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DAVID KAISER: OK, so today we're going to be talking about waves in the ether-- a great topic, I think. Welcome back to 8225 STS 042, Physics in the 20th Century. To Maxwell and his really quite extraordinary work from the 1860s where he unites, as we've seen a few times, really, the study of optics of light waves and brings that to be very intimately connected to the study of electric and magnetic fields in the ether. And then we'll be looking for much of that first section on how some very smart people tried to generalize Maxwell's work in the years after Maxwell's publications or, indeed, after his treatise on electricity magnetism from the 1870s. So we'll look, in that case, at some of the work by Hendrik Lorentz, a remarkably influential mathematical physicist from the Netherlands.

Then we'll look in the second part at one of the kinds of experiments that was making a lot of researchers around many parts of the world really scratched their heads about how to make sense of this question of waves in the ether. And we'll see what was going on with that experiment. That was, of course, the reading. The main reading you had for today was one of the publications by Michelson-Morley about their work.

And then we'll come back in the last part for today and see how Hendrik Lorentz responded to the Michelson-Morley experiment as well as to the more mathematical aspects of Maxwell's work. So that's what we're going today. And as I say, some of this stuff I'm going to skip some steps in their derivations. And the lecture notes will hopefully help fill those in.

So we've seen a few times by now that starting in 1865, James Clerk Maxwell came to the conclusion that light waves were nothing other than transverse undulations-- that is to say, a certain kind of wave of electric and magnetic fields propagating in the ether. And we all now have the possibility to purchase our own set of Maxwell's equations on a T-shirt. Some of you might actually already own one, in which case, I'm quite jealous.

So what I want to do first is walk through at least briefly, why did Maxwell think that? What was the basis for Maxwell's conclusion that light was nothing but these electric and magnetic waves in the ether? So first, you may recall from previous studies of electromagnetism that there are four different kinds of fields that appear here on this side, on the left-hand side of these otherwise quite succinct Maxwell's equations.

We see a D, a B, an E, and an H. Actually, as you may remember, those aren't all independent of each other. And in fact, D is often called the displacement field is, in most instances, just proportional to E, the electric field. And likewise, H, which is sometimes called the magnetizing field, is also, under many circumstances, just proportional to the magnetic field B. So really, what we're looking at for most applications of interest are four equations governing actually two physically distinct quantities-- the electric and magnetic fields.

Now, these terms of proportionality in modern parlance, epsilon, this Greek letter epsilon, that relates the displacement field to the electric field, that's what we would call the dielectric constant. Sometimes it's called the permittivity. We saw we had a little indication in the previous lecture, to Maxwell and his circle, that was really like a spring constant. It was a way of characterizing the responsiveness of either the ether itself or some other material that might be placed within the ether, like some insulating or dielectric material.

Likewise, we will call mu-- we today call mu the magnetic permeability. For the Maxwellians, it was also, again, a different kind of-- basically a spring constant, a kind of elastic feature of the medium. Now, what's important is that for Maxwell and his generation, within the ether, these took on simple numerical values.

They just became constants with reference values. This was a number with a particular value, and that was the value of, say, the permittivity of the ether or the magnetic permeability of ether. So epsilon just became some constant epsilon 0. Mu likewise became some constant mu 0.

Moreover, Maxwell realized, if you look at the source terms, the right-hand side of some of these equations-- sorry-- then you see that there are some terms referring to either the electric charge density rho or an electric current capital J. Well, Maxwell began to apply his own new equations before they were written in this very nice convenient form that we inherit from Oliver Heaviside.

Maxwell began applying his equations to a region of space that was filled only with ether, a region of what we would call empty space. To Maxwell, it was never truly empty because, of course, it was filled at least with this all pervasive luminiferous ether. But he wanted to, in particular, consider a region where there was no bunch of no clump of electrically charged matter-- so rho would vanish in that region of space. There was no electric current flowing, and so J would vanish-- capital J.

Then, it takes only a couple of steps, the kinds of steps that he was very good at as second wrangler at Cambridge. It was only a few steps to then rearrange these four equations on the T-shirt into actually two identical equations, to a pair of equations-- one for the electric field and one for the magnetic field.

And so you could manipulate those four equations by taking the divergence of one and so on and the curl of the other, the kind of manipulations that wranglers are very good at. And he boiled down his four equations in this simple case of considering the electric and magnetic fields in regions that were filled only with the ether. He could form two versions of the same equation.

Both the electric and magnetic fields would obey the same form of the equation. Again, just as a reminder in case you haven't seen it before, this upside down triangle-- sometimes called nabla-- that's a shorthand for the second derivatives in the spatial directions. That's like d by dx squared plus d by dy squared plus d by dz squared.

How is this quantity varying in space by taking the second derivatives of spatial variation? And what Maxwell found is he could relate those spatially varying quantities to the way that same quantity-- either E or B-- would vary over time. So you see, related to the second derivatives of time with some proportionality that turned out to be the product of those two spring constants-- the dielectric constant and the magnetic permeability when they take their simple constant values in the vacuum.

So this is why Maxwell started getting quite excited in 1865. He realized largely because of his Cambridge Wrangler or math tripos training that this form of the equation is very, very familiar. This was, as he already well knew, the form of a wave equation for a traveling wave.

Again, I go through this in a little more detail in the lecture notes if this is new for you. We'll just go through. We'll take a quick look here, unpack that a bit further.

So every good Cambridge Wrangler knew, in fact, even some of the not such good Cambridge students knew by this point that there was a general form to represent a wave equation for, say, a traveling wave. And it would take this form where you have the second derivative over space-- nabla squared or del squared.

You have second derivatives in time, and you have this proportionality given by the speed with which the wave was traveling. Say v was the speed of the wave. So if you have some wave-like quantity, like, say, the amplitude of the wave, it would vary over time and space. And it would vary according to this differential equation where the key part was v is the speed of the wave.

Now we go back-- oh, let's just simplify. Consider motion in a single direction of space. So instead of considering x, y, and z, let's just consider, to make it simpler, motion only along the x-axis.

Then we can very quickly solve this equation where you've all probably done many times. And the solutions in general will be a series of sines and cosines. It's just a periodic oscillation. It is, indeed, wave-like behavior, as we'd expect.

So I've introduced some notation here again, which might be very familiar for you. K is really just an abbreviation. It's called the wave number. It just goes inversely with the wavelength, as you might have seen before.

The lowercase Greek letter omega-- this one looks kind of like a w. That's the omega letter. That is the frequency.

In fact, it's the angular frequency. And that just goes inversely with the period of the wave. And so, again, in a way that's probably familiar for you, when you have a function that satisfies this kind of wave equation, then the solutions can be thought of as waves in both space and time.

