DAVID KAISER: So today, at long, long last, we meet this fella named Albert Einstein. We're going to talk a bit more about how he was approaching some of these questions in the early years of the 20th century.

So as usual, today's class has three main parts. We're going to look at Einstein leading up to this year of 1905, what were his early educational experiences like, how did he come to this question of the electrodynamics of moving bodies, and what did he think was the most kind of compelling way to start addressing some of these questions?

For the middle part of today, we'll talk about this paper, in particular. This excerpt of the paper that you had in the reader on the electrodynamics of moving bodies. What were some of the key ways in which Einstein was talking about, what we would now call the special theory of relativity.

And I have a little asterisk here to remind you for this section, for this class session, I wrote up a little short set of extra notes, not nearly so detailed as the previous set. And those are really just as a supplement for something I'm going to probably not have much time to linger on in the class session itself today. And that's a consequence of Einstein's work that he published in a separate follow-up article in which he derived this now-rather famous relation that E equals mc squared.

So I'm going to go through, quickly today, the nature of Einstein's argument that led him to that conclusion, and then you can have a couple of pages-- I think it's only about five pages or so-- to read a little bit more detail about some of the ways that Einstein came about that conclusion. So a little extra supplemental, strictly optional as always. But if you are curious about it, there's some more materials there.

And then, we'll pan out again. We'll kind of zoom out and try to make sense of, why did Einstein approach these questions in the ways that he did? How can we think about what else Einstein was thinking about, was immersed in, what was going on in his life, in his early professional career, drawing, in this case, very heavily on that article by Peter Galison on the reader to try to understand why Einstein approached, as we'll see, a very conventional question in rather unconventional ways. That's our plan for today. So let's jump in.

So remember what we're responding to. What's Einstein inheriting by the time he comes on the scene? So we saw, in the previous few lectures from last week, the questions about the behavior or the propagation of light waves in the ether in that all-pervasive, elastic medium called the light bearing or luminiferous ether. Those questions were really at the forefront. That was mainstream physics by the end of the 19th century.

And especially when we get to people like Hendrik Lorentz or Michelson and Morley, the topic that was often described was the electrodynamics of moving bodies, the effort to generalize from James Clerk Maxwell's work from the middle decades of the 19th century in which Maxwell had worked out this really quite beautiful combination of electricity, magnetism, and optics. But he really was treating light waves for the special case in which both the emitter and the receiver of those light waves were both at rest with respect to this light-bearing ether. So the question then becomes, what about moving bodies? What if either the sender or the receiver of light or both were in motion with respect to each other and with respect to the ether? That became known by this catch phrase, "the electrodynamics of moving bodies."

One of the key moments in that investigation that we saw from the 1880s was performed by Albert Michelson and Edward Morley in what's now Case Western Reserve University in Cleveland in the United States. So they used this enormous, specially built interferometer of Michelson's own design.

By the 1880s, late '80s, they were using an interferometer where each leg of this l-shaped instrument was 11m long. That's about 34ft on a side. Huge, huge, huge instrument that they designed and built expressly to try to measure changes in the behavior of light waves, in particular in the relative speed with which waves would move through the ether, depending on whether our own laboratory here on Earth was moving directly into the ether or some perpendicular-- or the light waves were moving perpendicular to the Earth's motion.

So whether it be what we could think of as an ether headwind, like if you're pedaling on your bicycle on an otherwise still day, you'll feel a breeze on your face in the direction of your own motion. And as we saw last time, Michelson had reasoned that there should be a similar effect for light waves because our whole laboratory on Earth was, assuredly, they were quite confident, was moving through the ether, so there should be some relative motion between the behavior of light waves as we measure them on Earth on an instrument like the interferometer and the all-pervasive ether.

And as we saw and even read their brief paper, despite some really exquisite experimental design and sensitivity, they never detected any clear evidence that would have been associated with the Earth's motion through the ether. That was what became known as a null result. The results were consistent with no change in relative speed, no matter what direction those light beams were traveling.

And as we saw, even though Michelson won the Nobel Prize, he was the first physicist based in the United States to win the Nobel Prize for physics, he won in 1907, he died 20 years later still convinced that he had just messed up. So that's sad for him, and maybe we all suffer the same fate. Maybe we all win the Nobel Prize, even if we're not satisfied with our work.

OK, meanwhile, some very leading, very elite physicists back in Western Europe Like Hendrik Lorentz were following Michelson's and Morley's work quite carefully. Lorentz was a mathematical physicist closer in spirit to James Clerk Maxwell. He wasn't building his own experiments. But he was very attuned to what results Michelson-Morley and other experiments were finding.

And Lorentz finally introduces a way to accommodate this null result to explain why experiments like Michelson and Morley's might indeed measure no offset, no change in the relative speed. And Lorentz argued it was because of dynamics. Because the previous analyzes had dropped, had missed one of the relevant forces.

In this case, Lorentz argued that if the entire apparatus, like everything else, is immersed in this physical, elastic medium of the ether, the ether should exert a force on the material, making up the arm of that instrument, one of those Ls, one edge of the L. The edge is moving directly into the ether wind. That should be compressed or contracted because of a physical force, a kind of resistive force onto the interferometer itself.

The Irish mathematical physicist George FitzGerald came up with a very similar argument right around the same time. This was, for some years, known as "the Lorentz-FitzGerald contraction," or sometimes just as "Lorentz contraction." And the idea was that if there's a contraction by just such an amount, depending on the relative speed of the object through the ether, V, compared to the speed of light, C, if you cooked up the amount of contraction just right by that factor gamma that we encountered a few times, then the expected offset in that race between the light waves traveling in the two different sides of the interferometer should exactly cancel.

The race should be a tie after all. One should actually expect a null result. And all this came down from treating the electrodynamics of moving bodies by starting with the question dynamics. Are there all the forces at play, rather than kinematics, which is the study of the motion of objects through space and time.

So young Albert Einstein then inherits that set of questions and moves into that discussion a little bit later. He was born in 1879. Here's a rather adorable photo of young Einstein, kind of elementary-school aged. So he was born just before Michelson and Morley actually began that series of experiments. So he was born after Maxwell's Treatise before some of Hendrik Lorentz's main work. He was born in the town of Ulm in what was then quite rural Germany, not near any of the main city centers.

Einstein's main ambition when he was a young child was actually to join the business that his father and his uncle had created. They were some of the first professional electrical engineers in these later decades of the 19th century, just like the kind of folks about whom Maxwell had written in England in the preface to his treatise, these so-called electricians that would soon be called "electrical engineers."

So that's what Einstein's own father did and his uncle, they formed a company together. They were much better at engineering than at business. The company went bankrupt multiple times. They had to actually keep moving. But they were working in this exciting new area during the waves of things like wide-scale electrification, the introduction of electric street lighting in more and more municipalities, more and more ways in which electrification and therefore electrical gadgets were entering into quite common experience. That's the world into which Einstein was literally born. And that's what he wanted to work on.

It turns out he dropped out of high school, so he never got a high school diploma. He developed a real allergy. He got very frustrated with what he considered an overly militaristic approach, a very disciplined-based approach in these Prussian high schools. So he ignored his teachers, and got into trouble, and finally just dropped out. By all accounts, his principal was just as happy to see him leave. No one liked each other.

But he set his mind on entering this elite Federal Institute of Technology known as the [NON-ENGLISH SPEECH], or ETH. That stands for the [NON-ENGLISH SPEECH], which is a phrase I never ever tire of trying to pronounce. We can just call it the ETH. This was basically like the MIT of Zurich. Although, that's a bit unfair because the ETH actually predated the founding of our own MIT. But it was a place a lot like MIT. It was a polytechnic institute with a real focus on science and engineering, including these new areas like electrical engineering.

