[SQUEAKING]

[RUSTLING]

[CLICKING]

PROFESSOR: So I'm going to come to 8.20-- Special Relativity. It's a great pleasure to introduce David Kaiser. David is a faculty in the physics department. He's also a historian of science. So he's in a super great position to talk about Einstein and special relativity and give kind of the frame for this class. So please welcome David. And take it along.

DAVID KAISER: Great. Well, hello, everyone. Happy New Year. Welcome back at least virtually to MIT. It's really a great pleasure to talk with you today about this material. I love this material. So hopefully you can all see that first slide-- smiling Einstein on the bicycle. OK.

So I want to talk about three main parts today for the material. And we'll talk about how all of the most accomplished physicists were thinking about motion of bodies through space and time during the middle, late years of the 19th century, roughly, say, 100 to 150 years ago, give or take, because that really sets up a pretty sharp contrast with how at the time a rather young and very little known person named Albert Einstein began asking similar questions but often in very different ways.

So we'll start with some of this context of what was happening before Einstein even came on the scene to help us better make sense of why his approach seemed really so unfamiliar and so surprising at the time. And then for the last part-- I find it really fascinating, drawing on work from some of my friends and colleagues, other historians-- we'll try to ask, what was going on with Einstein?

Why was Einstein's approach so different? And can we make sense of it since it wasn't just the ordinary routine that we might have otherwise expected? That's that last part about coordinating clocks.

Well, let's jump right in. Let's start not with Albert Einstein but with another very familiar name, James Clerk Maxwell. I thought about growing a beard like that during COVID. I haven't made much progress. But that's a typical 19th century, fine Cambridge beard-- Cambridge, England.

So we all know Maxwell's name. Many of you probably own a t-shirt with Maxwell's equations on it. If you do, I'm very jealous. I don't have one anymore.

Anyway, so we still use his approach to electromagnetism, as of course you all know very well. And we've been able to boil it down to basically a tweet or a single t-shirt.

It turns out, as you may know, what we now call Maxwell's equations were hammered out by Maxwell and actually some other colleagues during the 1860s and early 1870s, so approximately 150 years ago. And in fact when he first wrote them down, they weren't in such a nice, compact form.

It was in a 900-page, two-volume treatise that was first published in 1873-- two volumes, a total of 900 pages. It was a weapon. You could hurt someone with these books, it was so fat, even though now we can boil it down to a simple t-shirt.

And so what's even more interesting to me is that even though we still use Maxwell's equations, what we think they say about the world is really, really different than what Maxwell and his immediate circle thought. And the biggest difference of all is that for Maxwell and really for all of his contemporaries and his students, the equations of electricity and magnetism, as far as they were concerned, had everything to do with some physical substance, a medium that they called the ether that they assumed must be spread evenly throughout the entire universe, filling every nook and cranny of space.

So all of the phenomena that we would associate with electricity or magnetism, the flow of currents, the splaying of iron filings around a bar magnet, and even much more complicated things, to Maxwell and his group, these were all just evidence of the state of stress of this underlying physical medium. It was like a springy, substantial, resistive medium that they called the ether.

And he says that in the opening pages, for example, of his now very famous treatise and throughout, that the whole point of studying this field, as far as he was concerned, was to study the behavior of the distribution of stress in this medium extending continuously throughout the universe, the ether. It wasn't just Maxwell.

His a little bit more senior colleague, William Thomson, who went on to be known as Lord Kelvin, like the Kelvin temperature scale and many things we still use from Thomson's work, he wanted to give a sense to non-scientists a few years later in a popular lecture what all the excitement was about. He said, here's what we're doing. We want you to get a sense for what we're doing.

We're studying the physics of this elastic, physical medium called the ether. And he instructed his very elite, very fancy audience who went to one of these popular lectures, stick your hand in a bowl of jelly, he tells them. And see how it wiggles and vibrates as you move your hand around. That's the highest of high-end physics in the 1860s and '70s. It was all about understanding the behavior of this elastic medium called the ether.

And that had very specific follow-on implications for this group. So one of the first things that you all know already, one of the most exciting features of Maxwell's work that really got himself excited and solidified his reputation was this unexpected unification that he put together in the 1860s.

Not only was there a deep relationship between electricity and magnetism. That had been wondered about but never really formalized. But even more surprising, that these two areas, electricity and magnetism, were also deeply associated with optics, with the propagation of light.

So it was Maxwell, as I'm sure you know and probably have already done this on problem sets by now yourselves-- using Maxwell's equations, you can derive the quantitative behavior of light as it travels through space. Light, as Maxwell intuited, was nothing but a certain pattern of propagating electric and magnetic fields.

Again, to Maxwell, these were propagating in this material, physical ether. They were disturbances propagating, skittering through this physical stuff that filled all of space.

And in fact, by trying to calculate the speed with which disturbances would travel through space based on other properties of the ether that he and his colleagues had already measured, basically sets up like spring constants, he found that the speed of propagation would be equal to the value that had already been calculated many years before for the speed with which light travels.

And he says in his own words, in this lovely old-fashioned phrasing, "The velocity of transverse undulations"-- a certain kind of wave-- "in our hypothetical medium agrees so exactly with the velocity of light calculated from optical experiments"-- mostly astronomy at the time-- "that we can scarcely avoid the inference that light consists of the transverse undulations of the same medium which is the cause of electric and magnetic phenomena."

That's why his book was 900 pages, right? Today we can put in on a t-shirt. He was really just walking through this very old fashioned language to come to the point saying light was nothing but a certain kind of pattern in the ether. And so in fact they often called this not just the ether but an even fancier name. They called it the luminiferous ether.

And from the Latin, it means "light bearing" or "light carrying." So "lumin", like "lumos" for you *Harry Potter* fans, that part you probably recognize. And the "ferous" is like a Ferris wheel. That means, like, to carry or to move through space.

So this was the light-bearing or light-carrying ether. And that's what Maxwell and really all of his contemporaries were convinced was most exciting about Maxwell's work, that this was a way of characterizing the state of the ether including these optical phenomena.

OK, so that's where things stood in the 1860s and 1870s. But that led to a whole new set of questions. And the next generation quite understandably wanted to kind of follow up on that and ask ways to generalize that framework.

Maxwell's work had really assumed that there was no relative motion between either the source of light or the receiver of light, that everything was analyzed in what we would now call the same rest frame, or frame of reference, as the ether itself. But of course that wasn't the most general situation, as Maxwell's own contemporaries or the next younger generation began to wonder about.

One of the most influential of that next wave is this gentleman shown here, Hendrik Lorentz from the Netherlands, from Leiden. So Lorentz wanted to ask about the electrodynamics of moving bodies. What if either the emitter of light or the receiver or both were moving with respect to this all-pervasive medium?