So here, what I'm doing is presenting a snapshot at one moment in time-- let's say t equals 0. How is that wave spread out over space? If you can imagine just to freeze time and look to your left and your right, you'd see some regions where that wave reached a peak, at a crest, other positions in space, other values along the x-axis where the wave reached a trough or a minimum, and it would periodically rise between crest and trough. The distance between neighboring crests or peaks was simply the wavelength lambda inversely proportional wave number.

Likewise, we could stand at a particular location in space-- let's say, the origin x equals 0-- and just clock in how high is the wave as it passes us over time. So now we're saying staying in one position in space and clocking how the amplitude changes as a function of time. We once again see this very simple oscillating pattern where, at one moment, we see a peak of the wave passes by. Some time later, at that same position in space, we see a trough and vice versa.

And the time duration between peaks is the period, capital T, inversely proportional to that frequency omega. That's very likely familiar. If that's not so familiar, there's a little bit more write-up in this lecture notes. But that's how wranglers had learned to handle things like the traveling wave mathematically for a long time in preparation for the Tripos exam.

Now, let's go back to what Maxwell had found, as I showed you in the previous set of slides. He found an equation for the electric field and an equation of identical form for the magnetic field when he applied his four equations. In fact, it was more complicated with all the components-- what we would now consider the four simple equations for electromagnetism. When he applied them to a region of only ether, no nearby charges or currents.

And he found an equation of exactly the same form that would be obeyed by both the electric and magnetic field. And not only that, when he plugged in the best-known values for these kinds of parameters of the ether, these spring constants, what we would now call the dielectric constant and the magnetic permittivity or permeability-- excuse me-- he found the numerical coincidence that the product of those two constants actually was very, very close to what was already known to be the speed of light. In fact, he found it went 1 over the square of that speed of light. So this quantity looked a lot like 1 over the square of the speed of that traveling wave as it would look for a generic mathematical treatment of waves.

Now, the speed of light had been measured for 200 years by this point, both in optical experiments, but often in astronomical ones. So the speed of light was actually a constant, a number that Maxwell knew about, he'd heard about. So he was prepared when he began substituting in these seemingly totally separate parameters or constants-- epsilon and mu. And he found really, to his surprise, this numerical value that their product went 1 over the speed of light squared.

That's what drives him to conclude, starting in 1865, that light waves-- waves that travel at the characteristic speed c-- were literally nothing but traveling waves of electric and magnetic fields in the ether. These were these transverse undulations that he began writing about. That's what gets Maxwell to that conclusion.

I want to give this a little more example of his thought process for why he concludes that light was nothing but these waves of electric and magnetic fields in the ether. OK, so now Maxwell's whole analysis there, as really quite succinct and elegant as it was, had made a number of simplifying assumptions. You might have noticed he was assuming that both the emitter of those waves, the source of those waves, and also the receiver of them were both at rest, not only with respect to each other-- neither was moving with respect to the other-- they were both at rest with respect to the ether.

Let's imagine that we have some source-emitting light that's just sitting absolutely still in the ether, and it's going to generate those sine and cosine-like waves of electric and magnetic fields. And let's say, at some other location, fixed at rest in the ether is something that's going to measure or receive them.

So an obvious next question to ask is, can you generalize Maxwell's treatment of optics to the case where either the sender or the receiver, or maybe both, are moving not only with respect to each other, but even more important for these folks, moving with respect to the ether, with respect to that light-bearing luminiferous ether? And that was a challenge that many, many leading mathematical physicists recognized one of the next obvious things to try downstream from Maxwell's result, and this became basically the challenge of the electrodynamics of moving bodies, a title that we're going to come to many, many times.

For much of today's class, we're going to look at how a particular mathematical physicist, Hendrik Lorentz, tried to make sense of this. So he took on this task, as did many of his peers, this task of trying to generalize Maxwell's treatment to the case of moving senders or receivers of light. Now, on the one hand, this looked like a pretty straightforward challenge. Lorentz, like every trained mathematical physicist of his day, knew how to perform things like coordinate transformations.

In fact, it was the Galilean coordinate transformation. Galileo had worked it out in the early 1600s. It was hardly cutting-edge research. The idea was, as you may remember or you may know, Galileo imagined how to relate the coordinates of, say, someone riding on a boat moving at a constant speed down a river, let's say, and how that person might relate her coordinates to those of an observer standing on the shore or the side of the lake, standing still, they would have said, so that you could relate the one set of coordinates to the other by taking into account the relative motion.

If we imagine that we're the observer on the shore watching this boat drift by, then we can relate how the coordinates of the person on the boat-- let's say, the origin with that person calls x equals 0-- how that will shift with respect to our coordinate system. We realize the boat is drifting at some speed v. So at later moments in time, the position x equals 0 on the boat will have drifted away from what we call x equals 0 on the shore.

And we just take into account of the relative motion with this speed v. This is what's called the Galilean Coordinate Transformation, and this was indeed quite familiar. It got codified by Newton in the later part of the 1600s. This was really pretty old, literally textbook stuff by the time people like Maxwell and Lorentz came along.

But then Lorentz found something that he did not expect. When he used the totally standard way of relating coordinates when there's relative motion between, in this case, say the emitter and the receiver of light, he put those into Maxwell's equations that related, remember, derivatives or variations in space to rates of change over time, he got something that looked a bit more like a mess. So when he tried to apply the coordinate transformation to Maxwell's equations for the propagation of an electric field in the ether, he got a form that no longer looked quite so simple as Maxwell's original form.

Why that have bothered someone like Lorentz? Because that meant the solutions to this transformed equation would no longer behave as simple sines and cosines. And now, you're all on mute, but I can imagine you're screaming, much like this great Edvard Munch picture. That's how I feel. How could it be?

Why was it such a headache for Lorentz? Why was it so alarming? Because people had been measuring light on Earth for a long, long time and had already figured out that light behaved more or less like sines and cosines. In many, many, many applications here on Earth in laboratories in increasingly precise optical laboratories on Earth, really getting throughout the 19th century, people had measured properties of propagating light waves, or more generally electromagnetic waves of various wavelengths. And they routinely found that these waves were behaving like very, very much like sines and cosines, exactly as Maxwell had found. Why that matter?

Well, Lorentz knew that he was doing these measurements, or his colleagues were on the planet Earth. He knew the Earth was moving through the ether. It was moving in its rotation around the sun. There's no reason to think even the sun was at rest in the ether. The Earth was certainly very likely to be not the center of the universe anymore in the years well past Copernicus.