His main goal, Einstein's goal, was to-- even though he had no high school diploma and he dropped out, he would take the special entrance exam for this one special place he most wanted to attend, the ETH or [NON-ENGLISH SPEECH] in Zurich, Switzerland. And then, he could go in.

Well, he did take the exam. He failed it because he blew off the subjects that he didn't care about. But the examiner for the physics and math sections, a professor named Weber saw enough promise in Einstein's portions of the entrance exam, not on humanities, not on languages, not on history, those he was quite terrible at this time.

But for the physics and math portions, he showed enough promise that he pulled young Einstein aside and said, you failed. You cannot come to the ETH right now. But if you go to a local school, effectively a local community college, a cantonal regional kind of community college nearby in Switzerland, go there for a year, work with some new teachers, take our entrance exam again. And that's what he did. So he was admitted to his dream school the second time around and began studying in Zurich in the very late 1800s.

Once he worked so hard to get in, including this extra year of just trying to take their entrance exam, he then proceeded to cut classes and read on his own. This guy was-- I mean, he was no Einstein. He really just kept doing these stupid, stupid things.

So even after working so hard to get into his dream university, he basically cut his classes, or at least many of them, any of the ones that he thought were not worth his time or for which he didn't really like the professors. So he would read on his own the latest stuff, was still pretty new stuff, like Maxwell's treatise on electricity magnetism, like some of the very exciting work on statistical mechanics and the behavior of gases by people like Ludwig Boltzmann and others, he would read on his own.

Now for some reason, after cutting classes and letting his professors know how little he respected them-- he was not shy, much like when he was in high school-- for some reason, he couldn't get any good letters of recommendation upon graduating. This class is really full of good lessons for today. So don't do the following. Don't annoy all of your professors so much that they all refuse to write you a strong recommendation.

So basically, Einstein had a middling, fairly mediocre grade point average because he kept cutting classes and ignoring stuff that wasn't interesting to him. He was rude to the majority of his professors and, for some reason, couldn't get a job upon graduating. He really couldn't figure this out. The guy was kind of dumb for an Einstein in these young years.

So what happened was, really in desperation, with help from the father of one of his very close college friends, the father of Marcel Grossmann, he was able to land an entry-level civil service job in Bern, Switzerland, working in the local patent office. He was hired as a patent officer, third class. There was no fourth class. That was really the entry-level position since he had a degree from a leading technical institute but was not otherwise highly recommended. So even for young Einstein, it wasn't what he knew but who he knew. He had to depend on his friends for help on the job market.

We also know quite well what happened next. He fell in with some friends who were all around the same age, all recent university graduates, who were all living in Bern. And they all had an interest in science. This included a young Maurice Solovine, Conrad Habicht, and then recent graduate Albert Einstein.

They gave themselves the name the Olympia Academy because they were having fun. That sounds like a triumphant, very prestigious academy, like Mount Olympus like the Greek legends. It was actually three recent college graduates meeting literally in the pub to drink a lot of beer and talk about philosophy. But they figured if they gave themselves an exalted name, it would sound much more serious. So the Olympia Academy was mostly those three folks reading on their own after hours after work.

Now we even know quite a bit of what they were reading. They wrote lots of letters to each other in between. Many of those letters have survived, so we can reconstruct the kinds of questions and the kinds of materials of particular books that the Olympia Academy found really exciting.

One of the authors that they were especially excited about in the early years around 1900 was the Austrian polymath, Ernst Mach. Here's an image of the English translation of one of his very influential books. Mach was originally Austrian, wrote his own books in German. Einstein and his friends really just devoured these.

Mach was trained in mathematical physics, in experimental physics. We still talk about Mach numbers, like for the speed of sound. Mach 1, Mach 2 for jet planes and so on. That's the same Ernst Mach. He later held a professorship in surgery and, then finally, in the history and philosophy of science. Mach had quite a remarkable career.

So what he did in this series of books, including the one which in English translations known as a science of mechanics, which we know Einstein and his friends were really reading carefully, Mach proposed this scientific philosophy called positivism. His argument was that only quantities that could be, in his phrase, become objects of positive experience, things we could literally touch, and measure, and handle empirically and quantitatively, only these objects of positive experience belonged in any proper scientific theory. Anything else, Mach argued, would lead to just confusion and empty metaphysics, which was his word for bad, bad stuff. You'll just get yourself confused arguing about the equivalent of how many angels could dance on the head of a pin if you're not able to actually subject those questions to measurement or any kind of empirical input. That became known as positivism.

And a lot of what Mach did in this particular book, very thick book,*The Science Of Mechanics,* was basically take Isaac Newton's work to task. So Mach laid out this entire program to basically say that Newtonian physics, as successful as it was in celestial mechanics and all kinds of applications, it was riddled, charged Ernst Mach, with these empty notions that could never be subject to careful empirical measurement, things like absolute space and absolute time.

So Mach says no matter the successes of Newton's physics, it's riddled with these problems. We should get rid of all these empty metaphysical notions like absolute space and absolute time. The Olympia Academy just ate this stuff up.

So Einstein, we know from contemporaneous letters and notes and so on, was very directly inspired by Ernst Mach, and he pursued this critical reevaluation, deciding that we should begin with kinematics before even worrying about dynamics. Remember, kinematics is the study of bodies in motion through space and time, things that, at least in principle, could be subject to observation and measurement. So we better get that straight with this new critical edge granted by Ernst Mach before we even worry about things like the interplay of forces or the study of dynamics.

So while he's working at the patent office, he's still a patent officer third class meeting after hours with the Olympia Academy, increasing neglecting his first wife and his young child, basically blowing them off to go drink with his friends and talk about philosophy. In the space of that time, he submitted several papers to the leading journal of physics, really, in certainly in Europe or North America at the time, the Annalen der Physik, at this point, it was edited by Max Planck, someone whose work we'll come to pretty soon in this class.

In 1905, Einstein had what is often called his miracle year, or his annus mirabilis in Latin. It turns out it actually wasn't even a whole year. It was like a miracle two seasons. He needed less than six months to introduce this entire body of work. So here, I'm showing just the dates at which these separate articles were received at the journal, separate submissions that were clocked in at the Annalen der Physik.

And for now, what we're going to do is focus on this third in his series, which again, today, we refer to about by calling it the special theory of relativity. The actual article, the first page of which is shown here, is entitled, "On the Electrodynamics of Moving Bodies," a title, a phrase that, by now, sounded conventional to us thanks to the last few lectures, but especially to Einstein's readers back in the day, that was exactly the topic which leading figures like Hendrik Lorentz, and George FitzGerald, and Michelson and Morley, and many, many of their colleagues, that's what they cared about and what they agreed was front and center for cutting-edge physics.

So Einstein's paper on the electrodynamics of moving bodies has a conventional or recognizable title. And yet, as we'll talk about through much of today's class, the rest of his approach to that conventional topic was anything but conventional. It's quite unusual.

It didn't help his colleagues that the only real indication of where these unusual ideas came from was in the acknowledgments, where he says, in conclusion, let me note that my friend and colleague Michelangelo Besso steadfastly stood by me in my work on the problem discussed here. I'm indebted to him for several valuable suggestions. That didn't help clarify because Besso was equally unknown. He was another, basically, college friend of Einstein's, another occasional member of that Olympia Academy. So one totally unknown person is thanking another basically unknown person, and otherwise his paper appears like it's from Mars.

Let me pause there, ask if there are any questions on that first part. Any questions so far? Yeah, so in the paper itself, what I showed you just now on screen is the entirety of the acknowledgments. He only thanked Besso by name. And for some of the specific points in that paper, it does seem, from other letters that have survived and so on, that he discussed these things especially closely with Besso.

