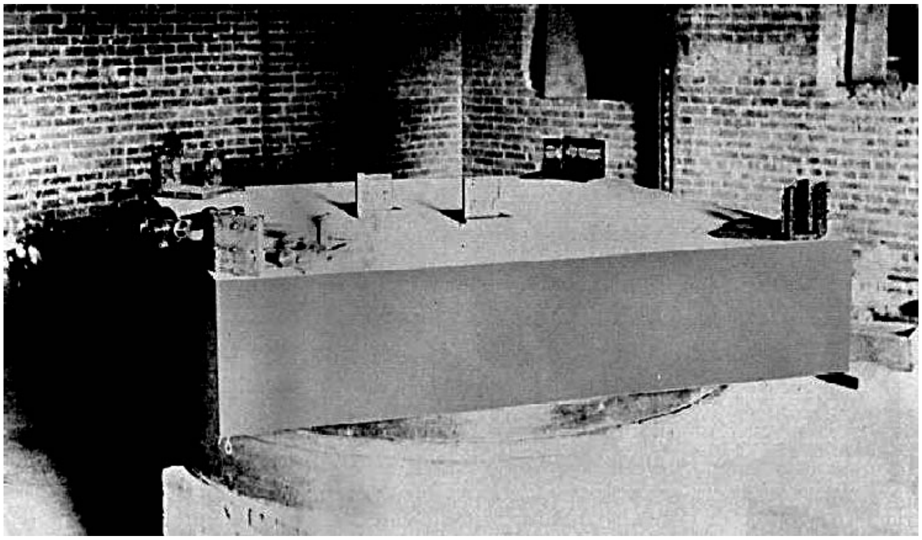

Figure 13.9: The Michelson-Morley apparatus on its huge concrete, rotating slab.

Furthermore with high quality mirrors the light paths were essentially increased by reflecting them back and forth to 36 meters in effective length, greatly improving the precision as well.

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. Figure 13.11 shows their results:

The sine-wave curve is what they expected to see as the slab rotated around a full circle. The vertical axis is the amount of fringe shift in fractions of the wavelength of the light. The sort of sad, flat curve is what they actually measured.

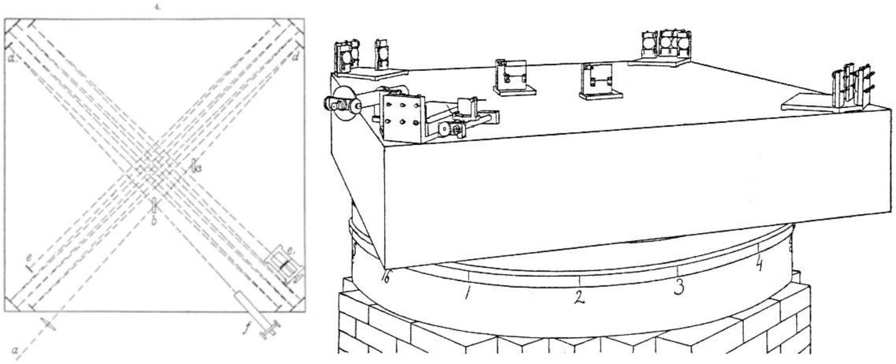

Figure 13.10: Plan and perspective engineering drawings

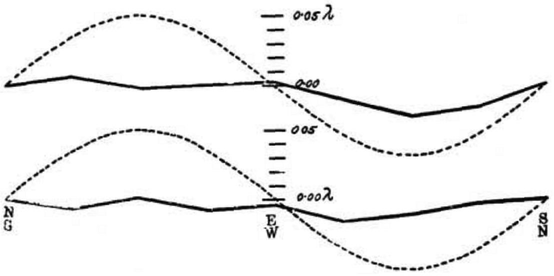

Figure 13.11: As they rotated the interferometer, if the speed of the Earth relative to a stationary ether were real, then they would expect to see the result shown as the dashe curve. The broken solid lines is what their results showed.

In August, 1887, Michelson wrote to Lord Rayleigh who had encouraged him to return to the ether experiment:

> 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.

What he meant was: result is definately 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 later hypothesis that molecular shrinkage with motion was the cause. (For more on this, see **The Fallout of Michelson's Null Result** in the Section 13.2 Modern Bits of Michelson below.) Neither Michelson nor anyone could imagine that the ether didn't exist.

Now the physics world was paying attention and people were beginning to try to explain it.

He never returned to this experiment again.