So it seemed all but certain that the planet Earth was in some state of motion through the ether with this light-bearing ether. So we should have to take into account this coordinate transformation because the light waves being either emitted or received on Earth were not being treated-- were not at rest with respect to the ether. They were on Earth. The Earth is moving, so we're in some relative motion with respect to the ether. And yet, in optics labs around the world, people really did measure properties of light as if they were just simple sines and cosines. How could you square these two things?

So Lorentz came up with one part of what turns out to have been a two-part response. So we're going to look at both of his responses today. This is going to take up much of our class today. His first response was really mathematical. He was, after all, a remarkably accomplished mathematical physicist.

So he published this first in the 1890s, this first part. He just introduces a new time variable. He calls it local time.

So if you recall in the Galilean transformation-- let me bring it back up for a moment-- the standard way to relate coordinates, I should have emphasized earlier, you take into account a change between x and x prime. You watch the boat drift, so you see that the boat observer's x equals 0 has moved with respect to your x. But you assume, as Galileo assumed, as Newton assumed, that there's no reason to change your time coordinate.

Your clocks shouldn't be affected by the fact the boat's drifting down the river. That was the assumption. So typically there was no change in the time coordinate, even when you were considering relative motion.

Well, Lorentz, in a move of really desperation-- cleverness, but also desperation-- said, well, what if we revisit that? What if we introduce a new time that he calls local time t prime where that also becomes a function of both the time of the original coordinate system, the location, say x, and also the relative speed of motion between them. If he then reverse engineers what form of transformation would he need for this new time coordinate t prime, then he could actually save the form of Maxwell's equations when he transformed both x and t-- not only x-- in a particular way, he could make sure that the Maxwell's wave equation was invariant under this new set of coordinate transformations. He could save the form of Maxwell's equations.

Now, Lorentz always, always thought this was just a trick. He absolutely did not think this was a physical change to how clocks would measure time. He did not think that this was a real effect in the world.

It was a clever way to try to relate coordinate systems that he left really as mathematical. In fact, he himself calls it fictitious in his own papers. This was just a way to try to say, let's refer everything back to the ether rest frame, and we'll have to do a little more complicated mathematical jujitsu to understand why light should continue to behave like sines and cosines.

So I'm going to pause there and ask if there are any questions on that part so far. Any questions on any of that? I see the chat has a few items.

So indeed, ether has been spelled many ways. I see that in the chat. That's definitely true. And thank you, Tiffany and Julia, for weighing in on that.

Good question. He was definitely fixated on this mathematical coordinate called t, and that had been the time coordinate since Galileo's time, if not before. He was intentionally adjusting how he would compare the time coordinate for, let's say, one state of motion versus another.

So that part wasn't so surprising, either for himself or his colleagues. It was the t coordinate. T stood for the time read by a clock.

That's what Galileo meant. That's what Newton meant. That's what Maxwell meant.

What he wanted to be very careful about was to make sure his readers knew he didn't take this literally. It was really a mathematical move to say, if we somehow have to relate our own local coordinates to the ether rest frame, which is the physically relevant comparison, as far as they were concerned-- these were disturbances in the ether-- then he wasn't sure what to make of the fact that the t coordinate for this person might not be the same t coordinate for someone at rest with respect to the ether. He would agree it was all about how we measure time on a clock.

He just was convinced it was a kind of illusion. It was a fictitious thing. But if you do that, then you can make Maxwell's equations look like the way one wants to.

Ah, good. Gary asked the question, why did Einstein later say he built his theories on Maxwell rather than on Lorentz? That's a great question. I can invite you to ask again in about one or two class sessions. We'll talk quite a bit about that, actually.

Yeah, that's an excellent question, Gary. But I'm going to pause on that one. Any other questions on what Lorentz was doing in the 1890s? What was the nature of the challenge or this question about the behavior of that wave-like equation that Maxwell found? It looked so pristine and powerful until you asked the next obvious question, what if either the sender or receiver of light is in motion with respect to the ether? Uh-oh, the usual tricks for relating coordinates seem to lead to some real difficulties. That was the main point of that first part.

Any other questions on that? If not, I'll jump into the next part. OK, good. Let's go on now to the next part, which is all about the reading you had for today, the Michelson-Morley experiment.

So we've seen many, many times by now Hendrik Lorentz, like pretty much all active mathematical physicists and experimental physicists of his day-- Lorentz knew, just knew, that light propagated in the ether. These were these transverse undulations in the ether.

So another natural question to ask is, could you ever detect the fact that our Earth, our own home laboratory, was moving through the ether? As I mentioned on that slide a few slides ago, the Earth was moving around the Sun. That was very clearly established for this generation long ago well past the age of Copernicus. So there's no reason to think that the Earth is at rest in the ether. Maybe even the sun isn't at rest. There could be all kinds of complicated motions that we on Earth are going through with respect to the universal ether.

So could we ever detect our own motions through the ether based on the behavior of light? Light are these waves in that all-pervasive ether. We're moving through the ether. We measure properties of light all the time. Could we recognize that we're actually in motion?

And the idea was an analogy much like you might think of these days if you're lucky enough to get some fresh air and go for a bicycle ride. So first, imagine you step outside on a day like today, where, at least where I'm sitting, I can see out my windows there's very little breeze or wind.

If I were to walk outside right now, I would feel no particular wind in my face. The air is still. If I just stand still outside, I don't feel anything on my face because the atmosphere is not in any kind of state of motion.

If, however, I were to either run really fast or get on a bicycle and pedal really fast, I would feel a wind on my face. I would feel the breeze. Even if I had stopped pedaling and stood still again, that breeze would go away. I would feel the effect of my motion through the medium a headwind, not because the medium was in motion, but because I was moving with respect to the medium.

Even on a still day with no breeze, the leaves on the trees are still, the blades of grass are not being blown around. If I move rapidly through that medium, I will literally feel it. I'll feel a breeze on my face. I'm belaboring the point probably quite familiar to you, also like you might see on this cartoon.

So the question was, could we measure the effect of our own headwind? Could we feel that effect of our own motion through this physical medium-- the medium, in this case, being the all-pervasive elastic luminiferous ether if we, like the bicyclist, are in a state of motion through it? So that was a challenge that many people thought was a neat question to ask. One of the first to really tackle it in a very systematic experimental way was this remarkable figure named Albert Michelson, who began in earnest to try to tackle this in the 1880s. I should just say, I think Michelson is really, really amazing and fascinating as an individual.

He was born to a very poor Jewish family in Central Europe on the border of what would soon become the borderland between Germany and Poland. When Michelson was two years old, his family emigrated to the United States. They actually made their way to California in the midst of what became known as the Gold Rush in the late 1840s, early '50s.