And so Lorentz, as we'll see, had really two distinct motivations in mind when he tried to think about the electrodynamics of moving bodies, or let's say optics for moving sources or receivers. He had a kind of mathematical set of quandaries. And we'll talk about those first.

But he also had a series of very puzzling experimental results. So he had an empirical set of ideas that we'll come to in a moment and also these more formal or mathematical. We'll start with the math.

Lorentz was really one of the best-trained, leading mathematical physicists of his age. So he knew very well how to handle relative motion. Galileo had derived that in the 1610s. That was hardly news in the 1890s.

We would do what we still call the Galileo-Newton transformation. For example, Galileo wrote very famously in his charming dialogues in the 17th century, if you watch your friend float down a river on a boat that moves at a constant speed, neither speeding up nor slowing down, then you know very well how to compare the coordinates between you, sitting at rest on the bank of that river, and your friend as she floats down on her boat, that what you call the origin, the spatial origin, of your coordinate system, you can fix at, say, x equals 0.

But your friend could call the center of her boat the origin for her coordinate system. And then you can see how her system coordinates will move with respect to yours. If the boat moves at a constant speed, little v, then you just have to calculate the offset between where the origin, the center of her boat, is as it floats further and further down the river.

So what she calls the origin of her spatial coordinates will be offset from yours because this relative motion, this relative drift. Meanwhile, as Newton himself famously said in the beginning of his *Principia* where we learn about Newton's laws of mechanics, that time is time is time. There's some absolute time. He actually referred it to the sensorium of God. He thought there was only one possible time to consider.

And so formally there'd be no change to the rate at which your clock ticked versus the rate at which your friend's clock ticked on her boat. This is called the Galileo-Newton transformation. I made a big deal out of it. You probably would have done this in your sleep. Lorentz did this in his sleep.

However, it drove him to nightmares because when he then applied this to Maxwell's really beautiful and much newer set of equations for things like optics or the propagation of electric and magnetic disturbances in the ether, he found that in that transformed reference frame if you take into account that relative motion between either emitter or receiver of light, then Maxwell's beautiful description of light, his quantitative description, looked very ugly.

And in particular, it would no longer suggest that light should behave as oscillating sines and cosines. It worked beautifully with Maxwell's equations if you look only at both sources and receivers of light that are fixed in place and not moving with respect to the ether.

Once you apply the very, very well-known transformation to take into account relative motion, then your description of light gets all literally out of whack. And this was a mathematical conundrum for Lorentz. It didn't seem to make any sense because on the Earth, on the moving Earth presumably moving through the ether, he and his colleagues could measure light to behave like beautiful sines and cosines all the time.

So we have an empirical reminder that Maxwell's description seems really, really accurate for describing optics even on our own moving ship of the Earth. So this is a real conundrum for him.

He was a very, very clever, mathematically gifted physicist. So he introduced a mathematical clue. He introduced a mathematical stopgap to address this.

He called it local time. And he was actually very clear in his writings. He said it was a mathematical fiction-- his word. It was literally just a mathematical trick.

If he introduced a new transformation for the time variable, so when you compare your coordinates with those of your friend on the boat, what if you actually did make a transformation of t prime, not just of x prime? And the transformation he kind of worked out, he reverse engineered the form it would need to have so that Maxwell's description of light waves would be restored to the very simple form that Maxwell himself had written down a few years earlier.

So this is where we still call this the Lorentz transformation. Many of you might have seen it. If not, you'll have plenty of time to learn about it and practice it during IAP.

We call it Lorentz, not Einstein, because Lorentz derived these equations first in a series of papers in the 1890s. And he was responding to this question of the electrodynamics of moving bodies. How do you preserve this beautiful description of light from Maxwell even if there's relative motion with respect to the ether?

He said it was a trick. It was merely mathematics. But it would at least get the right form back. So that was the mathematical motivation. Lorentz, as we know, was also concerned about an empirical or experimental curiosity.

He was following very closely the work of a US-based physicist named Albert Michelson. Michelson's story is really fascinating. I won't take too much time now, but super interesting. He was actually an immigrant from what's now Germany, was often part of Poland, central Europe.

He moved to the US when he was about two years old, very young, and was raised right around the time of the gold rush in California. And before I get carried away, I'll stop talking about Michelson, although he's super interesting.

So what Michelson wound up doing was he was fascinated by this question of Maxwell waves, of waves of electricity and magnetism in the ether. And he was convinced that if we are on this moving ship of the Earth moving through the ether, that should have a measurable impact on the light waves that we can produce and measure here on Earth.

So he set really his life's goal starting from very, very early trying to build devices, extremely sensitive instruments with which he could measure the fact that the Earth was moving through this ether. Like all his contemporaries, Michelson believed without any hesitation that there must exist the material, the ether. What else could light waves be but disturbances in the ether?

And then he figured that much like if a bicyclist going for a bike ride, we should be able to tell that we're moving through that medium. So before I describe his device called the interferometer, let me just give a little more of an analogy for why Michelson was so convinced there should be a measurable effect.

If we walk outside our houses, which is now a luxury-- we can still do it with masks on-- walk outside on a still day when there's no wind or no breeze, we won't feel any particular wind on our face if we're standing still. So we're outside in a physical medium. There's a physical atmosphere. But if we're at rest with respect to that atmosphere, if there's no wind, we don't feel it on our face.

On the other hand, if it's still a still day, there's no breeze, when we get on our bicycle and pedal really quickly, we'll now feel a breeze on our face because we're moving through that physical medium. We're moving through the Earth's atmosphere.

Even if the atmosphere seems to be perfectly at rest, no strong breeze, no hurricane, whatever, if we're going quickly enough through it, we'll feel a breeze on our face. And Michelson thought the same thing should be happening for light waves as they are carried by the Earth through this medium, not the Earth's atmosphere but this all-pervasive, light-bearing ether. So he really thought it would be like the bicyclist.

Now, his real genius was devising this device, we now call it the interferometer, with which he could try to measure the impact of that motion of the Earth, the entire Earth, through the medium. So he took a source of light. Today we use lasers because they're awesome and they're also monochromatic. Their light shines basically at one frequency, or very dominantly one frequency.

Lasers of course weren't available to Michelson. So he used very bright sodium arc lamps. Sodium lamps will shine mostly at one dominant color, not nearly so monochromatic as modern lasers. But they were the industry standard at the time.

So he basically took sodium lamps that mostly shine a particular yellow color, shined them at what we now call a beam splitter. It was a half-silvered mirror, as its name implies, that would let half the light through. It would act like a window roughly half the time. But it would act like a mirror the other half of the time.

So half of this incident beam will go right through this as if it were just a plate of glass. It would be transmitted. It will then make its way to a fully reflecting mirror-- sorry-- a fully reflecting mirror at the end of the path. It'll be reflected and come back. And then, again, half of that return light will be reflected by the mirror and come out to a screen.