He did not thank his then-wife Mileva Maric. We can talk about that. They had talked about some of the ideas some years earlier. It's a continuing point of historical interest how much Mileva had talked about these specific ideas closer to 1905. It looks like not so much, partly because she was working in her new motherhood role in a very-- what was by then a very traditional gendered role and not able to really keep up with her own physics and math studies. So he was not thanking Mileva in the paper.

He did not thank by name, either, Konrad Habicht or Maurice Solovine, although he was writing with them. In fact, he was talking with them in the letters more about some of those other papers that year, at least from the letters that have survived. In the actual printed paper the only person he thanks is this, again, largely unknown figure, Michele Besso

He also, as you've seen even in the excerpt that is in the reader for today, he cites almost no other literature. So we do know from some of the reading notes that have survived they were actually quite interested in work by people like Maxwell but also more recent work by people like Hendrik Lorentz.

But he doesn't even cite Lorentz's work in the paper, very, very sparingly anyway. So he's being very, very, we could say selective, which is a nice way of saying he's being kind of a jerk, frankly-- being incomplete, at least, in not citing his sources. If he submitted that paper for our class, he would not get a good grade. You should cite your sources. That's a little reminder for everyone.

So in the actual published version, he was not sharing the love very broadly. It was very, very limited acknowledgment of where this was coming from. Any other questions? Let's continue on. Let's see what else we can do now with Einstein once he actually does then move into the electrodynamics of moving bodies. You can see the screen again, I hope? It's back on for everyone? OK.

So as you've seen, the very opening paragraph begins with this puzzling pronouncement, puzzling at least to readers of the most prestigious physics journal in, at least, Western Europe and North America at the time. He starts out by saying not that there is an error in Maxwell's equations. He doesn't say, I found a missing factor of 2 pi or missing minus sign. He doesn't say I've conducted new high-precision experiments and I found a glitch or some empirical anomaly compared to previous experiments.

He starts out by saying, there's "an asymmetry in the explanation" that is not present in the phenomena. That's a pretty astonishing opening. What is he referring to? Not some very complicated hard thing to calculate, he's referring to something turns out to have been something like a school exercise that he'd encountered very similar to what he encountered when he was a University student.

What if we take a simple bar magnet, just a simple north and south pole, and a simple conducting coil that's connected to an ammeter we can measure if any electric current is flowing through that conducting coil? What if the bar magnet and the coil are in some relative motion with respect to each other?

Then, it's a rather simple demonstration to find. It's actually quite similar to what Ernst had done in the 1820s and then Faraday soon after-- that when the magnet and the coil are in relative motion, a measurable electric current will be induced. So the phenomenon is, these two things moving with respect to each other, current begins to flow, where otherwise none had flown before.

So physicists, Einstein insists, had given two completely different explanations for what he argued was only one single physical effect. The physicists' explanations, to date, had depended entirely on which item was really moving. So if you imagine there's a state of absolute rest, then perhaps the bar magnet is really moving, and the ammeter and the coil are really at rest. And then, you could analyze the system one way or the inverse. This is the asymmetry in the explanation that Einstein says is not present in the phenomenon.

Let's take the first case. Let's imagine that the magnet is what's moving, the bar magnet is moving back and forth. This is the Faraday induction case from 1820-21. We keep the electric coil perfectly at rest.

Then, using Maxwell's equations, which we can read off from our t-shirt of which Einstein well knew by this point, there's going to be a changing magnetic field in this region of space. We're shaking, we're moving that magnet back and forth so, at any given location nearby, the strength of the magnetic field and even the direction is a change in quantity over time. So the variation in time is non-0. Because we're actively moving the magnet.

From Maxwell's equations, that will induce necessarily some electric field in that same region of space. Then, we know that there's an electric field present in, say, around this area. The electric field will exert a force on any little, charged object that's within, for example, this conducting coil. It will push the charges along the coil. It will generate a current. Electric current was nothing but the motion of electric charges.

So the argument here would have been, we're moving the magnet, and that makes a time-varying magnetic field from Maxwell's equations. And this particular one of Maxwell's equations, a third one, that induces an electric field, that exerts a force that pushes charges along. We measure current. That's case one.

Einstein goes on to say, what about the inverse? This is the one that actually Ernst had first found by accident. What if the coil is moving but the magnet is at rest? Well, then, we'd say there's a static magnetic field that nonetheless varies through space. Remember those curving field lines, the Faraday field lines around a bar magnet? So there's some inhomogeneity in space, even though it's static. It's stuck in time. So this spatial curl is non-0.

By Maxwell's fourth equation, that will induce some electric current nearby. And then, you have this static electric field with charges moving around it. So they have some velocity. And the cross-product of their velocity times the magnetic field will induce a force. That will push the charges along, will induce a current.

So Einstein argues that there's actually only one phenomenon when the magnet and coil are in relative motion. You should measure a current. And it can't matter, he argues, it shouldn't matter which one you say is really at rest or not. Although not citing it, he's borrowing that from Ernst Mach's critique of Newton. So you have one phenomenon that had been given two completely separate explanations, and he says that's the asymmetry in the explanation. There should only be one explanation. There's some relative motion. Current is induced.

So that's the opening paragraph of this somewhat strange-looking article. A little while later, just still on that first opening two pages, he then introduces two postulates, two axioms or conjectures. He doesn't defend them. He doesn't derive them. He doesn't say I've tested them in a laboratory, and they hold up to within experimental error. He says, as you can see the quotation here on the screen, we're going to raise this conjecture to a postulate and, basically, see what follows from it.

The first one is that the laws of physics, all the laws of physics, must remain valid in any frame, any state of observation that's moving at a constant speed. These would later be called inertial frames of reference, meaning not accelerating. It doesn't have to be at rest. It can be moving at some constant speed, as long as it doesn't speed up or slow down, so no acceleration.

Now that's just elevating the well-known relativity from Galileo, going back to the early 1600s. What had been called Galilean relativity applied to the laws of mechanics. Galileo himself had argued, and Newton agreed, that the laws of mechanics should remain valid in any inertial frame of reference. And all Einstein is doing here, as he says, he's raising it to a postulate and extend it to all the laws of physics. Not just mechanics you see in this first part, but electromagnetism, optics, even thermodynamics. That's just an extension of the Galilean relativity.

The second posit, he says, is only apparently irreconcilable with the first, is that the speed of light will be constant independent of the motion of the source. So any observer, no matter what their state of motion, as long as they're in some inertial frame of reference, will always measure light to be moving at the same speed C. Even if they're barreling down the road in the same direction as that light wave, they'll measure that light wave moving away from them at the same speed C as if they were sitting at rest. And he says, it's only apparently irreconcilable with the first. We'll see that in a moment.

He says, if we adopt these two postulates-- again, he hasn't proven them. He hasn't really told us necessarily yet why we should buy any of this. But if we adopt those two postulates to start our argument, then he says, as you see later in that paragraph, "the luminiferous ether will prove to be superfluous." It's amazing. [GERMAN] is the word in German.

He doesn't say he'll disprove the ether. He'll say it's just irrelevant. In one sentence on page two on an article by an unknown patent clerk, he's basically not just said that people have misunderstood Maxwell's equations. People for 100 years have been chasing an object that, he says, is merely irrelevant. It is literally a red herring, he argues, that it would be merely superfluous. That is quite a strong opening to this paper.

Now, why did Einstein introduce that second postulate, the one about the constancy of the speed of light for any inertial observer? Again, he doesn't tell us why in this paper itself. In the intervening more than 100 years, other scholars have been able to fill in some of those pieces based on, at the time, in unpublished notes, and correspondence, and reminiscences, and so on.

So we now have a pretty good understanding of what led Einstein to that strange-sounding second postulate. And, in fact, it goes back to a thought experiment he'd had as a high school dropout at age 16. One of the things that literally kept him up at night was, what would happen if you could catch up to a light wave?