And so his father became a merchant to try to supply the people chasing their fortune in the Gold Rush in California. They moved around from one little tiny mining town to another. Michelson actually wound up getting a fellowship to the Naval Academy, so he got a free university education because he qualified for Annapolis. And that's where he really fell in love with physics and mathematics and began thinking about optics, in particular-- more to be said, totally crazy, fascinating story.

Michelson then got a fellowship to study after his undergraduate days in Germany. So he was able to learn some of the latest innovations in electromagnetic physics from some of these experts who had studied with people like Hendrik Hertz and others who were deeply, deeply enmeshed in Maxwell's equations and the propagation of light in the ether. So Michelson sets himself this task-- could he design an experiment or a device with which one might measure this headwind of the Earth's own motion through the ether?

And what he did was design a really quite novel, very ingenious device called an interferometer. And there's a lot on this in those separate lecture notes. You get a little taste of it from the Michelson-Morley reading for today as well. So we'll talk a bit about what this instrument was like.

So Michelson's work is also interesting not only because of his own quite dramatic life story. He was a championship boxer when he was at the Naval Academy. I often joke, perhaps unfairly, he was probably the only championship boxer who also won a Nobel Prize in physics. If you know a counterexample to that, please let me know. He's the only one I know about. anyway, interesting guy.

Not only was he interesting because of that, he was also interesting historically because the work that we'll look at in this part of today's class was really among the first examples of research in any of the natural sciences, including physics, that really started getting the attention and earning the respect of some of the very elite scientists in Western Europe. There were a few others in Michelson's day, but this was pretty new. The United States was still seen, often rightly, as a intellectual scientific backwater, at least as reckoned by the experts in Western Europe.

Michelson's work begins to change that. And in fact, as I mentioned, or as you see here, he becomes the first physicist based within the United States to win the Nobel Prize. He wins this Prize in 1907. And he wins it for the kind of work that we'll talk about now.

So to get our heads into what was going on with this interferometer, I like to think of this analogy in terms of swimmers. And again, we'll go through it here. Some of the extra steps of these derivations, you can find in the separate lecture notes. So what Michelson was really doing-- as you know from the reading, Michelson, especially with his partner, Morley, was using the interference of light waves to conduct tests and experimental tests of really unprecedented precision and accuracy.

So before we talk about interference of light waves, let's talk about a race that we can imagine being conducted by two swimmers in a river. So we'll sit with this analogy for a few moments here. So imagine we have a race where one swimmer is going to leave from point A, swim directly to point B a distance L, and then swim directly back from B to A. That's swimmer 1.

Swimmer 2 is going to cover the exact same round-trip distance, but she's going to swim across the river instead of directly up the coast here. So swimmer 2 has to set out from point A, swim across the river a distance L to point c, and then swim back to point A again. The question is, who will win? Which of those two swimmers will get back to point A first?

And the other thing to bear in mind is that the river is flowing. There's a current in the river of a constant speed, v. So there's a downward current here of a constant speed.

So let's consider swimmer 1. Swimmer 1 is leaving from point A, swimming directly against the current to get to point B. So for that half of her lap, she's swimming at a net speed of c minus v. As you can see in the text here, each swimmer is required to swim at a constant speed with respect to the water.

And swimmer 1 is swimming at speed c with respect to the water, but the water itself is flowing back against her with a current of speed v. So her net speed is measured, say, from the shoreline, from, say, the judges sitting here on the shore or the banks of the river. Her net speed for that part of the journey is c minus v.

So she takes a time to get from A to B. That's the distance traveled divided by her speed. So her time to go from A to B is just the distance L divided by her net speed, c minus v. That's probably pretty clear for you to go through the reasoning.

On the way back, now she gets the boost. Now she's swimming with speed c with respect to the water. But the water itself is flowing and helping her out because she's now going with the current.

So her net speed as measured, say, from the shore or the riverbank for the return journey is actually quicker. It's now c plus v, same distance L. So just a few lines of algebra-- and again, you can go through that a bit more on your own or with the notes.

Her round-trip time, her lap time to go from A to B and back to A again turns out to have this relatively simple expression. It depends, of course, on the distance traveled. There's a 2 here because she has to go there and back. She covers total distance 2L, her speed with respect to water and then, it turns out, going directly against the current and directly with the current with a little algebra leads to this correction factor here, 1 over 1 minus the square of v over c. That's how long it takes swimmer 1 to complete one lap.

Now, what about swimmer 2? Swimmer 2 knows that she has to accommodate the fact that she's going to be encountering this current of the river. So she has to leave point, and she has to actually land at point C to qualify for her race. That is a distance L across the river.

To get there, she has to swim at this diagonal. So while she's swimming across the river, the current will nudge her downward. So by the time she crosses the river, she winds up at point C. If she just set out and tried to swim straight across river, she'd get knocked off course by the current.

So she has to travel along the hypotenuse of a right triangle. So she's traveling along this path, capital R, during the time that she's heading from A to C, that tAC, she's drifting down in this direction a total distance of v times that time. That's the distance that she'll that she'll be nudged in this direction by being in the water for this duration of time and being nudged by the current at that speed.

So thanks to the greatest invention of ancient Greece-- which I often say was neither democracy nor the epic poem, it was, in fact, the Pythagorean theorem-- we now know how to relate the squares of the lengths of these sides of the triangle. The direction the length of this side R squared is, of course, equal to the sum of the squares of the other two sides of the right triangle, this side squared, and this side squared.

We have a little extra information we can use because we know the length of this line segment R is the speed with which she swims with respect to the water times the duration that it takes her to cross the side. So now we can plug in a new value for capital R as well as for this drift displacement, vtAC. And now, again, just a few lines of algebra, which I know you can do, and there's a little bit more steps in the notes, but just a few steps.

We see that her lap time, her total time to go from A to C and back to A again, looks pretty similar to swimmer 1, but not identical. It also is proportional to the total length. That's a 2L. It, of course, involves her speed with respect to the water and has some correction due to the flow of the current.

OK, so I'm going to put these both back up side by side, the lap time for swimmer 1, the lap time for swimmer 2. The question is, who wins the race? Who gets back to point A first? Now, it might not be so clear if you just eyeball it. So let me define a very helpful quantity, a quantity you might have seen before, a quantity we'll see many, many times in the coming lectures, including throughout today.

Typically it's abbreviated by the Greek letter gamma. So I'm just going to define gamma as a convenient combination of v and c. I'll define it as 1 over the square root of 1 minus quantity v over c squared. And here's a plot of what a gamma looks like as the ratio v over c gets closer and closer to 1.