Meanwhile, you can run the same kind of story for light that gets deflected towards path 2. From that same, single incident source, half of the incident beam will be reflected by that beam splitter, that half-silvered mirror. It'll travel a path down to a fully reflecting mirror, come back. And then half of that returning light will be transmitted.

So you have light coming together on some detector screen, that it started out as a single light wave from a single, nearly monochromatic source. But you split it into two beams so the beams travel different paths.

And now the light starts out fully in phase with itself. It's one light beam. So crests are with crests and troughs with troughs. And the idea was that you then split it to set up a race to see if there was any difference in the travel for light that traveled through path 1 and out to the screen versus light that traveled path 2 and back to the screen.

All the light starts as a single light wave in sync or in phase with itself. If there was any difference in the travels of that light between path 1 and path 2, you should see a shift in the interference pattern. Crests should no longer arrive lining up with crests or troughs with troughs. You should see a very characteristic set of interference fringes. What is called an interferometer, extremely sensitive.

Now, his idea was if, like the bicyclist, we're on the moving Earth, then the path is heading directly into the ether. That is, say, the path that's along the Earth's motion through the ether should be just like the bicyclists feeling the direct headwind of that breeze directly on her or his face. That means the effective speed-- let's say this is the direction of the Earth's motion.

The effective speed with which this light beam could travel toward its mirror should be experiencing a direct headwind for its upward path and a direct tailwind for its downward path. It should have a different speed than the light that follows the more orthogonal path so that even the light starts out perfectly in phase, you should find a shift in the interference fringes because the light's effective speed through the medium is different for path 1 than path 2-- again, an analogy to the ether wind of a bicyclist through the atmosphere.

Not only that-- a little foreshadowing for what's to come later-- this device is so sensitive, it's sensitive to second order in a very small quantity. So it could measure differences to the second order in the relative speed of, say, the Earth through the ether compared to the speed of light. So that's called a second order because it goes this small quantity squared. That's how sensitive this really ingenious device was.

And as many of you might know, we use interferometers all the time now in all kinds of industrial applications. Even more, my favorite example is from our friends who detect gravitational waves with LIGO. That's essentially a super-sized interferometer with very, very similar principles of design.

So Michelson was doing this really cool work. It was among the earliest work that any of the super fancy, elite European scientists paid any attention to coming out of the US. Michelson was among the first who made even the people like Hendrik Lorentz sit up and pay attention at a time when the US was still otherwise pretty much a scientific backwater.

So it's a really cool idea. It's a remarkably clever design for a device. Michelson built a small prototype. Then he super sized it with his colleague Edward Morley. They built a device 11 meters long for each arm, so roughly 33 or 34 feet long-- huge, huge for its day, very long arms.

They floated the whole thing in a vat of mercury, which I don't recommend. But they were trying to tamp down any vibrations from nearby cable cars. They wanted to have a clean laboratory environment.

Then they did this for years and years and years, months and months and years and years because, of course, you never know what the ether's actual rest frame is. Who's to say that at this moment, this is the direction of the Earth's motion through the ether? Maybe it's this direction or some other angle in between.

They would look for day to night variations. They would look for annual variations as the Earth went around its orbit around the sun. They would try to find any time, day or night, winter versus spring, year after year when they could measure some measurable offset or change in those interference fringes because at some point, this direction should have lined up with the Earth's direction of motion, even it wouldn't be every time. That's why they kept doing this over and over and over again.

And as you might know, they found nothing. So after years of painstaking data collection, they found no compelling empirical evidence of the Earth's motion through the ether.

Michelson won the Nobel Prize for this and related work. He was an astoundingly accomplished experimentalist. He was the first US-based physicist to win the Nobel Prize. He lived 20 more years after that and died considering himself a failure.

So I hope you all win the Nobel Prize. And I hope you think better of yourselves and give yourselves more credit. Michelson knew for certain the ether must exist. And yet he had failed to find it.

So Lorentz was following this back in Europe. And this was really his second main motivation to think about these funny ways of handling coordinates in what we now call the Lorentz transformation.

So I mentioned his mathematical concerns about the transformation properties of Maxwell's equations. He was also following the Michelson-Morley work with great interest and citing it. And we know he was really following each update.

So he was concerned about this failure to measure a shift in the interference fringes. But Lorentz said, oh, but actually maybe there's a physical reason to account for that. If there really is, as he knew there must be, this physical, resistive medium, kind of elastic medium through which the Earth and everything else is moving, then there must be a force exerted by that viscous medium on every single atom and molecule making up all the stuff in Michelson's device as well as in everything else.

And so it would be like picturing a beach ball. If you try to drag a beach ball underwater, in a resistive medium, the shape will be deformed along the direction of motion. If you drag that beach ball fast enough underwater, it will shrink in the direction of motion. It will be deformed like this picture here.

And so Lorentz said that must be happening for every bit of matter in the arm of Michelson's interferometer that's most subject to that resistive force of the ether. There should be a contraction along the direction of motion.

So then, again because he's a very gifted mathematical physicist, he calculated exactly how much shift must there be for the resultant path to be shortened just enough to make it a tie race after all. So the arm of the interferometer that's experiencing this shrinking, this extra force due to the resistive medium, would have to shrink by a specific calculable amount.

We now use the Greek letter gamma. If you haven't seen that already, you'll see it throughout IAP and the rest of your life. It takes this somewhat simple-looking form-- 1 over the square root of 1 minus v over c squared. If you plot it, you can see it diverges. When the relative speed gets close to the speed of light, you have 1 minus 1 in the denominator. You divide by 0.

Your eyes bug out. And cats and dogs live together. Everything goes crazy. So it diverges at v equals c. On the other hand, for small speeds, small compared to the speed of light, this factor is indistinguishable from 1. So here's a quick plot.

For ordinary speeds that we encounter on the highway, let alone on a bicycle, our speed compared to the speed of light is vanishingly small. So this factor gamma is very, very close to 1.

Only when you get to speeds approaching the speed of light would you expect to measure any shift from that. Nonetheless, Lorentz said in principle this happens at any speed. And the shrink, the amount of contraction, is governed by that relative speed given by this Greek letter gamma.

So gamma is always greater than or equal to 1. That means 1 over gamma must be smaller than 1. And that's saying that the contracted length of one of those arms of the interferometer got shorter by a certain amount depending on the relative speed.

That would be enough to account for this null result, Lorentz argued. It turned out that exact form of gamma was the same form he'd found for his mathematical local time manipulations. So here's how we can live in a physical ether even though we don't measure its effects. OK.

Let me now shift to how a different person began thinking about very familiar questions by that point but coming at them quite differently. That's young Albert Einstein.

So Einstein was born in the midst of all this. He was born in 1879 in kind of rural, roughly speaking, nowheresville Germany, not near any of the big cities. So Lorentz was already a practicing physicist when Einstein was born. He was much younger.