So imagine being like a surfer here, riding a long wave on the ocean. If you're moving with that wave, if you're surfing at the same speed as that wave and you look up, you chance to look up and see this wave crest menacingly over your head, at that moment, the wave will appear frozen in space. You're moving at the same speed as the ocean wave, so you and the wave move together toward the shore. And it looks like you have a static wave configuration. The wave has a crest here, a trough there, and they're moving-- they're not changing as you move together toward the shore.

Now, Einstein argued that should never be able to happen for a light wave. He first just kind of intuited. Later, he learned more at university when he studied a little bit of Maxwell's equations. He could fill this in a bit more quantitative detail that, with the power of Maxwell's equations, if you're in a region of space away from charged matter with no electric currents flowing-- so if rho and J both vanish, rho and J, then there's no way to use these equations, Maxwell's equations, to construct a static field configuration, where you have a fixed frozen crest here and trough there. The electric and magnetic fields just don't behave that way if you're in a region that has no immediate sources.

So then, if you could never see this frozen, static field configuration with a crest that just stays fixed like that, then you'd better make sure no one could ever see that. You better make sure no one could ever do like the surfer does and ride at the same speed as that light wave. So he's really trying to avoid a reductio ad absurdum. He's trying to avoid a contradiction.

How do you make sure no one ever would encounter this frozen field configuration, which he argues, is not at all consistent with the linear form of Maxwell's equations? Make sure no one could ever catch up with a light wave. If we could never surf at the same speed as a light wave, we would never see this frozen field configuration with a height here and a trough there but otherwise static in time. If we could never catch up to the light wave, we'll always see it traveling past us at the speed of light. That was, at least, the intuition that he nursed over the course of 10 years between the age of 16 and 26.

Thank you, Lucas by way of Julia. That's a great question. So I didn't want to spoil this because your first assignment, as I'm sure you've seen, is to imagine you're a referee for the journal reporting to the main editor, Max Planck. That is still your assignment. You still have to do that.

However, the real answer as to why this paper was most likely published, it was almost certainly never sent out for refereeing. Our modern idea that every single scientific paper should be subjected to peer review is quite recent. In fact, it only gets put in place with real regularity or standardization in the second half of the 20th century, well after this time.

What was happening at many journals, including the Annalen der Physik, including Physical Review here in the United States and many other leading journals at the time was that the first one or two submissions to a journal from an early author, a new author, those would often be very carefully scrutinized and reviewed. They would be subject to peer review. Peer review had existed. It just wasn't applied uniformly.

Einstein, it turns out, had published half a dozen or more articles in this journal before this time on, frankly, minor topics, minor even by Einstein's own reckoning. He had published fairly conventional, perfectly legitimate scientific articles in this journal so a few years downstream from that, like most other authors at the time, his later communications could be published at the discretion of the editor, without going through this rigorous refereeing process. And by all likelihood, Max Planck thought this was interesting enough-- it was on a timely topic because people were clearly concerned about the electrodynamics of moving buddies-- that it got into the journal without being subjected to the kind of scrutiny that Einstein's own first articles would have been or that any new authors would have been.

You should ignore all that when you write your paper one. Pretend that this paper really is being subjected to careful and thorough peer review. The short answer, historically, is that this wasn't a special favor to Einstein. The general policy was usually to basically let later articles by an established contributor get into the journal, with much more discretion to the editor. Very good question. Any other questions on that?

Yeah, I mean, so he was known enough by people like Max Planck to say, let's let this young guy's next article come in. This wasn't his first work ever. On the other hand, the other work that he published was kind of, we might say, workaday. It was perfectly competent, neither interesting nor innervated by the standards of the day, even by Einstein's own-- he was very harsh about even his own earlier work. So he had a small early paper trail.

He, in the meantime, had, as I mentioned before, had annoyed almost all of his superiors, both at the patent office and when he was a university student. And he was, by this point, out of the mainstream. He was not working in any of the prestigious scientific research institutes. He was not being invited to attend the usual scientific conferences. He was, by this point, not well known. He was a person who contributed the occasional article to an otherwise very busy journal.

And so he had the bare credentials-- he had not yet, by this point, even finished his PhD in the early years. He was a competent recent graduate from a highly respected technical institute but was otherwise not considered any great shakes. It's a good question, Diego. We'll come back to that actually in the next lecture on Wednesday, more the reception of Einstein the person, his career, and also this work. But the short answer was that it was not standing out.

So I see Jade asked a good question. How large was the scientific community at this time? Very good. So around 1900-- a number of my colleagues did this famous census some years ago. In round numbers, there were around 1,000 professional physicists in the world, not just in Western Europe but including what could be reconstructed from Japan, from parts of China, from many, many parts of the world-- from India. There were basically 1,000 people whose day job, whose actual profession was something like working physicist, 1,000.

So Einstein was, whether you count him in that 1,000 or not, he wasn't really being paid as a working physicist. He was one of on the order of 1,000 or a few thousand who might be contributing, at any given time, to these leading journals like the Annalen. So it's not hundreds of thousands, not a million people. But it's not like there's only a dozen. So it really was easy to have a young person get a few competent articles in a journal but otherwise not stand out, not really be noticed. And that really seems to be where Einstein was in this point in his career. Excellent question.

Let me press on. I want to get on to what Einstein does in this paper. We'll walk through these first few sections of his paper from 05. So again, he doesn't tell us he's inspired by Ernst Mach, though it's quite clear from some of his other unpublished materials at the time. He wants to begin by rethinking kinematics, the motion of objects through space and time, not start with dynamics. What can we observe about how these things move?

And so he has these comments like this early, again, on either page two or page three, quite early in the article. "If we wish to describe the motion of a material point, we give the values of its coordinates as functions of the time." This is like-- we expect most high school students would have encountered how you use coordinates to describe the motion of objects.

He goes on. "Now we must bear carefully in mind that a mathematical description of this kind has no physical meaning--" that's very mocking-- "unless we're quite clear as to what we will understand by time. We have to take into account that all our judgments in which time plays a role are always judgments of simultaneous events. If, for instance, I say 'That train arrives here at 7 o'clock,' I mean, something like this. The pointing of a small hand on my watch to 7:00 and the arrival of the train are simultaneous events."

This is in page 2 or 3 of one of the world's leading physics journals, he's trying to explain how to use coordinates to describe things like the passage of time. It's unbelievable. He was, as you probably noticed, enamored of trains. Trains come up over and over again in his examples in this era.

OK, so if there's no absolute time, if we're going to be forced to think about what he comes to call the "relativity of simultaneity," how can we compare the times associated with different events? He says, well, we can send light signals because at least if we by that second postulate that every inertial observer will agree on the speed at which light travels. Then, we can use light signals as a universal tool. So imagine, again, this train scenario. We have us standing here. We're at position M on the train platform or the embankment, watching this train go by at some constant speed.

As far as we're concerned, when we stand here watching the train go by, there were two assistants of ours, two partners standing at locations A and B, and they both had lanterns in their hands. And the question is, did they turn on their lanterns simultaneously? How could we tell?

If we know by prior measurement that we are equal distance from both A and B, we're standing here, we've measured out maybe ahead of time the exact distance between each of our colleagues, our partners, we're in the middle. If we receive those light signals at the same time, if they reach our nose at the same time as the small hand of our watch clicks to 7:00-- so like that-- then we must conclude that the emission of that light happened simultaneously.

The event of A and B turning on their lanterns must have occurred simultaneously. Because the light waves traveled the same distance. The light waves couldn't have sped up or slowed down. So they arrived at the same time; they must have left at the same time. The emissions must have been simultaneous.

What about our colleague who's riding at the midpoint of the train as the entire train rides past the train platform or the embankment at some constant speed? The person's in the middle of the train, so she knows she's equidistant from the people who are at the front of the back of the train at A and B. She sees them both turn their lanterns on, but she receives the light signal from person B first.