In fact, it diverges. It actually becomes infinite if v is exactly equal to C. I just truncated my plot here. But you can see it stays it stays pretty close to 1, but greater than 1 for any nonzero speed. And it rapidly becomes very large at larger speeds compared to the speed C.

So let me ask again, who wins the race? If I do a little extra algebra, making use of this new quantity gamma, we can rewrite the total lap time for swimmer 1, who goes from A to B and back. Her time is proportional to gamma squared.

Meanwhile, the total lap time for swimmer 2 goes across the lake and back, across the river and back. Her lap time is proportional only to gamma. Now I just emphasized for you, gamma is always greater than or equal to 1. If there's any current flowing, if v is nonzero, the gamma is a quantity bigger than 1.

So now hopefully it's a little more clear to see swimmer 1 will actually lose the race. Swimmer 1, time tABA, is actually a larger quantity in general than the time for the return journey for swimmer 2. tABA is actually bigger than time tACA. There's a time difference.

That means there's a clear winner. They have different times to complete the laps. And it turns out, the person who goes directly against the current and then directly with the current will take overall more time to complete her lap than the swimmer who goes diagonally across the river and is with that drift displacement from the current.

Not only is there a difference in time that depends on this quantity gamma, if we expand gamma for speeds that are small compared to c, if v over c is a small quantity, then we can just do a Taylor expansion in that small quantity. We see the difference in time is what's called a second-order effect. That's just a fancy way of saying that the difference in time goes like the square of that small quantity, the ratio of v over c.

So there should be a winner if there's any current flowing in the river. If v is nonzero, then there should be an absolute clear winner in this race. It should go like the second order in the ratio v over c.

So now, why did I talk about this crazy swimming race? Because that's pretty close to what Albert Michelson designed for light waves. And this is his instrument called the interferometer. It's really quite brilliant.

So the way the interferometer worked was instead of swimmers, he had a bright source of light of nearly-- it was nearly monochromatic. He was using sodium arc lamps in the beginning. So it was shining very brightly with basically one characteristic color or wavelength of light. That was important.

He shines that light from a single source onto a half-silvered mirror. As the name suggests, that's an object that lets about half the light pass straight through like a window and reflects about half the light. So it's not totally reflecting. It reflects, on average, half the light that falls upon it.

So from this single source of light S, this sodium arc lamp, half the light will pass through like it just sees a clear window and travel a path, a distance L, until it encounters a fully reflecting mirror, this top mirror up here. That mirror then will reflect all of the light that hits it. That light will then bounce back to that half-silvered mirror, a portion of which will, again, be now reflected and hit some screen. That's like swimmer 1 starting at point A, traveling to point B, and coming back to point A.

Meanwhile, half the light that encounters this half-silvered mirror will not pass through. It'll actually be reflected. And so this becomes like swimmer 2.

So half of the incoming light that is incident upon this half-silvered mirror will be deflected along path 2. It will travel a fixed distance L until it encounters a fully reflecting mirror at the end of that path. That will reflect the light back. Half of that light will then pass through the half-silvered mirror.

So now we've set up a race. We have a single light wave that starts off at the same time. Swimmers 1 and 2 both start at point A at the same time and set off on their distinct journeys.

If there's any difference in the distance they need to travel-- or excuse me-- if there's any difference in the time it takes them to travel along either path 1 or path 2, those light waves will come back no longer in phase. The crest of one will no longer line up with the crest of the other. You could get interference.

So if the light waves that travel these distinct paths take different times, just like the swimmers took different times to complete their laps, the waves will come back out of phase with each other. And you should see interference when the two waves can be joined back together on some screen. You should see a characteristic interference pattern. The amount of offset will depend on the amount of time delay between traversing these two paths.

So that was the idea. Michelson first built a 1-meter version, where each of these paths' capital L were about 1 meter in distance between the half-silvered mirror and the fully reflecting mirror. And then he actually got external funding-- partly from his father-in-law, or an uncle, or something like that, and from other sources-- to build a super-sized version. And this is the second version he did with his colleague Morley once he was now on the faculty at Case University, which is now Case Western Reserve University in Cleveland, Ohio.

They built a ginormous version of this interferometer. The lengths between the half-silvered mirror and the fully reflecting mirrors were 11 meters, like 33 or 34 feet-- enormous paths. And to try to damn down on vibrations from things like not only horse-drawn carriages, but early trolley cars outside the laboratory to try to dampen any kind of source of systematic error, they put this entire 34-foot long optics table floating on a VAT of mercury, which I do not recommend, by the way. They were breathing in horribly, horribly poisonous fumes throughout this experiment. Don't try that part at home.

So this is a figure taken from that paper-- we have the paper in our reader for today-- where they then finally tried to put together, was there any offset? Did the interference fringes-- when those two light beams came back together on that collecting screen, was there any evidence that one path required a different amount of time than the other?

And the short answer was no. They found no compelling evidence that there was any time delay, any time difference, between the path taken by light that traveled path 1 versus the light that traveled path 2. There's a little wiggle to these curves. They were convinced that was almost certainly just experimental noise, systematic noise.

In fact, as they wrote, the dotted curves that you were comparing to are actually 1/8 of the size of the effect they would expect. And even that dwarfs the measured variation they actually managed to measure. Their instrument was sensitive to the square of v over c. Remember, there's a second-order effect according to those swimmers. So they should have been sensitive to a ratio of speeds one part in 100 million.

If you think about the likely speed, say, of the Earth through the ether just taken as an order of magnitude estimate, the speed with which the planet Earth moves around the sun during the course of its annual orbit-- take that as a characteristic speed for our motion through the ether, compare that to the speed of light in the ether. These are incredibly small velocities. And yet, he should have been sensitive to even very, very tiny displacements. There should have been a measurable shift in the interference fringes, even from such a small relative motion. And yet, trying this for days, and days, and nights, ultimately for months, and months, and even years, they find what becomes known as a null result.

And here's a quotation from their paper. "It seems fair to conclude from the figure--" meaning from this plot here, "--that if there is any displacement due to the relative motion of the Earth and the luminiferous ether, this cannot be much greater than about 1% of the distance between the fringes. The actual displacement was certainly less than the twentieth part of this expected value, probably less than the fortieth part. It was consistent with no offset at all."

They found no shift in the interference fringes that they could have attributed to the motion of the Earth through the ether. So they found little wiggles that were basically consistent with no wiggles at all. So they didn't just try this once.