Einstein's main ambition was actually to become an electrical engineer at a time when that term itself was actually brand new. Einstein's father and uncle had gone into business together in this really brand new field of electrical engineering. This was the age of electrification. Think about extended street lighting, trolley cars with the shared electric lines above.

This was transforming the face of everyday life in cities and eventually even in more rural areas. And Einstein's father and uncle were in on that. They were early professionals in this new field of electrical engineering. And Einstein loved it. He loved to tinker with electrotechnical gadgets.

He had many strong feelings about many things. Among them, he hated what he considered the overly militaristic German high school that he attended. He would argue and insult his teachers. They didn't like him any better. They were delighted when he dropped out, so they didn't have to kick him out.

He was really very obnoxious, it turns out. So he was a high-school dropout. He dreamed of entering the Swiss Federal Technical Institute. It was kind of like the MIT of Switzerland. Except to be more proper, MIT is the Massachusetts version of their school. Zurich's was founded first.

It's often called the ETH, or the Eidgenossische Technische Hochschule. It was really a very elite technical university in Zurich, Switzerland. Einstein, by this point, had renounced his German citizenship. He dropped out of high school. And one of the best things about this technical university in Zurich was that you didn't have to have a high school diploma. He said, perfect. That's the place for me.

So they had an entrance exam, which he very dutifully studied for and then failed because, after all, he ignored the topics that weren't of interest to him. He did well enough on the physics and math portions of the overall exam that a kindly physics professor took him aside and said, you know, if you go to basically a kind of regional, something almost like a community college, go to a local, regional school for a year, study up, retake the exam, you might do better.

And that's what Einstein did. So he went to a little regional school in, again, in rural Switzerland for a year, took the exam again, and passed. So now he's able to enter his dream school, the ETH in Zurich.

Once he then worked so hard to get in, he proceeded to cut classes. This guy was a horrible student. Whatever you do, don't be like Albert Einstein, at least while you're in university.

He worked so hard to get in. And then he, again, would insult his professors as much as he'd insulted his high school teachers. He thought everything they did was boring. They didn't know what was really interesting.

So he would cut classes and read on his own and then borrow notes from his girlfriend, his long, suffering, very patient girlfriend, Mileva Maric, who was doing very well in her own physics and math courses. And likewise, he borrowed notes from another friend of his, Marcel Grossmann.

So he'd just cram and scrape through for the exams. Not an ideal student. For some reason that Einstein couldn't possibly fathom, because he actually was a dolt frankly, he impressed none of his professors. So when it came time to graduate, none of them would write him a strong letter of recommendation.

Again, his life bears many important lessons for us today. Attend class. And be slightly less obnoxious to your instructors. And maybe things will turn out better. So none of his teachers would basically support him because he had middling grades and he was rude to them. So he couldn't get a job after graduation.

So finally one of his close friends, Marcel Grossmann, one of the folks from whom he'd borrowed notes, his father had connections. And so basically through connections, he was able to get Einstein an entry-level civil service job at the patent office in Bern, Switzerland.

So still in Switzerland. He was a patent officer, third class. As I'm always fond of saying, there was no fourth class. You were the lowest entry-level gig. So even for young Einstein, it wasn't what you know. It was who you know.

What he then proceeded to do was he had a day job at what they called the electrotechnical desk, much like what his father and uncle were doing. He was a patent examiner for a lot of these cool, new electrical gadgets. And then he would go hang out with a bunch of friends and drink beer a lot at the pubs.

So they formed what they called the Olympia Academy. And this was very ironic. They gave themselves the most elite sounding name because they're basically three semi-bums hanging out, reading, and blowing off their families.

So they gave themselves a very, very prestigious name, even though it was literally three recent college graduates hanging out. It was Maurice Solovine, Conrad Habicht, and young Albert Einstein. And they would go and sometimes drink coffee, often drink beer, and talk about stuff they'd read.

And they would read a lot of physics and read a lot of philosophy and talk about it. And one of the books that we know from their correspondence at the time that they were really interested in was this fascinating book by an Austrian polymath named Ernst Mach.

Here's the book translated into English, known as *The Science of Mechanics.* It had come out in the 1880s. Mach was really remarkable. He was both a mathematical physicist and experimental physicist. You might know the terminology for Mach number, like speed of sound, Mach 1, Mach 2, Mach 3-- same Mach.

He did a lot of studies of acoustics and optics but also of what we would now call psychology, like sensory experiments and so on, and eventually medical surgery. And then at the end of his career, he was a professor of the history and philosophy of science. This guy did it all.

He wrote these very, very dense, conceptual critiques of Newtonian physics, among other things. And Mach was convinced that Newton was really getting himself into a horrible muddle because he had not paid sufficient attention philosophically.

And this is what the young members of the Olympia Academy got really excited about. We know from their letters and their notes at the time. Mach was advocating a position that came to be known as positivism.

According to Ernst Mach, unlike Isaac Newton, or for that matter even some folks like Maxwell, Mach argued that only quantities that could become objects of positive experience, that is to say things we could actively measure or sense or feel or touch, only those things belonged in our scientific theories. Anything else was just like mere speculation, like counting the number of angels that could dance on the head of a pin.

He was scathingly critical of Newton. And in particular, Mach wrote in detail that Newton's notions of absolute space and absolute time had no meaning because how could you ever measure absolute time? Show me the clock that could measure absolute time. That was the kind of classic Machian response.

I can measure the passage of time by using a clock. But who says that's what Newton wrote absolute time was? This had an amazing impact, as we know, on the young Einstein.

So he's in this milieu. He's now not in a university setting. He scraped through his undergraduate studies. He has a nice day job. But he's not doing particularly well professionally.

He's hanging out with his buddies and reading some interesting and hard, obscure philosophy science in the evenings. Well, he has what's now commonly called his miraculous year, his annus mirabilis, in 1905. In fact, he only took about six months. It was, like, half a year, during which he submitted four really astonishing, original papers to the leading journal of physics, the *Annalen der Physik* in Germany at the time.

They've since been published and translated. There's a particularly nice edition you can find edited by John Stachel with very nice essays to accompany them. You can find them online.

So for IAP and for the rest of today and even throughout the month, we're really interested in what was the third of these articles that he submitted. He submitted it to the journal in June of 1905. It's on what we would now call special relativity.

Its title, as you can see up top, was actually, in translation, "On the Electrodynamics of Moving Bodies," a thoroughly familiar title, exactly what Lorentz and all of Lorentz's colleagues have been talking about for decades by that point. So the title of Einstein's paper in 1905 was not surprising, even though, as we'll see, his approach was quite distinct.

He begins this now very well done paper not by saying, I found an error in Lorentz's calculation. There was a missing factor of 2 pi or whatever. He doesn't say, I conducted my own measurements. And I found these results with an experimental error.

He starts out by saying there's an asymmetry in the explanation which is not present in the phenomena. It sounds very philosophical. He goes on in his very opening paragraph to say that when we use Maxwell's equations, we come up with very different kinds of accounts for what should be the same phenomenon.