Now she concludes that A and B did not turn their lanterns on simultaneously. How could they have? She's clearly equidistant between them. She clearly receives a light from event B before the light from event A. So clearly, A and B could not have been emitted simultaneously.

Now, who's correct? We might stomp our feet and say no, no, no. You're moving. It doesn't work for you. And she will just as stubbornly stomp her own feet and say, according to Einstein's own postulate number one, the laws of physics are exactly as legitimate for her as they are for us. She's moving in an inertial frame of reference. She's moving in a constant speed. All the laws of physics work for her. She can draw all the same conclusions that we can. She clearly was at the midpoint of A and B. She clearly received light flash from B first.

This is what Einstein means by saying, as he writes in the paper, we can attribute no absolute meaning to the concept of simultaneity but rather that two events, which examined from one coordinate system are simultaneous, like us on the train platform, can no longer be interpreted as simultaneous events when examined from a system which is in motion relative to that system. Remember, nothing about forces, not about her being knocked off course. She's in a perfectly legitimate physical laboratory, moving at a constant speed. Her conclusion is exactly as valid, Einstein says, as ours is. Therefore, simultaneity is not shared across reference frames.

OK, what do you do with that information? This is what begins to lead to some new phenomena, new at least for Einstein. How do we measure the length of an object? Well, as any good Machian philosopher would say, tell me exactly the empirical procedure to be followed. Well, here's a good procedure. At the same time, measure the locations of the front and back of the object and then subtract. Take the difference at the same time.

So here's the train at rest in the station platform. We're on the train-- on the embankment. We measure the front of the train, the back of the train, take the difference. We measure the length of the train to be length L. What if we on the platform measure the length of the moving train as the train speeds past us at a constant speed V? Well, at one moment in time, simultaneously, we measure the positions of the front and back of the train, and we measure the train to be short. We measure some length L prime, which is shorter than L. In fact, we'll see shorter by how much in a moment.

Now, the passenger on the train, our colleague who's sitting at that midpoint m prime says, no, you messed up. You got the wrong length because you messed up on simultaneity. She accuses us, we first measured the location of the front of the train, waited for the train to slide by, and later measured the position of the back of the train. So, of course, our measurement was shorter than it should have been.

How does she know that we did them at different times? Because she asked her friends at the front and back of the train to release their lanterns. She clearly got the light signal from B first, so she knows we measured the front of the train at one moment. And at some later time, not simultaneously, we measure the back of the train. So, of course, we got the wrong answer because we messed up the measurement.

With only a little bit more work, Einstein shows we can find out by how much these two measurements will disagree. They disagree by exactly that factor, Gamma, that we've now seen many, many times, that 1 over the square root of 1 minus the quantity V over C squared.

Just by taking into account kinematics, how do we account for the motion of objects through space and time? Nothing about forces, nothing about an ether. Einstein arrives at exactly the same quantitative form as the Lorentz contraction because of our relativity of simultaneity, not because of forces from the ether.

So just to beat this dead horse, length contraction have nothing to do with forces or an ether. It wasn't about dynamics. It was simply a consequence of kinematics once we take the time to understand how objects move through space and time and how we assign coordinates to that force-free motion.

He goes on. The next step that he discusses is actually what comes to be known as time dilation. How can we measure the duration between two events, the time duration, how long between how much time passes between the events?

Well, we can imagine building something called a light clock, a thought experiment. Take two mirrors, two reflecting mirrors, and fix their relative height. Hold them in position so they have some height, H, between them. And we'll tell the tick of a clock by bouncing a single light wave between them. That's what sets our reference time between ticks.

And so the time between ticks, when we're standing at rest with this clock, is just the height between those mirrors divided by the speed with which the light-- speed with which the light will travel. So we have a fixed-clock rate when we hold this clock at rest with respect to us. It's given by the height and the speed of light.

What if our partner has an identical clock as she races past us on that moving train? She's now moving on the train at a constant speed, V. How do we on the train platform watch the rate of her moving clock?

Well, we see this light wave travel this sawtooth pattern, right? It's emitted from the bottom mirror, the entire assembly drifts to the right as the whole train moves by. So by the time that light wave reaches the top mirror, the entire assembly has moved. It's moved some distance B. Likewise, from the top to the bottom, it's moved another distance B and so on. So we're watching their light beam in the moving light clock trace out this sawtooth pattern as opposed to moving with what, for us, would look like straight up and down.

So once again, we can use this great invention of the Pythagorean theorem. We have a beautiful right triangle. We can relate the distance traveled as seen by us of the light beam in the moving clock. That's this distance capital D. We can relate the square of that distance to the sum of squares of the two sides of this right triangle to the drift distance. While that light waves in motion, the entire clock drifts a distance B. Square that length, plus the square of the height, the height between mirrors, OK?

Well, now, we know, much like when we talked about the swimmers in the race last time about the Michelson-Morley experiment, we can fill in a bit more information. We know that this distance, capital D, is the distance at which that light wave traveled-- that's this one and only constant C-- times how long it was in motion. It was in transit from the bottom mirror to the top mirror, some time, delta T prime. That's our measurement of the duration of ticks of the moving clock. That's our measurement of their clock rate.

So the distance it traveled is its speed times the duration it's in flight, OK? Likewise, it's drift distance is the speed at which the entire assembly is moving, that's the capital V, times that same duration, how long between when the light wave is at the bottom mirror and the top mirror. And then, we still have h squared on the end. Sorry, gang.

Well now, we can fill in some other information. We know what h squared is. That's just related to our clock rate in our own reference frame. H, remember, we can relate to the speed at which light is traveling times our tick rate on our clock. And now, it just takes that same amount of algebra, just like in the Michelson-Morley experiment, just like therefore in the lecture notes from last week, it takes very little work to derive a relationship between our measurement of the moving clock's tick rate and our measurement of our own clock's tick rate.

And in fact, remember that gamma is always larger than 1 if there's any relative speed. We measure their clock to be running slowly. The time between ticks on the moving clock will be slower than the time between ticks on our own clock that's at rest with respect to us, not because there's a force, not because of any resistance from the ether, but simply because of kinematics.

This last part here will be especially sketchy, but here's why I invite you to look it up-- optional, but you're invited to look at the brief lecture notes on the Canvas site. A few weeks later, he submits this article, the one we've been talking about, the electrodynamics of moving bodies, he submits to the Annalen der Physik in early June of 1905. He writes up a three-page follow-up that's submitted to the journal in September of 1905. So he basically takes the summer and derives what is probably his best-known equation ever, which is E equals mc squared. The nature of his original derivation goes like this. And again, the notes fill in some details of an alternate derivation.

Einstein imagines a box, a sealed box that's moving at some constant speed, v, just moving otherwise in isolation at some constant speed. In the middle of its journey, two bursts of radiation of equal amounts but moving in opposite directions are emitted by that box. So the box emits a total amount of energy in the form of light waves and radiation, total energy E, half the energy carried off in one direction, half in the other.

Now, because the momentum carried by that radiation is equal and opposite, he argues it has no impact on the speed with which the box is moving, right? The recoil from the emission in one side is exactly balanced by the recoil from the emission in the other side. So the box's motion is unchanged-- its velocity is unchanged, even as it emits a total energy, E, in the form of radiation, and then it just keeps speeding along its way.

Well, Einstein argues-- again, it only takes three pages of the journal-- that the kinetic energy of the box must have changed. We have to conserve total energy. It has given up on energy E in the form of this radiation, but its speed hasn't changed. So what must have changed? Its mass.