They wondered about maybe try a day/night effect, depending on which arm of this big L-shaped interferometer happens to be moving directly into the ether wind at a given time. That might shift day versus night. It might depend on the time of the Earth's orbit around the sun. So they would check fall versus winter versus spring. And it was this incredibly precise instrument with data collected very, very, very carefully and with great order and regularity.

That's what began grabbing the attention of even some very, very elite scientists in Europe. And despite all their efforts and all their attempts to replicate it, they kept finding results consistent with a tie, with no time offset at all. And here is, I think, the saddest part.

Michelson lived for decades after the 1880s. He died in 1927. He was the first US-based physicist to win the Nobel Prize in 1907.

And yet, 20 years later on his own deathbed, he still considered this work to have been a failure. I say, may all of us win Nobel prizes and still not be satisfied. This is a sad, sad thing.

So let me pause there and stop sharing screen. Any questions about that part? I see some things coming up on the chat. So Jade clearly has read ahead or has taken other courses.

Jade asks, is there any connection between this correction factor that involves a square of v of a c and the Lorentz factor? They look very similar. They do, Jade. You're exactly right.

In fact, we're going to come to that even today, and we'll continue seeing this factor gamma both today, in the next class, and the class after that. And to give away the story, you're right. It should look familiar if any of you have had any coursework on relativity. We'll see that factor does come up, and we'll see exactly what Lorentz thought it would mean. And then we'll later see what people like Einstein thought it would mean.

So when we do this experiment today, Alex asks, and we use lasers, does using sodium lamps make any difference? Good, excellent question. Today we do use lasers, both because, first of all, lasers are awesome. Let's just agree on that, because they're cool. But also more important, slightly more relevant, lasers are what we call monochromatic. They emit nearly all their light at one frequency, one color.

So Michelson did not have access to lasers. No one on the planet did in the 1880s. So what was really state of the art was to use sources that emitted most of their light at one dominant frequency. And often, they would use these sodium arc lamps. They could measure the output-- we'll come to this actually in a few lectures when we think about early quantum theory.

The researchers at the time were getting quite good at measuring how much energy came out of a certain emitter in different colors, in different frequency bins, so they could characterize what we call the spectrum actually quite precisely. So they knew that certain kinds of emitters were pretty close to being monochromatic, and sodium was one source that had become pretty common to use.

So it certainly could have mattered if you were doing-- it would have mattered in an interferometer if the light waves were of very different wavelengths to start with. But in that case, you would still be able to use the interferometer because what you would worry about would be whether the interference pattern would shift. If the light that travels the different paths is of inherently different wavelength, then you would not expect to find zero interference fringes. There should be interference fringes even at rest.

Then what you look for is a shift in that pattern due to the Earth's motion through the ether. So you could still use interferometry successfully, even if you don't have a perfectly monochromatic source. It's a great question. But they were aware of that, and they were able to make pretty strong arguments even without lasers.

Good, another question. Abdulaziz asks, do you need nanoscale precision to make sure the tracks are of exactly the same length? Great question. Again, it comes back to the same kind of answer I just gave. In the cartoon version I described, you would think you would need to have absolute hyper-precise control over those path lengths.

It turns out, even if the path lengths are grossly different-- let alone nano scales-- if they're inches or even meters different, then you would have some basic reference interference pattern, and then you could still check to see if the interference pattern changed due to relative motion. So what you really are sensitive to are shifts in the pattern of the interference fringes. And that is what's sensitive to the square of v over c.

So in fact, you don't have to machine these parts to one part in a nanometer, thank goodness, right? You actually are sensitive to a shift in the existing interference pattern. And that, again, they could measure with really quite extraordinary accuracy with optical frequency light.

Thickness of the half-silvered mirrors could introduce errors. These are excellent questions. Again, what it came down to is none of these effects, they were convinced, would affect the behavior of the interference patterns as the whole apparatus moved through the ether. They could accommodate an existing zeroth-order baseline interference pattern, which could arise from all these very excellent, excellent observations you're making. And the question was, did that baseline interference pattern or a starting pattern of fringes,l did that shift due to, say, the Earth's motion? And that's what they kept finding no evidence of.

So we're going to talk-- and I I see other questions about relativity in 1927. Oris asks-- Oris, I see you have your hand up. I also see you in the chat. Is it the same question? Or do you want to ask your question directly? Same question, OK.

Were people just not taking relativity seriously? And we're going to spend a whole lecture on that coming up in not too long. The short answer is relativity of the form that we would recognize, of the form that you'll analyze for 1-- due October 2, don't forget-- that was published in 1905. It was certainly not considered a standard or universally recognized result in 1905. It was pretty well accepted by many, though not all physicists, before 1927. But there is still lingering question, including by people like Albert Michelson.

So it was not universally accepted, even in Michelson's own lifetime. The balance had certainly shifted by 1927. By 1927, Michelson was a member of a minority, a Nobel Prize-winning minority, but a minority nonetheless. In 1910, that would have been quite standard to either have never heard of Einstein's relativity or think it's probably wrong, or irrelevant, or trivial, or not worth paying attention to. We'll come to that kind of stuff pretty soon, and same with general relativity.

Julius asked an excellent question. How did they know the ether is moving at velocity v? So I probably explained it poorly. They assumed the ether was totally at rest.

The ether, they assumed, had no inherent motion at all. It was, on average, just sitting perfectly still. But things could move through the ether, including things like us on Earth.

So the idea was the ether set an absolute reference frame. Things could be at rest with respect to this comparison substance, the ether, which they assumed was sitting, on average, perfectly at rest. But then things could move through it. Planets and stars could move through it. And if the Earth was moving around the sun in our own solar system, then maybe either the Earth alone or the entire solar system was actually moving through this elastic medium.

So they were convinced the ether was the reference point with respect to which our own motion might show up, much like if we step outside on a still day. When we're standing at rest with respect to the medium, we don't feel a breeze on our face. When we start moving on our bicycle, then we feel a breeze in our face. The air hasn't had to move for that to happen. Our motion through the air, the atmosphere, will create that kind of headwind.

So how do they zero the interference? Good. So Julian asks, if they were convinced the Earth was moving, then how could they ever get rid of it? Again, the answer is they didn't have to get rid of it. They had to carefully note what the baseline interference pattern was and then measure any tiny deviations away from that. And deviations would happen because they assumed the Earth was moving.

So you set a initial interference pattern. The spacing between interference fringes, actually a circular pattern, usually. There's little circles within circles-- concentric circles. And you can measure the space in between those bright spots, the fringes, actually quite accurately even in the 1880s. And the question then became, did the spacing between those tiny fringes expand or contract, a shift in the interference pattern?