Very simple. Nothing super fancy like an interferometer. Just take a bar magnet and a coil through which current could flow. And make sure you have a current meter, an ammeter attached to the coil.

So if electric current flows through the coil, it will be measured. The ammeter needle will be deflected. And we are free to move either the magnet or the coil.

In his opening paragraph, Einstein says, physicists had treated this situation completely orthogonally even though, as far as Einstein was concerned, there's only one explanation needed. And so with case 1, if you assume the bar magnet is moving, you're shaking the magnet back and forth and keeping the coil fixed in location, then you would appeal to one set of Maxwell's equations.

And again, on the t-shirt it would be this one. You have a time-varying magnetic field which will induce a spatially varying electric field. And that will exert a push, a force on the little ions, the little electric charges within that coil. They'll feel a push. They'll move along the coil.

Electric current, as Maxwell himself had argued, was nothing but the motion of these electric-charge bearers. So because you have a time-varying magnetic field, the little bits of matter in the coil will be pushed along. You'll induce a current. That's case 1-- moving magnets, stationary coil.

But if you want to analyze the other situation, to hold the magnet rigidly fixed in place and shift the coil back and forth, then physicists would give an entirely separate explanation. They would appeal to a different one of Maxwell's equations.

Now they'd say that there's a static magnetic field that varied in space. It's spatial gradients were non-vanishing. And that would exert a force, like a kind of Lorentz force law, on those charges. So they have some velocity in a magnetic field. They'll be pushed along the wire. And you'll measure a current.

Einstein said that's one explanation too many. All that we could ever measure-- again, you can almost hear the kind of Mach coming through-- all we can ever see as an element of positive experience is some relative motion between the magnet and the coil which induces an electric current. Who's to say one was actually still while the other was moving?

So Einstein begins this paper by saying that there's something wrong with the stories we tell about the equations. He doesn't argue about the equations. He argues about our interpretation of the equations. Very striking.

He then goes on, just in, like, paragraph 3-- still very early in the introduction-- to posit two postulates. He doesn't prove them. He doesn't derive them. He doesn't say, I have demonstrated these by doing experiments. He says, let me hypothesize these and see what follows.

And these are the two in rough paraphrase. The first one was actually already called the principle of relativity, or sometimes simply called Galilean relativity, going back again to the 17th century.

Galileo had argued by thinking about that boat floating down the river, that to a person on the boat, as long as the boat is moving at a constant speed, neither speeding up nor slowing down, that all the laws of mechanics should work perfectly well for that observer the same as they would for us at rest on the shore. If you toss a ball, it'll land back in your hand as you expect.

Even though to us, we see the ball trace a complicated parabola, to the person on the boat, she's perfectly entitled to say, I'm sitting at rest. The ball went straight up and landed straight back in my hand. All the laws of mechanics should work equally well in any reference frame that's moving at a constant speed.

Einstein just takes that existing principle of relativity from mechanics and just assumes, just hypothesizes that that should apply not only to mechanics but to every physical phenomenon-- electricity, magnetism, optics, thermodynamics. And that's just a leap. He just says, what if? What if this applies to any kind of physical phenomenon, not just mechanics?

And then he introduces the second postulate which seems actually to be in tension a bit with the first. His second postulate is, the speed of light is a constant independent of the motion of the source. What? That doesn't sound right.

If you go back to Galileo and watching his friend on the boat, if she fires a cannon, the speed with which we measure the cannonball is different than the speed she measures it, right? If you watch her lobbing a tennis ball, our measurement of the speed of an object in her reference frame is not the same as ours.

And Einstein here is saying light is special, that unlike tennis balls, ping pong balls, cannonballs, or trains, or anything else, the speed of light, as a postulate, will be constant for any observer as long as they're in an inertial frame of reference. And here's an excerpt from the English translation. I won't read all this out. But he says, what follows from these postulates is that the luminiferous ether will prove to be superfluous-- [GERMAN].

He doesn't say, I've disproven it, ether. He says it's just irrelevant. 50 years' worth, by that point 100 years' worth of study by all of Europe's most prestigious physicists was irrelevant. That's probably why he didn't have many friends in physics at the time.

So he doesn't disprove the ether. He says we just won't even need to refer to it anymore. It makes the entire set of questions that had driven people like Lorentz really kind of fall away, at least as far as Einstein himself is concerned.

So why does Einstein introduce that second postulate? And again, historians and physicists and philosophers have studied this question a lot. And we have some good documentary evidence because Einstein was writing letters and diaries and stuff all the time. And a lot of those have survived.

So we have some contemporaneous documentation as well as his own later recollections and so on. We know that actually 10 years before this paper, back when Einstein was a mere teenager, he'd like to pose these kind of thought experiments or questions to himself. And one of the questions he would return to really over the course of a full decade was, what would it look like, what would you experience, if you could catch up to a light wave?

And he reasoned it would be like a surfer riding along an ocean wave, that to us on the shore, we'd see both these things moving. We would see a dynamical wave moving over time, not just a frozen waveform in space. But to the surfer, if she's really moving at the same speed as the wave, then she would see the wave frozen in time.

It would be a crest here, a trough there. At least for some extended period of time, the surfer would see the wave frozen, not dynamical-- a frozen waveform varying in space but frozen in time. So Einstein said that doesn't make any sense if we think about Maxwell's equations.

When he got a little more sophisticated and learned more about Maxwell, he said there's no solution to Maxwell's equations. If you're in a source-free region, if there's no clump of electric charge around, no electric currents around, if both rho and J vanish, then there's no way to have spatially varying electric and magnetic fields that are nonetheless static, right? That seems to be a contradiction.

So how do you get out of this contradiction of thinking you would have a static waveform of light if you could catch up and move at the same speed as that light wave? How do you avoid that? You just make sure you can never catch up to the wave.

How can you never ever catch up to the wave if the wave is always traveling at the speed c even if you're traveling on a very fast train or now a hypersonic jet or a spaceship of your imagination? That second postulate for Einstein we now know was really the endpoint of a 10-year series of thought experiments about, what would it look like to catch up with a light wave?

And he said that would make so many other things mutually inconsistent. Let's make sure no one could ever catch a light wave. And that's what starts driving much of the rest of his thinking, not worrying about interferometers and all the rest.

So what he does, unlike Lorentz and really all the masters in the field at the time, Einstein begins with kinematics, with the force-free motion of bodies through space and time, which is a very Machian thing to do. What can we see? We measure objects moving through space and time. Whereas people like Lorentz, and Maxwell for that matter, have been starting with forces, with dynamics.

Remember, Lorentz has this great idea that there's a force from the ether on the matter. And in Michelson's instrument, it's all about dynamics, forces. Einstein inverts that order. He says forces will be important. But first let's make sure we understand force-free motion kinematics first. After all, that's what could become objects of positive experience.