If we imagine starting with the kinetic energy of the box, one half mv squared, he's convinced himself that v hasn't changed. Yet, the kinetic energy of the box must have been reduced by some amount, E. The only thing that could have changed was the mass of the box. So he argues-- he actually has a brief calculation-- that some amount of mass of the box has been converted into the energy carried off by the radiation. How much mass? E divided by C squared.

And in fact, if you do a little more work for arbitrary speeds v, they're not just small compared to the speed of light. In fact, the expression is gamma mc squared. And again, I'll go through that a little bit more detail in the lecture notes. The point is this is a kind of three-page afterthought that he submits to the Annalen der Physik in September of 1905 in the context of his work on the electrodynamics of moving bodies that he'd submitted in June. Let me pause there. Any questions on how Einstein is approaching this quite familiar question of electrodynamics of moving bodies?

I see, DA asks in the chat, did Einstein's earlier papers have improper citations? Well, they had-- that's a good question. I haven't reread his early papers in quite a long time. He was never overly generous in these years. He wasn't oversighting. So that's true, even from his articles from the very early 1900s.

I don't know that they were quite as bereft of relevant citations as this 1905 paper was. And his earlier ones, frankly, were probably a little more conscientious because it was his first set of papers. They were going to be-- he would have assumed they would have been subjected to more careful scrutiny and review. So it wouldn't surprise me if he was a bit more conscientious in citing work. But it's a good question. We can look 'em up. His papers are now easily available, thanks to an international team of scholars in something called the Collected Papers of Albert Einstein. And so I don't know. That's a good question. I have to go back.

How would you describe the advantage of his theory over the leading theory of the time, Seedler asks. That's a great question, Seedler. So I'm going to actually pause on that because we're going to look a lot at that exact question in the next lecture. So it's one thing for us to ask today, do we think it's better or not as good, and we can vote and so on, and have our ideas about that. I think it's a separate question, but I think it's more like what you're-- maybe what you're after, how did experts at the time evaluate this work? What did they think was novel about it? Did they care? Did they consider this an important improvement? And we'll look at that early reception, really, for the entire class next round.

Jade asks, why was the mass energy equivalence included in the paper on electrodynamics of moving bodies? Oh, good. That's a good question, Jade. So Einstein came at that because he was still thinking about this motion of radiation, the way that different observers would handle the question of the radiation of light. This was light being emitted from a moving source. This is us sitting at rest watching a box move past us at some constant speed, emitting light. In the rubric of the day, that was an example of the electrodynamics of moving bodies, the emission of electromagnetic radiation, as seen from a reference frame different from our own.

So in that sense, it fit within the rubric. Einstein then made use of some particular relations he had derived in his longer paper on the electrodynamics of moving bodies. But for Einstein, at first, it really came from thinking about how different observers, observers in different states of motion, characterized this radiation from a source that was either moving with respect to them or not.

He later comes to argue this is actually quite general. It's not restricted to light waves or radiation at all, or really even about electrodynamics. He comes to see this in a very, very general relation. But he comes to it, originally, from very directly from his work on electrodynamics of moving bodies. Good question. Any other questions on that? Now, we can turn to the last part for today.

So let's talk about Einstein, and experiment, and something like engineering practice. For a long, long time, really from early in the 20th century once Einstein's work did become known, and celebrated, and then scrutinized-- for a long time, there was a tradition by scientists, by philosophers, by historians, by many kinds of scholars, a tradition of trying to read Einstein's paper from 1905 as some of direct response to the null result of the Michelson-Morley experiment.

So let's say the fact that Michelson-Morley could not find any measurable effects of our motion through the ether, the argument had gone, must have convinced Einstein to then get rid of the ether because it had been somehow empirically disproven. And that was really the conventional way of trying to make sense of Einstein's own work on the electrodynamics of moving bodies.

There's a really quite amazing critical review of that line of thought in this book by Gerald Holton. Professor Holton is a retired professor at Harvard. He was a member of both the Physics department and the History of Science department. And he wrote this really iconic, quite lovely collection of essays that was first published-- well, the essays were published throughout the 1950s and '60s. The book pulled together in the early '70s. Still in print, it's a lovely book.

And Holton argues, I think really quite persuasively, that this reading of Einstein as somehow responding consciously and directly to this Michelson-Morley null result has almost no basis in fact. In fact, it's not clear whether Einstein even knew about the Michelson-Morley results at the time. If he did, he seemed pretty unconcerned about them. They did not seem to play any major role in his thinking. And that's an important distinction from people like Lorentz, like George FitzGerald, or like others whom we've mentioned.

Plenty of people in Europe at the time were very concerned about the Michelson-Morley results. Einstein seems not to have been one of them. He might literally have not even heard about it yet. Or if he did, he didn't pay it much attention.

We get some textual evidence just by looking carefully at Einstein's paper itself. This is, again, in the excerpt that you had for today. Right in the early, early part of the paper, he talks about what he calls unsuccessful attempts to discover any motion of the Earth relative to the light medium, the ether. They've all been unsuccessful. And he's talking about the quantities of the first order. Let's say it's a quantity to excuse me to the ratio V over C to the first power.

One of the things that was so exciting to people about the Michelson-Morley experiment was actually sensitive to quantities of the second order. So Einstein is not only not citing a source as telling us which particular experiments he had in mind, which were these unsuccessful attempts to measure any motion of the Earth relative to the ether, he's dismissing his entire class of first-order experiments of which there were many, Fresnel aberration and so on.

He's not even talking about second-order experiments, let alone mentioning more specifically the Michelson-Morley experiment. So Holton, I think, makes a pretty compelling argument that whatever Einstein was doing, it was probably not responding in any kind of self-conscious careful direct way to the Michelson-Morley null result.

Now, that was sometimes taken by other people downstream, even from Professor Holton's work, to suggest that Einstein was somehow uninterested in experiments altogether. And that seems like not correct, either. That's the kind of overinterpretation of this question that's more specifically about Michelson and Morley.

So here's where this article by Peter Galison is really drawn from a really fascinating book. That's why I think Galison's work can help put us back into Einstein's very specific world, to his context, to the things he really was concerned about and sometimes even quite obsessed about in the years, and months, and days, and weeks leading up to his work on the electrodynamics of moving bodies.

And a lot of it has to do with things that we've already talked about, things like train travel, which he really, really was enamored with. So until the late 19th century, during Einstein's own childhood, in fact, there were no coordinated time zones. We now know about time zones very well. We have to navigate them carefully with these-- our asynchronous Zoom sessions and all the rest.

But even into Einstein's own childhood, there were no coordinated time zones. Each town kept its own local time based, usually, on a clock in its town square, basically make sure an easily visible clock that everyone could see and agree on. That would set time, and you set your watch based on the highest clock tower in your town.

And there were these clock towers all over the place, including, of course, at places like train stations, or churches, or other tall buildings. And that wasn't true only in Europe, that was also true in North America. So, for example, in this time period, passengers riding the train between Boston and New York City had to change their watches, on average, by about 37 minutes after the trip because there was no long-distance coordination for clock, for time. So what we would have called 12 noon in Boston was off by, on average, more than half an hour compared to what would have been called noon in New York City and vice versa.

Now, that was true already, starting from the earliest days of rail travel. This became an especially pressing concern, one that now had both commercial and soon military concerns for people like General von Moltke in the newly unified Germany. You may remember, I mentioned briefly before, Germany was actually a collection of separate-- there was no country of Germany. It was a bunch of separate, German-speaking lands until unified into a single country of Germany in 1871 right on the heels of its war with France in 1870.

And one of the leading military leaders from that who was elevated to a count became a-- he was knighted, essentially-- Count von Moltke is recounting why it was so important in this new system of a single unified Germany to pay closer attention to how we coordinate time. And this is now a quotation that I learned from Peter Galison's articles in your reading.