13.1.7 Michelson and Chicago

By 1888 Michelson had become unhappy at Case. There was the on-again, off-again, strange replacement of Michelson's position. Furthermore, the huge fire on campus in 1886 that destroyed his laboratory forced him to move into Morley's lab but the university never seemed able to find funds to rebuild it. 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 later in that same year a 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 Clark University was formed 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. But it wasn't a match made in heaven for any of the faculty recruited to Clark. By 1892, Michelson and 12 of the 16 scientists on Clark's 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 owning the distinction of losing Michelson. To the new University of Chicago in 1892, along with the other 11 from Clark. The University of Chicago promised big and delivered.

A Meter

But Michelson's arrival was delayed. The International Bureau of Weights and Measures in Paris recruited him for an important job: determining the most precise length of the standard meter. The French metric system relied on a platinum bar housed in Paris which defined 1 meter according to the original 1791 definition: 1 m = one 10-millionth of the distance from the north pole to the equator on a meridian passing through Paris. More precision was needed since the Earth is a non-spherical, geologically active object—it's not great as the basis for a standard length. And, even though there was a "standard" platinum bar kept at a controlled temperature in Paris, each nation, even many regions within a nation, had their own copies of the original standard meter. So there were lots and lots of "meters"![5] Sir Humphrey Davy and Maxwell suggested a standard which could be independently replicated using a natural phenomenon of some sort: the wavelength (for length) and frequency (for time) of light.

One of the outgrowths of the Michelson-Morley experiment at Case (Western!) was the realization that the interferometer could be used for other purposes. For example, by making one of the arms moveable and with a careful micrometer measurement of just how far it moves, one could watch the interference fringes change place. By marking where one peak was, changing the distance of the movable mirror would march the peak across the eyepiece and when a trailing peak lined up at the origin spot again, the lengthening would correspond to one half of a wavelength. So, one could precisely determine the wavelength of spectral lines of various light sources. In 1887 they proposed using interferometry as the tool for precisely measuring the meter and proposed that the spectral lines of Sodium light might serve as the source. (Sodium vapor emits a bright pair of yellow emission lines.) Then they decided Mercury's green line would be suitable, but discovered that Mercury's line was actually quite complicated—many lines. So they actually made a discovery about the element Mercury! Of course they could then measure the spectral lines of other elements an important addition to the nascent science of spectroscopy.[6] They kept at it and found that the red Cadmium spectral line ($\lambda = 6,438$ Å where an Angstrom is 10^{-10} meters) was singular and could become a calibration point.

That's what the International Bureau of Weights and Measures wanted. They invited Michelson to come to Paris and find an emission-line standard for a meter. This he did with

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[5] Also, there was real concern that were a war to break out that the unique platinum bar could be destroyed.

[6] They and others became less interested in the interferometer for this purpose and it went out of style. Only to be resurrected in the 1950's as "Fourier transform spectroscopy."

characteristic precision and accuracy with a result that lasted for four decades. After being repeated in 1905, two years later the standard meter became 1,553,163.5.180 wavelengths of that Cadmium red line's wavelength with an uncertainty of 0.08 parts per million. This measurement was referenced as a part of the justification for Michelson's Nobel Prize in 1907.

When his work was done, he reported to duty at the new University of Chicago. Margaret and the children bought a house on the East Coast and didn't join him for a while.

University of Chicago

The University of Chicago's origins were due to foresight and a vision of a first-class university. Marshall Field donated land and other Chicago businessmen donate money. The new Ryerson Physical Laboratory was completed in 1894 and Michelson and others moved in. Students who could pass the difficult entrance examinations came from all over the world. It must have been a heady time as the new faculty knew that they were participating in something special in the Unites States. He was to spend the next 40 years there.

The next couple of years were replete with honors: the Société Française de Physique, the Royal Astronomical Society, the Cambridge Philosophical Society, and the Société Hollandaise des Sciences. But they were not without heartache as well.

In 1897, the Michelson's shocked the tight-knit faculty when Albert moved to a hotel. Margaret sued for divorce and he agreed to support his three children (Albert Heminway, Truman, and Elsa) with $10,000. The court proceedings were humiliating as the children had been trained to describe cruelty at his hands in their upbringings. He vowed to never see them again.

He met Edna Stanton while his divorce was still pending. She was the daughter of a former diplomat to Russia (she lived there for 12 years) and a German mother. And she was radical and a free-spirit. . . and 20 years younger than Albert. Nonetheless, they were married in 1899 and subsequently had three children.