And so he has these wonderful quotations. It's now from the introduction of the paper. It's on the bottom of page 2. He's really redescribing how to lay out coordinates. It sounds childish. It sounds thoroughly unprofessional to the folks of the time.

Hendrik Lorentz says don't bother with 'what do we mean by coordinates?' But Einstein was convinced we have to think through how do we describe motion through space and time first. And I won't bother reading it out. I'll share this slide. And you can see it. But that's really what he's doing in the very opening paragraphs of this paper.

And that leads him to other follow-up conclusions, one of which very famously becomes known as the relativity of simultaneity. And you might have heard of that before. You'll spend more time with this in IAP, I'm sure.

If there's no such thing as absolute time, if time is what we measure with time-measuring devices like clocks, if that's all time is, is what can be measured by an actual instrument like a clock, then how can we compare the times in different places? After all, I'm sitting here with my clock.

Well, he says one thing we could do is trade light signals because, at least according to his postulate number 2, light is special. If I throw ping pong balls, that's not so special because we will disagree on the speed with which those ping pong balls travel. If I send a light wave, then we had better agree on the speed with which that light moved from point A to point B because of postulate 2.

So he starts thinking about one of his favorite things in the universe, trains. He loved trains. It came up all the time. So he imagines a train moving along a platform at a constant speed, a nice, inertial frame of reference.

Einstein is standing here on the embankment, the train platform. He has two friends. We can call them Alice and Bob, A and B. Einstein has marked himself out to be in the perfect midpoint of where Alice and Bob are standing.

So they mark this all out ahead of time. He marks himself perfectly in the middle. Alice and Bob are each equipped with a lantern and a watch. And by prior arrangement, they say at 12:00 noon on the dot, turn on your lanterns. So the light will travel from both A and B toward the midpoint. Point your lanterns toward Einstein at point M. Turn them on at the same time.

Meanwhile on this zooming train, there's another friend of Einstein's sitting at the midpoint of the train. At the point, this is Marge, M prime here. She knows that she's in the exact midpoint of the train.

She knows by prior arrangement that Alice and Bob are standing one train length apart from each other. And again, she's expecting that they will turn their lanterns on at the same time. So how do these different folks describe this series of events that follow?

Let's focus first on what Einstein sees when he's standing still on the train platform, the embankment, watching the train go by. The observer who's standing still on the platform at point M was, by prior arrangement, at equal distance from Alice and Bob.

I guess I changed it. Now it's a she. So Mileva, his wife, is standing there. Maybe M stands for Mileva. So she receives the light waves from points A and B at the same time. So she can conclude that the light flashes were emitted at the same time, that the event of person A and person B shining the lights, those events were simultaneous.

How do you know? Because the light had equal distances to travel. And the light could only travel at but one speed. And they arrived at the same time. They must have started the journeys at the same time. The act of shining those lanterns must have been simultaneous.

But what about the person who's on the moving train? She sees the following as she is zooming along at point M prime. She sees the light from point B arrive at her location first.

Now, Mileva or Einstein would say, oh, that's because you're racing toward it. She says, not so fast. I'm in a perfectly self-consistent mechanical system. All the laws of physics work as well for me as for you. And the light couldn't have sped up or slowed down by your own postulate, she would say-- she would be entitled to say.

So if she's equal distant between points A and B and she receives the light from B first, the only possible explanation is that the lights were not shown simultaneously, that A and B did not turn the lanterns on at the same time. So the person on the train platform and the person on the moving train disagree about what happens simultaneously.

This becomes known as the relativity of simultaneity. So who's correct? I've already said, according to Einstein, no one or both of them because of postulate 1. They're both entitled to work out a perfectly self-consistent set of laws involving electromagnetism, optics, and mechanics.

They agree they were at the midpoint. They agree that light didn't speed up or slow down. So they are both right, which is to say there is no right answer to the question, what was really simultaneous? Simultaneity becomes relative to one's frame of reference.

That's a pretty deep change from the Newtonian system. And as Einstein says-- again, it's bottom of page 2, very early in the paper-- "we see that we can attribute no absolute meaning to the concept of simultaneity, but that two events which examined from a coordinate system are simultaneous"-- like him on the embankment-- "can no longer be interpreted as simultaneous events when examined from a system which is in motion relative to that system."

OK, that's about kinematics. It's not about forces or resistive medium or dynamics. So now he goes on-- again, very early on in the paper-- once you get to the relativity of simultaneity-- again, as you'll have a chance to unpack with more patience in the coming days and weeks-- other strange phenomena seem to follow from that, argues Einstein.

One of the first he talks about is length contraction. So this had been found and published by Lorentz. Einstein is about to give an entirely different derivation, even though quantitatively it's the same form of the equation.

For Einstein, it has nothing to do with forces. It's all about kinematics. In general, like a good Machian, he asks, how do we measure the length of an object? How do we make length an object of positive experience?

Well, at the same time measure the location of the front of the object and the back of the object and take the difference. So if you want to measure the length of the train, that's fine. Just measure where the front is and the back is at the same time, and then mark off the difference between those two locations in space.

Our friends Alice and Bob can do that with the train. And they find the answer capital L. The train is length L long. Meanwhile, Alice and Bob-- and I should say that's when the train is at rest.

When they do this with a moving train, Alice and Bob measure the length of a moving train, they measure some length shorter than what the person on the train was expecting. The person on the train expected the full length L. The person who's moving with the object, either at rest with it or moving together with it, says the train is L units long.

But when Alice and Bob measure the train by measuring the front and back at the same time, they find a shorter answer. They found it shrunk along the direction of motion by some specific amount.

Now, how could that be? Remember, we disagree about "at the same time." So if we disagree about simultaneity, we will-- perforce, we must start to disagree about lengths.

So the person on the train says, you did your measurement wrong. You measured the front of the train first. We know that event B happened first, she says, because we got the light from event B first.

So you measured the front of the train and then waited while the train slid and then later measured the position of the rear of the train. So of course you have a shorter distance because you performed a bad measurement, because you didn't measure the front and back at the same time.

We say, don't be silly. They were at the same time. We checked by trading light beams. We know they were simultaneous. And we got the answer L prime. Your train is short. Who's right? Sort of both and neither, that because we disagree on simultaneity, we disagree on the outcomes of simultaneous events like measurements of length.

And so he goes on with just a few lines of algebra to find the exact form of what was already known as the Lorentz contraction, that same factor gamma that you'll be using all IAP, that the measurement of an object in motion shrinks along the direction of motion. Whereas if we were at rest with that object, we'd find a longer length.

And the amount it shrinks depends on that relative speed v over c. It depends, in particular, on this form gamma. This has nothing, for Einstein, to do with forces or dynamics. It's a totally different derivation than Lorentz's. It's simply a consequence of kinematics and, in particular, about simultaneity.