He says that "unity of time is indispensable for the satisfactory operating of railways that's now universally recognized as not disputed. But, my gentleman, meine Herren, we have, in Germany, five different units of time. We have, in Germany, five zones with all the drawbacks and disadvantages which result" There's no nationwide coordination.

"These we have in our own fatherland besides those we dread to meet at the French and Russian borders." We dread because those were sites of recent war. "This is, I must say, a ruin, which has remained standing out of the one splintered condition of" a Germany when it wasn't yet a unified country. "But which since we have become an empire, it is proper should be done away with." We need to coordinate clocks at a distance.

And as I say, this was especially relevant after the recent war with France that led to the unification of a single country of Germany. This is all happening, literally, in Einstein's childhood. Remember, Einstein was born in 1879. The country into which he was born itself was actually quite new.

So one of the main ideas that a lot of engineers and scientists were working on throughout Central Europe, not just in Germany, was to install what became known as mother clocks, and to install them in central train stations connected to other clocks by way of electromagnetic signals, either telegraph or increasingly radio waves. This is what Peter Galison wrote about in his really quite lovely book, "Einstein's Clocks, Poincaré's Maps." And, of course, the reading we had today, Peter's article kind of draws on that larger body of work.

And so some of you may know the Eiffel Tower in Paris was under construction around 1910. One of the earliest uses for that was not only to draw American tourists.

That wasn't such a bad outcome, either, for the French. But it was actually to serve as a transmitting tower for radio waves, in part, to transmit clock coordination signals. It was one of the standardizing beacons to send out standard time. "It is now 12:00 noon" and beam that out by electromagnetic signal. Other municipalities were laying telegraph lines or stringing above ground telegraph cable to do the same thing, to connect especially main hubs on this now intercity rail system so they could coordinate clock signals, even across the entire expanse of the continent.

And so every single part of these new systems were subject to patent claims. This is exactly what Einstein was immersed in. I was talking with some students before the class really began this afternoon. It's really quite extraordinary. Peter writes about this a bit in his book. There was a rule at the barren patent office, where Einstein was a patent officer third class, that any records, any unpublished records regarding the review of patent applications had to be destroyed after some passage of time, a couple of decades. And so they wound up destroying even the stuff that Einstein had served as a principal examiner on.

So we have very few clues as to the very specific patents on which Einstein would have served as the lead examiner. What we do know, however, and what Peter makes very good use of in his study, are the patents that were issued from that patent office in various years. We also know that Einstein was working on the so-called electrotechnical desk in particular. So it's all but unavoidable to conclude that Einstein was examining at least some of these gadgets along the way, which exact ones we don't know.

We do know from the volume of patents being applied for and the kinds of work being done that this was very much a major concern in the Bern patent office as well as other parts of Europe. Peter goes on, this is one of my favorite examples, he actually was able to reconstruct from Einstein's correspondence the walking path that Einstein would have taken between his apartment in Baron and his office at the patent office.

And here, you see this map of all of the newly coordinated clocks literally dotting the line of the path along which Einstein would have walked that would have just recently been connected by these telegraph and/or radial signal methods, to say that when you receive this electromagnetic signal, that means that it's 12 noon at the mother clock. Implement an appropriate offset to take into account your distance from that mother clock and the speed of light. So we know that Einstein was literally immersed in these kinds of things even on his walk to work, let alone at his patent desk.

So we come back to this very strange-looking paper submitted to the Annalen der Physik in June of 1905 on the electrodynamics of moving bodies. Again, as I've mentioned many times, the title sounds quite conventional. The approach seems anything but conventional in terms of ordinary physics articles of the day, of their own day, let alone of our day today.

And yet, if we think of this as the work of a patent clerk who's obsessed, who's enamored with this new technological stuff, maybe begins to make a little more sense. The lack of references might not only have been Einstein being lazy or uncharitable. It also could be a way to emphasize priority and downplay precedence, much like one would have to do to get a patent. I mean, this is actually novel compared to what was done before.

There's a very close focus on what we might call the operational details. How would we really measure distances of space and time? How would we actually coordinate our clocks if we're not right next to each other? Or, if we have some intervening state of motion, how would you step by step establish things like clock coordination, taking advantage of the exchange of electromagnetic signals?

It begins to look a bit more like a patent application and less like an exercise in mathematical physics of the sort that Hendrik Lorentz or others had done. So that's the main takeaway, that I keep in mind at least, from Peter Galison's article and book. And we can pause there. And again, I'll ask, are there any questions?

So Babu-Abel says, I noticed the paper began with saying the Michelson-Morley experiment as a prerequisite. That's certainly not by Einstein. So it depends on which translation you're looking at. It's true that later editors, including Arnold Sommerfeld, who actually made one of the first translations, or one of the first-- actually, one of the first annotations-- many later editors have put stuff onto Einstein's paper, and they're usually marked carefully with footnotes. In some of the translations, it gets a little cluttered as to who put that footnote in. So you have to be a little careful.

So Babu-Abel, I'm quite confident that whatever footnote you have in mind was one of these later additions from a well-meaning editor, someone who thought they were helping to clarify, but in fact was falling into this, what becomes now, a kind of historical trap. So if we go back to the Annalen der Physik itself or some of the more bare translations, for example from the Einstein papers project, the Collected Papers of Albert Einstein, now the kind of industry-standard version, we can go very clearly, what was exactly in Einstein's first published version and what was added by later-- well-meaning, but later editors. So that's a good point. Thank you for raising it.

Stanley asks, can we explain again why a stationary observer measures the length of a moving train to be smaller? Yeah, very good. Because of different notions of simultaneity. It's a great question Stanley. It's worth sitting with this a little bit longer.

Let me preview by saying, we're going to come back to that in the next class session as well to consider not how Einstein himself made sense of that, by how some later people wrestling with Einstein's work made sense of things like length contraction. So this is not the last time we'll see it, even in this class.

But what did Einstein argue was the origin of length contraction? Remember, he very clearly says the ether will be merely superfluous. He's going to not talk about a physical medium that's going to exert forces the way Lorentz did about that squeezed beach ball. For Einstein, it's all about how we perform the measurement, that kind of mock-like operation for how do you perform a measurement.

So he says, here's how you perform a measurement of length or of distance. Measure the front of the train and the back of the train at the same time and subtract. Take the difference. So if we're at rest with respect to the object, that's not very challenging. The train is at rest in the station, we can leisurely measure the front, the position of the front, mark it off on the train platform, leisurely mark the back, we can then take the difference and say, OK, the train is 25m long or whatever the answer might be.

What happens when we try to measure the length of the moving train? When we watch the moving train, we should measure the front of the train and the rear of the train, mark those positions at the same time, and subtract. The problem is, based on this argument about the exchanged light signals, we no longer agree on what counts as, "at the same time," as the observer on the moving train does. So the observer on the moving train watches us do this and watches us do things at different times because of our relative states of motion.

So we think we've been very careful measuring at the same time, the locations front to back and take the difference. Our partner on the train says, you measured the front of the train first. And then, you waited. Some time went by during which the train is sliding past. And then, you mark the position of the rear. So it's an unfair measurement. They watch us mark the front of the train, wait a while, and then mark the rear of the train after the train has moved. So along the direction of motion, of course, we measure a shorter distance because they argue we messed up on the timing.

Now we could say, no, no, you're wrong. We did it right because of this and that. And they'll say, no, no, I'm right because I have these light signals that were exchanged from my partners A and B, who were stationed at the front and rear of the train, and I got the light signal from the person at the front of the train before I got the light signal from the person at the back of the train. So you can't tell me you were simultaneous. You messed up. You were lazy. You were too slow. You messed up.