His time at Chicago was nonetheless productive and pleasant. His students enjoyed him. He played tennis regularly and had a professional 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 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."

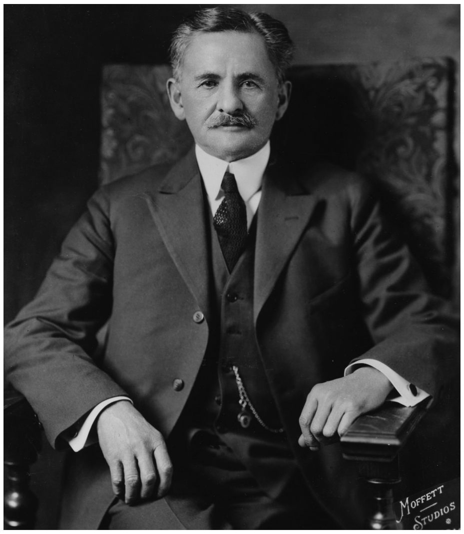

Figure 13.12: Michelson around the time of his Nobel Prize.

Michelson died in 1931 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 was 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.

A nice side-story to the Nobel award was in the crowd who surround him after his Nobel

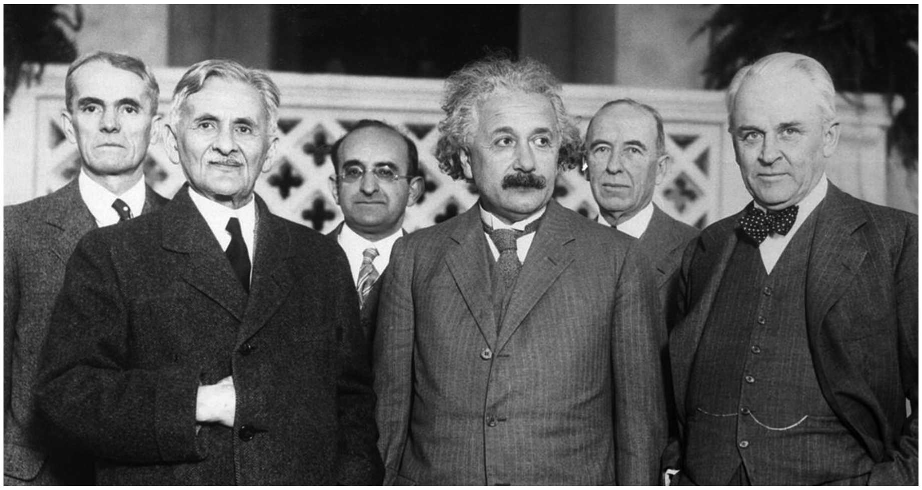

Figure 13.14: Michelson with Albert Einstein and former Chicago colleague, Robert Millikan in California in 1931.

lecture. A young man approached him to say, ""You don't know me. I am your son." The bitterness of the divorce from Margaret left Albert estranged from his two sons and daughter 11 years previously. Young Albert had graduated from Harvard and at 29 was the American consular agent at Charleroi, Belgium. He'd been in Italy at a meeting, saw that his father had won the Prize and was bound for Stockholm and traveled north to meet him. Michelson abandoned his plans and spent time with his first-born son.

13.2 The Modern Bits of Michelson

The Speed of Light

Synopsis:

1. A survey of historical attempts to measure the speed of light.
2. Detailed description of Fizeau's method of light passing through water.
3. Detailed description of Foucault's method.
4. More detailed description of Michelson's method.

Figure 13.13: Michelson in his Ryerson office late in life.

His Interferometer

Synopsis:

1. A more detailed description of the interferometer in the Michelson-Morley approach.
2. A description of interferometry in modern optics labs.
3. A description of interferometry in astronomy.
4. A description of LIGO.

13.2.1 The Fallout of Michelson's Null Result

Synopsis:

1. Lorentz's attention to the null result and his subsequent treatment of Maxwell's equations.
2. The Lorentz-Fitzgerald model of the null result.

13.3 Appendix The Technical Bits of Michelson

Synopsis:

1. Derivation of the Roemer measurement of the speed of light.
2. Derivation of the times required to cross the river.
3. Derivation of Fizeau's cog-wheel light-speed measurement and his measurement of light speed in water.
4. Derivation of the Lorentz-Fitzgerald model of the null result.
5. Overview of the Lorentz Transformations required to preserve the invariance of Maxwell's Equations.