It's a very simple exercise. You'll probably wind up doing it very soon to find a similar consequence for the rate at which clocks will tick. This has now became known as time dilation.

Imagine a very simple kind of clock, the simplest one-- two highly polished mirrors with a light beam that just bounces straight back and forth between them. If the clock is at rest with respect to us, we hold the clock perfectly still at a fixed height, then the time it takes for that light to travel from the bottom mirror to the top mirror will count as one tick of our clock.

[SNAPPING]

And we know that light can only travel at a fixed speed. So it's a really great, uniform clock. As long as we can hold that height really fixed, this is a great way of defining a unit of time and therefore our clock rate.

What happens if our friend has an identical clock, same mirrors, held equally rigidly at the same height apart but zooming past us on that moving train? Then we watch the light have to travel this longer path because after the light beam leaves the bottom mirror, in order to reach the top mirror, the whole assembly has moved with the train to the right, some distance v times t in the time during which that light beam was in transit.

So it has to travel the hypotenuse of this right triangle. Instead of just this simple up and down, it travels perforce a longer distance and likewise back down. So our observation of the moving clock is that it takes longer between ticks. That becomes known as time dilation.

The time between ticks has stretched, which is to say the clock is running slowly as we measure. We measure the moving clock to run slowly by that same factor gamma. The time between ticks gets stretched. Remember, gamma is greater than 1. So the time between ticks gets stretched. And that's the same with the clock is running slowly.

Meanwhile, the person on the train says, you're ridiculous. I had the clock with me the whole time. It kept perfect time. But your clock ran slowly. I watched as I ran by the station. Perfectly symmetrical conclusions.

So Einstein was working all this out, very much inspired by Ernst Mach, by this notion of positivism, of what can we hope to measure, not starting with forces but with the force-free motion of objects through space and time, and really trying to bring it back to, what would be measurable? What would I see if I were in this situation?

One of his teachers at the ETH, a mathematician named Hermann Minkowski, had formed a deservedly low opinion of student Einstein. Einstein used to cut class, was very rude. But one of their mutual friends, after Einstein's paper came out, sent the paper to Minkowski saying, you know, it's actually kind of interesting. Take a look, to paraphrase.

And Minkowski said, well, despite the fact that I knew Einstein was never going to amount to anything, I read the paper. And I was right, Minkowski says. He really made a mess of this, as well.

So Minkowski's just interested enough to redo Einstein's work in a form that made much more sense to Minkowski, who was, after all, a professional geometer. He wasn't just a mathematician. He loved geometry most of all.

So Minkowski, not Einstein, is the one who actually brings these pieces together a few years later in-- it was published in 1908 instead of 1905. And he says, all this talk about moving trains and polished mirrors, all of that's just a distraction.

To a properly trained mathematician, which Einstein was not, all we're doing is performing rotations or projections in a certain kind of space, in this case a spacetime in which there's, say, one direction of space running along the horizontal axis and one dimension of time running up the page. We now call these Minkowski diagrams in his honor, or simply spacetime diagrams.

None of this appears in Einstein's early work. This was done by his former teacher in response to what Minkowski considered to be Einstein's continuing confusion and sloppiness.

And there's a benefit from doing that, Minkowski finds. He agrees with Einstein that we will disagree on certain kinds of measurements, for example lengths and durations of time, because we disagree on simultaneity. But Minkowski finds something that had not been so clear to Einstein himself. There are combinations of those kinds of intervals on which we will all agree.

This is what we would now call a spacetime invariant. Put together, a combination of the time interval minus the space interval, a relative minus sign and each of those quantities squared, that combination we will all agree on as long as we're each in states of non-accelerating motion even though we disagree separately on the duration between two events, delta t, or the lengths between them, delta x.

And that, from Minkowski, is what any geometer should do. Some relationships remain invariant even under changes of coordinates. And for Minkowski, that was what any undergraduate geometry student should know to do first.

So we actually have this notion of one kind of thing called spacetime coming from Minkowski kind of redoing Einstein's work. And as Minkowski famously writes in his own article-- it was published posthumously; he died quite young. And he gave a lecture. And it was published soon after he died.

And he wrote upon introducing this new work, "Henceforth space by itself and time by itself are doomed to fade away into mere shadows and only a kind of union of the two will preserve independence." And by shadows, he really meant projections, just drop perpendicular to the appropriate axis and then think about coordinate transformations in that spacetime of x and t.

So that's, again, something you'll get much more practice with if you haven't seen it already. But that's a preview. That comes in response to Einstein's work. It wasn't an Einstein's own original. Although, just to jump ahead very briefly, Einstein first thought that was horrible because he didn't like Minkowski.

But then over the next several years, the better part of a decade, Einstein himself became more impressed by that way of thinking and really adopted it for his own later work on what became known as the general theory of relativity. That's for later.

OK, very briefly here's the third part of the material I wanted to share with you. And then hopefully there'll be some time for discussion, as well. So this last part is much more brief. But it's, how do we make sense of this? Why was Einstein doing all this seemingly unusual, maybe even crazy stuff, certainly out of step with Lorentz, with his own teachers like Minkowski?

How can we account for Einstein's quite idiosyncratic approach to what was otherwise a common set of questions about the electrodynamics of moving bodies? Now, here's some of my favorite work by other colleagues, by other historians and physicists who really looked at this in great detail.

So for a long, long time, I mean literally for the better part of 100 years, since people began taking relativity seriously, which is a long time by now, it had become very common to say, well, Einstein must have been motivated much like Hendrik Lorentz was, really like that much of that generation was. Einstein must have been responding to the null result from Michelson and Morley and their interferometer, that Einstein must have been trying to explain why they couldn't measure our motion through the ether much as Lorentz, we know, very explicitly was trying to do.

And there's a fascinating-- one of the first really careful examinations of that claim was by Gerald Holton, who's a real kind of hero of mine. Holton did his first PhD in physics, low-temperature physics, and then retooled many years later in the history of science.

And he wrote a series of really remarkable essays about Einstein once a lot of Einstein's papers and letters and notes became available. Holton was among the first to really dig through these with great care and almost like a detective going through the evidence.

And what Holton concluded was it's not clear that Einstein even knew about the Michelson-Morley interferometer. Lorentz knew about it and followed it carefully. There's very little trace that Einstein paid it any attention at all. If he did know about it, it was kind of in passing. It was certainly not front of mind in the months and years leading up to the 1905 paper.

He might have known about it secondhand from reading through all the footnotes of Lorentz. But it's not something he seems to have been paying much attention to at all.

And so there's nice textual evidence even in Einstein's paper, that 1905 paper that I keep showing some brief excerpts from. Again, this is on the first or second page. When he's trying to reason why we should think about maybe giving up on the ether, he mentions-- without citing any of them-- he mentions several unsuccessful attempts to discover any motion of the Earth relative to the light medium, the ether. He doesn't say which ones he means.