And we can't say, I'm right; you're wrong. We can, but she can say it with equal confidence and equal fervor. That's what Einstein wanted to get at by pairing those two starting postulates, that all the laws of physics, including all the laws of mechanics, electricity, magnetism, optics, thermodynamics, all the laws of physics hold just as valid for our partner on the moving train, if she's not speeding up or slowing down, if it's an inertial motion, they hold just as valid for her as they do for us. So she can appeal to things like the behavior of light signals, the behavior of her clocks on board and so on. And she very clearly unambiguously receives a light signal from the front of the train first and later from the rear of the train.

So therefore, if these light signals were emitted at the moment people tried to measure the front and back of the train, she said, well, you messed up. You didn't get the timing right because you measured the front of the train, and then some time later you measured the rear of the train. And in the intervening moments, the train slid in that direction of motion. So you measured the wrong location of the rear because you measured the rear of the train at the wrong time.

So, again, if that's still not super clear, go over the slides. The picture might help a little bit. I'd be glad to chat more during office hours and so on. But we'll also come to that again on Wednesday's class, seeing it from still a different perspective. So if it still doesn't quite sit right, it's OK. We'll get another crack at it on Wednesday.

Great, [INAUDIBLE], thank you. Very good observation. So I think the way Einstein would have reconciled those two, he's saying, we can always establish a coordinate system. We can always say, this is my reference frame with respect to which I measure the passage of time. I assign some coordinate t. He even tells us how to measure the time of an event when the train pulls in, and my watch says 7:00, right? So we can always-- in fact, we have to always establish our own coordinate system that's especially convenient for us, let's say at rest with respect to our own motion.

We can't appeal to any "real," any true coordinate system or any absolute coordinate system because, he argues, there is no such thing. But that doesn't stop us from laying out our own coordinates. We have to do that. In fact, we have no choice but to set up our own coordinates because there's no absolute system to which we can appeal.

So he's arguing, in the case of the clock coordination, that all these locations down the line, the Bern train station wasn't picking up and moving with respect to the Zurich train station. We should be able to apply one set of coordinates to all those things across space. But how do we get our time coordinates to line up? We have to do a little more work. Because they can't appeal to absolute time any more than we can, right?

So we have to therefore find a mechanism, find an operation according to which we can line up our own coordinate system, we can get our coordinate systems to be in agreement or in alignment. Because there is no absolute standard to which we can separately appeal. How can we do that? Well, we're all going to agree on the speed of light. Whether we're at rest with respect to each other or moving, according to his second postulate, light becomes this absolute meter stick or measuring tool because we'll all agree on it.

That means that if we're using, say, radio waves from the Eiffel Tower to coordinate our clocks at a distance, we know exactly how much time must have elapsed in our own coordinate system between when the clock struck 12 noon in Paris at the Eiffel Tower and that electromagnetic wave carried that signal, it's 12 noon in Paris, it's 12 noon in Paris, it's 12 noon in Paris. And then, we receive that signal some time later, we know exactly how long in our time units, how long it's taken that signal to arrive because the light wave could only have traveled at the speed of light.

So we can use this as a universalizing tool to coordinate our coordinate systems at a distance, and then we can make sure that our clock is in the same reference frame as the Paris clock, not by saying, I got the signal from Paris. Now, I'll make my clock say 12 noon. That wouldn't work. By saying, I got the signal from Paris, I now know it's 12 noon plus the propagation time. And I can calculate that without worry because the propagation of that signal is some universal constant, the propagation rate.

So if I have separately measured the distance between my house and my train station in Paris or whatever the mother clock is we're referring to-- the Germans would never have used Paris, by the way. They would have hated that. But whatever the mother clock is, whatever standard we're using, you can separately at your leisure measure your distance between them. And then, you'll know how long it will take for an electromagnetic wave to get from that mother clock signal to you. It can't speed up or slow down because it's just the speed of light.

And so now, you say, I got the 12 o'clock signal from my relevant so-called mother clock. I now set my clock automatically to be 12 plus appropriate offset. And now, I know my clocks are synchronized. So if I had a partner standing between us, midway between say Zurich and Paris or Zurich and Bern or whatever and we did the lantern trick, we could confirm that our coordinates are now aligned.

How could we agree on the time coordinates at distant events? Trade light signals. If I have a partner who's midway between me and the distant mother clock, we can make sure we're still coordinated. We can do something like a calibration by doing another trick with light signals. Did the person in the middle receive the two light signals at the same time if she was equidistant? Yes? OK, then our clocks, indeed, are synchronized.

So the idea is to take advantage of this universality of electromagnetic waves, even if Bern is not literally flying past Berlin. They're not in relative motion that way, but they're still using a universal feature of electromagnetic waves and doing local coordination because that's all we can ever do because Einstein says there's no absolute standard to which we could otherwise appeal. Does that make a little sense? Great, thank you.

OK, Babu-Abel says, does anyone know why [INAUDIBLE]? Is it just a postulate? That's a really deep and hard question, Babu. So Einstein made no effort to prove this or even justify it. He didn't even tell us about his surfer idea, which was a pretty cool idea. I mean, that thought experiment is pretty awesome. It's awesome for a 16-year-old. It's awesome for a 49-year-old. It's just an awesome thought experiment. He didn't even tell his readers that, the dummy. He could have at least put that in his paper.

He gives us no reason, no compelling argument in this article to take on board this very strange-sounding postulate about the constancy of the speed of light. He has that very strange, abbreviated paragraph I read out to you near the end of the class today about the failure of efforts to measure relative speed with respect to our motion in the ether. He doesn't tell us which experiments. He almost certainly doesn't mean Michaelson-Morley. So there's some modest, weak empirical evidence that seems to argue against that. He's not giving us a hard proof.

In the years since then, there have been more and more ideas built up going well beyond the original framework of Einstein's own work towards, which we can appeal and we'll get a glimmer of, actually, some of those first kinds of arguments, actually in Wednesday's class, other kinds of symmetry arguments which were absolutely not the kind to which Einstein appealed at the time, that guarantees certain kinds of invariances, certain kinds of geometrical properties that we'll look at quite squarely on Wednesday's class.

But in Einstein's own day, it was, frankly, an article of faith. That's why he calls it a postulate. And Stanley asks a follow-up about measuring the length of a moving train. Slicing and measuring the locations front and back at the same time, take the difference, but they did-- at the same time is not well defined. That's right. So Stanley, that's exactly right.

So the idea is if our operation to measure that length is measured front and back at the same time, and we disagree about what counts as at the same time, and everything else flows from that, argues Einstein, which is why it's all about kinematics, not dynamics for him. It's all about, how do we lay down coordinates with which to reckon the motion of objects through space and time.

So Stanley asks, do we need to make sure the measurements taken are simultaneous? Yes, that's right. Or rather, it's to say, our measurement of length will be relative to our reference frame. It'll be totally correct in our own reference frame, according to our coordinates. It just will no longer agree with someone's equally correct set of measurements in their own equally valid but moving reference frame. That's what is pretty hard to get our heads around.

Julian says, do you even need the second postulate if you use the argument of the thought experiment. Good question, Julian. Einstein himself returned to this in later writings. If we really, really-- we'll actually come to this a bit later in Wednesday's class, too. If we really take on board that Maxwell's equation should apply equally in every frame of reference, then once you know the answer, once you're a post-Einsteinian, you can go back and say, oh Maxwell's equations are invariant with respect to the speed of light.

They predict it should be the same for all observers, so maybe you just need postulate one. That's convincing if you already know the answer. Einstein, in 1905, didn't get there that way. He wrestled with whether it was an auxiliary hypothesis later in his career. That's a great question.

I'm going to pause there. I know some folks will probably have to jump off for other classes. Great, great questions. Feel free to email me if you have other questions. I'll have office hours on Wednesday this week at 11:00 AM Eastern. Feel free to pop in for that. And we'll pick up the story then on Wednesday. Stay well, everyone. See you soon.