So a great question. So again, partly, the big problem with everyone in this class is you've all heard of Albert Einstein, which is not such a problem. Remember that he was born in 1879. He was barely on the planet during this stuff. He certainly wasn't active yet.

So part of what we have to remember is that that wasn't even in play yet. And part of what I find actually so fun-- it's challenging because of all that we've learned in between, but it's actually pretty fun to try to put our heads back into say a pre-1905 or pre-1927 mindset. What was an obvious question to ask? What would really smart people like Hendrik Lorentz really want to spend their time on?

The behavior of light waves when either the emitter or receiver is in motion with respect to ether. What did Michelson set his life's work to be? Really, really precise measurements of optics to go after this big question about things like the electrodynamics of moving bodies. So more specifically, DA, you're absolutely right. There were many ways to try to account for these null results.

Michelson himself thought of several. Michelson himself redid this experiment throughout his lifetime. He helped encourage other really quite world-class experimentalists to redo the interferometry tests well into the 20th century, well after the publication of relativity because it did seem, for at least some of that time, to be quite reasonable, maybe even compelling, alternate explanations. These experiments were tricky.

The interferometer is an exquisite instrument, but theoretically it works one way. Anyone who's taken Junior Lab, or will soon take Junior Lab, or done any experimental work will know the instruments don't always work the way the manual says they're going to. That's what happens with me all the time, by the way.

And so there are all kinds of alternate explanations that actually seem quite compelling to many of these folks that might account for the null result. That's why I find it so tragic, not that Michelson considered himself a failure in 1887. It's that 40 years later, after many, many more efforts to test this and really pursue these alternate possible explanations, that he still considered himself a failure, even after a variety of new developments had come up in between.

So there's a question here about Ligo. Was the interferometer an inspiration for Ligo, Muriel asks and the short answer is yep. And so part of what the ironies here, again-- and we will come to some of this a bit later in the term-- is that the Michelson-Morley experiment was done really to try to test for the existence of the ether.

As we're finding, Michelson and Morley themselves find no compelling evidence for the ether. And yet, roughly 100 years later, a very similar kind of experiment could be used to now try to test relativity, which denies the existence of the ether. So the instrument has a remarkable intellectual continuity, even as the theories it's somehow designed to be testing or in conversation with have changed quite a lot. So we'll come to that pretty soon.

So let's see. Johan asks about these constants like c, mu 0, and epsilon 0, they were measured separately and independently. That's right.

Ah, good. So basically, Maxwell, in 1865, was really impressed by just how close the product of these values mu 0 and epsilon 0 happen to be. They didn't equal exactly what the textbook answer for the speed of light was, but they were really pretty close within what seemed to be too close to be merely coincidence.

Maxwell, by this point, actually did have a lot of experience with laboratories. He actually became the director of the Cavendish Laboratory for Experiment at Cambridge around that time. So he was quite aware that there would be a unavoidable jostle around any of these experimentally determined numbers. But in principle, there was no reason why the product should be anywhere near 1 over the square of the speed of light, let alone within actually a pretty compelling small interval.

So he really takes that as indicative that this probably isn't coincidence. And then that sets up new efforts to both measure the speed of light with more accuracy. That's actually the first thing that Albert Michelson did that really got attention on the continent. He built new efforts to measure the speed of light to new accuracy, and he came within amazing closeness to the modern value.

So that's one thing that the Maxwellian work inspired is, can we measure any of these constants to more precision and then pursue theoretical implications if it really is not a coincidence that these things fit together? It's a great question.

I'm going to go back to share screen. These are great questions. Let me go back for that last part of today's prepared material. And as usual, if questions come up, please do put them in the chat.

OK, last part for today. So we saw that Lorentz had this mathematical response for the behavior of Maxwell's equations when he applies them to bodies moving with respect to the ether. Lorentz absolutely was also following the Michelson-Morley work. You see it in his citations, in his own articles. When the Michelson-Morley stuff starts getting published in the 1880s, Lorentz is very eager to keep up with the latest experimental work.

And this really convinces him of a second reason to keep pursuing it, dig in even more on this topic of the electrodynamics of moving bodies. Partly, he wants to actually respond even more directly to this null result from Michelson and Morley.

And he comes up with this idea that, to this day, we still call Lorentz Contraction. If you remember-- I'm sorry, I don't remember who put it in the chat. Someone had asked, hey, that factor gamma looks familiar from Lorentz. It sure does. And here's how Lorentz came to it.

Lorentz argued that we'd actually left out part of the balance of forces when trying to analyze things like the Michelson-Morley interferometer. He argued that the molecules within one arm of the interferometer, the arm that's heading directly into the ether wind, would actually feel a force on it. There would be a net force squeezing literally the matter-- the molecules in that one arm of the device-- squeezing them closer together because they're moving through this physical resistive medium.

I like to think of this in my mind as trying to take an inflated beach ball and dragging it underwater in a viscous resistive medium. The shape of that ball will change. It will get flattened in the direction of motion. It'll become oblate or prolate. I think it's oblate.

Anyway, it'll get squeezed in the direction of motion so that the beach ball might be perfectly spherical, at least to our naked when it's outside of that medium of the water. Put it underwater and drag it at some high speed. The water will exert a force literally on the matter of that beach ball. And it'll squeeze it along the direction of motion.

Lorentz says the same thing must be happening to every single molecule that makes up that interferometer arm of length L of, say, 11 meters. The arm that's heading directly into the ether, is getting the full brunt of that resistive force, and it should shrink.

What if it shrinks by exactly this factor gamma? What if it doesn't just shrink by any old amount? What if the amount of contraction is controlled by that ratio of the object speed v with respect to the speed of light c? Then the arm of the interferometer that's heading directly into that ether wind would have every molecule shrunk by just such a small amount, by a nonzero but tiny amount given by gamma. And there would be a contraction in that direction.

In that case, if you think back to the swimmers, let alone the light waves, that's like saying that swimmer 1, who heads directly into the current for the first part of her journey and the directly with the current for the second part, the literal distance she has to travel between points A and B has been shrunk by a little bit. It's been contracted by 1 power of gamma. And he hypothesized. He wonders, is that the case?

Is there just enough force exerted by this resistive elastic medium to actually make it an unfair race? Can swimmer 1 actually had a shorter total distance to travel? If you go back to what we calculated earlier, how long her total lap time would be to go from point A to B and back, and you adjust the length she had to travel-- that length of shoreline had been shrunk because of the effect of the current-- then actually you cancel out one of those factors of gamma because her length is shorter. And then it should actually be a complete tie.