But he actually then goes on to say in the same paragraph, none of these have found any deviation to first order in v over c. And what's so striking, as Holton reminds us, is Michelson-Morley was actually second order. Einstein seems to be talking about a whole different class of earlier experiments even before Michelson got in the game. He's certainly not obsessing over the Michelson-Morley interferometer the way other people were.

And so some people then read Holton's analysis to say a kind of overcorrection. Does that mean Einstein didn't care about any kinds of experiments at all? If he wasn't trying to respond directly to the Michelson-Morley experiment, was he just off in a kind of philosophical dream world?

And that's where I think we again can now say quite firmly no. In fact, it makes sense to go back to Einstein's own early years, his early fascination with electrotechnical gadgets, and remind ourselves what his day job was in the early 1900s, including 1905. Put him back in the patent office in Central Europe at this very specific moment.

So let's think about Einstein's favorite technology, trains. Trains and railroads themselves were actually fairly new in the 19th century. They were introduced to widespread commercial usage for commercial transportation really only in the 1830s and '40s.

Remember, Einstein was born in 1879. They were relatively new even in his childhood. During this whole time until very late in the 19th century, there were no coordinated time zones. There was nothing like Eastern Standard Time or Pacific Time or Central European Time.

Each town set its own local time. And all the residents could coordinate by agreeing that we'll use that clock tower, either some municipal building or often a tall church in the town square, say that's our local time. We'll set our local watches to when that clock chimes 12:00 noon.

So each town kept its own local time. And before railway, who would ever need anything else? Because one was rarely encountering more than one town in a given day. After the advent of railroads, you still have this local time. But that became more and more of a problem. It was true in North America as in Europe and other parts of the world, as well.

So here, closer to Boston, passengers riding on the train between Boston and New York during this time would have to change their watches by an average of 37 minutes. Today we're all in the same time zone. But that's how different the local variations tended to be just up and down the US portion of the mid-Atlantic seacoast and likewise throughout Europe.

That was becoming more and more of a problem when you have to coordinate lots of trains traveling across large distances. It wasn't only a problem for commercial railway or for shipping. It became a very potent, added challenge in Germany during Einstein's youth.

So again, as many of you may know, there only became one single country of Germany, a unified Germany, in 1871 following yet another war with France. That was basically the story of the previous 500 years, German-speaking lands fighting with French-speaking ones.

There was another one, the Franco-Prussian war, throughout 1870. The German-speaking folks prevailed. And it was at that moment, in the wake of that war, that there was then a first unification of a country of Germany, now a much larger expanse of what had otherwise been independent German-speaking territories.

So now there's an added reason to worry about trains that have to be coordinated across distances. There's now a new country's worth that has to defend its borders all the way from basically Poland or Russia on the East and France on the West.

And there's a famous quotation from a leading German general, Count von Moltke, who in the 1890s, 20 years into German unification, is basically saying, we have a problem on our hands. We have to coordinate trains for military purposes as well as commercial, passenger rail, and merchant shipping. We have a problem with the fact that we don't have unified time zones.

This is all happening in Einstein's childhood. Remember, Einstein was born in 1879, very early in this period of unified Germany and a new focus on coordinating clocks at a distance. So one of the main ideas that many clever people, inventors, came up with throughout Europe and other parts of the world, as well, was to try to coordinate clocks and therefore help coordinate train stations in these different cities.

Now, much of continental Europe was now being connected by rail. If the major hubs, if the major train stations could agree on the time, then you could set your watch then. And the trains could be better coordinated throughout even into the hinterlands.

And the main idea that many inventors and entrepreneurs kind of zeroed in on was to install these so-called [GERMAN] clocks, mother clocks, central clocks that you would say were the standard ones. And then connect those by electromagnetic signal, either telegraph or, increasingly, radio waves, literally traveling electromagnetic waves in the ether.

Some of you might know that the Eiffel Tower, which is under construction in just this period, was originally built to aid radio communication. It was a radio beacon before it was a reason for all of us to go visit Paris. There were other reasons before that.

The Eiffel Tower was built really in this period in large part to become a radio beacon to broadcast standardized time signals. And then the idea was you would know how far you were from Paris. You know there'd be some delay of when you'd expect to receive the radio beacon.

If it's 12:00 noon in Paris when that beam was sent, you have an offset based on how far away you are and the speed of light that it would take to get there. So then these very clever folks who make all these gadgets to both receive the time, either telegraph or radio wave, and then implement the offset and then reset the clock in your next train station clock and down the line.

So imagine these coordinated sets of coordinates where you have local clocks at every important location that are sending and receiving electromagnetic signals to coordinate the local time. That's exactly the scenario that Einstein mentions in the abstract in the opening pages of his 1905 paper.

He doesn't talk about these patent applications or about trains in this more practical way. But it turns out, as my friend Peter Galison shows in this beautiful book *Einstein's Clocks, Poincare's Maps,* this is the subject of an enormous tech spree. This was the tech challenge of the day for all these very smart, young electrical engineers to build up and patent every bit, every switch and gear, for this way of coordinating clocks at a distance often using electromagnetic signals.

Not only that, Einstein was at the electrotechnical part of the Bern patent office, where a lot of these were flowing through. So he was an examiner on many of the little widgets and gadgets as part of this clock-coordination sequence.

Even better, my favorite part of Peter's otherwise quite fascinating book, was that Peter and his research assistants pieced together the walk that Einstein used to take from his apartment to the office-- he had a lovely stroll through Bern during this time of his life-- and then finding out when each of the clocks along his route were wired up to this now coordinated system.

So literally the clocks that Einstein would walk past between his apartment and his office were in this exact moment being wired up in this new, explicit, electrotechnical clock coordination system, not just across distant train stations but soon even across the semi-urban regions where he lived. It was literally his day job and the path that he walked to get to work.

So this notion of using electromagnetic signals to coordinate clocks in a measurable, repeatable way was of philosophical interest. It was certainly inspired in part by the writing of Ernst Mach. But Einstein was also immersed in a different set of realities than someone like Hendrik Lorentz or the other Maxwellians.

And so when he comes to the question of electrodynamics of moving bodies, Einstein's immersed in different conversations and day-to-day questions compared to those of the physics elite of his day. So we come back to this very iconic but kind of unusual paper from 1905, "On the Electrodynamics of Moving Bodies." I think we can make a bit more sense of it, informed by work by people like Peter Galison.

Einstein's paper has almost no references. Much like many patent applications, you want to emphasize priority and downplay precedence. Einstein focuses on the operational details. How would you actually perform these measurements and compare the answers at some distance?

It starts to look sort of like a patent application, not like a fancy exercise in mathematical physics. So we can come back to this question of, why was Einstein doing things differently? And what was he up to? And we see him really enmeshed in just a different set of ideas, of philosophical conversations, of mathematical techniques, and also of actual gadgets compared to some of the other experts of his day.