So if you take into account this physical contraction, a physical shrinking in the direction of motion, then the total duration for swimmer 1 should now be predicted to be identical to the total duration for swimmer 2. It should be a tie after all. And so if there's a physical effect from our motion through the ether, if there's a force exerted by that physical elastic resistive stuff, like that bowl of jelly that Lord Kelvin asked us to put our hands into-- it acts back on our device-- then you would predict 0 total time offset between the two paths. The race should be a tie, just as much for those two light waves as for the two swimmers.

So Lorentz is now trying to respond literally directly to the Michelson-Morley results. He says, this could account for why they actually find no shift in the interference fringes. So now Lorentz has two different motivations for reconsidering how to handle coordinates. We had that first one we looked at the first part for today's presentation, this local fictitious time where he's really just trying to figure out how does the wave equation transform? Do I have to do something funny with time or not?

And now he has a second, more experimentally inspired or empirical reason to keep drilling down on that same question about how do we transform our coordinates, now with this notion of a physical length contraction. So keeping that same factor gamma in mind, which already looked familiar to some of you, Lorentz introduces what we would now call the Lorentz Transformation. It is to replace the Galilean Transformation.

As you can see, and as you might have learned in other classes, this ubiquitous factor gamma, 1 over the square root of 1 minus quantity v over c squared-- that now shows up both when we take care of our spatial coordinate and theirs and our temporal coordinate and theirs. We have a gamma factor, both for x prime and for t prime. And also, both the x prime and the t prime both are directional of motion, our comparison for the spatial direction along which the relative motion occurs, and our comparison of the clock rates, t and t prime. Both of those depend on the relative speed as well as on the positions.

So you have a drift or an offset, both in time and in space, the amount of which is governed by that new quantity gamma. And so here's that factor gamma again. And just as we had done before, we can expand this quantity in general for a small ratio of the relative speed v compared to the speed of light. It's a second-order quantity to lowest order, which would explain why Galileo, or Newton, or anyone in between their time and Lorentz's time had never measured or noticed these new kinds of ways to relate our coordinates.

Galileo's transformations had worked perfectly well quantitatively for every example they'd been able to test up until that time precisely because the relative speeds involved had always been, it turned out, much, much slower than the speed of light. And so you were worried about a square of an already small quantity. The correction to the Galilean transformation would have been minuscule in nearly every application until you get to light.

Until you think about light and either a moving emitter or moving receiver, then, Lorentz says, there's a physical force that will contract any object made of any real atoms and molecules in one direction in the direction of motion. It's a small effect, but a nontrivial one. When we incorporate that, we both get back to the expected form for Maxwell's wave equation for electric and magnetic fields, and we can account for these latest experiments like the Michelson-Morley.

So as I had hinted at a moment ago, when Lorentz used his own new system for relating coordinates that incorporates that gamma factor as well as the t prime, his so-called local time, now even in this new set of coordinates, even if either the emitter or receiver or both are moving with respect to this still ether, the way that electric and magnetic fields should behave goes back to looking the way we'd expect. It goes back to being the simple traveling wave expression so that the solutions, even in a moving laboratory-- like for us on Earth-- really should travel at the speed of light, really should behave like oscillating sines and cosines.

And so now just to wrap up this part for Lorentz, and we'll have some time for some more discussion in a moment. Lorentz addresses these two puzzles about the electrodynamics of moving bodies-- a mathematical one just about the behavior of a certain kind of equation as he handles coordinates in various ways, and also an experimental or empirical one. He really was following Michelson and Morley's work quite carefully.

As I was just emphasizing, Lorentz says there's a physical force, dynamics-- there's a force being exerted by the ether on this object, like the arm of the interferometer, that's going to cause a physical effect, a contraction. The quantitative effect is governed by that new factor gamma, which is there for small speeds compared to the speed of light.

So as I say, the strategy for Lorentz and indeed for his whole generation, as we'll see for several classes to come, is you begin with dynamics. You begin with a study of all the forces that are relevant for the physical system you hope to analyze. And you use that to figure out how are things going to move. What are the impacts on what we call kinematics?

Start with dynamics. Ask about the full range of forces at play, and use that to solve what we call the equations of motion to say how will objects move through space and time, or kinematics. As we'll see-- and some of you probably have seen already-- there was a different person who was just coming onto the scene at this point at the time, a rather unknown patent clerk by the name of Albert Einstein, who had a bunch of other ideas about that.

So I'll stop sharing screen there. We have time for a couple of more questions. So Oris writes quite, quite accurately, this sounds a lot like length contraction special relativity with a strikingly different interpretation. Totally right. I agree. So we're going to see, starting in the next class,

Einstein starts coming up with the exact same equations, in many cases, as Lorentz had done. And not only Lorentz, others have found these things too. Sometimes it's called Lorentz-Fitzgerald contraction. There was a researcher in Britain, Fitzgerald, who found the exact same form of gamma right around the same time as Lorentz. Poincaré in France was doing very similar things.

So we'll see that Einstein comes to many, many identical equations. And yet, he reads them as telling us quite different things about how the world works, much as we saw with Maxwell's equations then, and now, and so on.

Julian had a question about Lorentz's educational background. Very good. I don't remember the details. We could each look it up. Lorentz had certainly become a world premier mathematical physicist by this time.

So his training would have been similar to the Cambridge Wranglers. He didn't literally go to Cambridge University, but he was very well steeped in the latest tools of mathematical analysis. He was very, very good at solving complicated differential equations very quickly-- a lot of stuff the Wranglers were drilled in. And so his background would have been pretty similar to, say, James Clerk Maxwell's. He was a little younger, but he would have been drilled in pretty hard math, including differential equations quite a lot.

Did Einstein refer to Lorentz when he found the equations? Or was he aware of Lorentz's work? Ha-ha, good question. One of the things that you might consider if you were to review Einstein's paper is whether he makes adequate reference to the work that had come before. Did he cite his sources appropriately? When you tackle paper 1, which is due October 2, your job will be to pretend/imagine you're an editorial assistant at the journal, *The Annalen der Physik,* to which Einstein had submitted his paper.

One of the questions a referee should ask, then as now, is whether the summation accurately reflects the existing literature. Was Einstein appropriately citing the work that had come before him? I'll pose that as a question, and then I'll answer no. The answer is no. He was not citing the stuff at all appropriately, as we'll see actually starting even in this coming next class session.

Gary asks, other than the poor citation practice, did Einstein know of Lorentz's work? The short answer is he probably did. As we'll see in the coming class sessions, Einstein was very avidly reading a lot of this work-- probably not Michelson's work, actually, but certainly the work by people like Lorentz and Poincaré in Paris. He was not citing it very carefully. But he and his buddies were encountering this as their off-hours reading group. This is what they did for fun, which I recommend.