[SQUEAKING] [RUSTLING] [CLICKING]

DAVID KAISER: Hi, everyone. Welcome back to 8225 STS 042. Any questions on, again, any kind of logistical stuff? If not, then I think we'll jump right in. So I'm going to go ahead and share screen. I'm eager to get into this next set of material together. So hopefully, you now see my shared screen. Nods or thumbs up, just to confirm? Looking good. Thanks, everyone. OK, great.

So today's lecture is still going to be situated pretty squarely in the late 19th century. We're going to pick up from where we were during the previous discussion. So as a reminder, the lecture today-- actually, unusual for me-- has four parts. Usually, my lectures have three parts. These will be four a little bit shorter parts. And we'll break for some questions and discussion between each of these.

Quick recap though of where we were last time-- so in the previous lecture, we looked at a few exemplars, pretty telling examples of the kinds of work that was coming together in the middle and late 19th century-- in that case, largely in Britain. We looked at people like Michael Faraday.

Faraday is fascinating for his personal story, his biography, but also for what he indicates in terms of what were the pressing questions for natural researchers in his day and what were the kinds of institutional arrangements. Where did he think it would make sense to get his work done? So we saw that he had very little formal education.

He was apprenticed at around age 13 to a bookbinder, and then later basically apprenticed in a new kind of position as a natural philosopher at this special kind of place called the Royal Institution, which, remember, was not a school or university. It did not have students enrolled. It was a place that fostered research and also a lot of what we might today call public outreach, public lectures, and so on.

So in Faraday's own case, we know he had many reasons to dig into the topics that he wound up studying throughout his life, one of which seems to have been inspired, at least in part, by his unusual religious faith. Remember, he was a Protestant, as we talked about last time, but not an Anglican, not a member of the official church of England. And so his Protestant sect was particularly fascinated by this interconversion, an underlying unity of nature.

And for Faraday, that reinforced an interest for him in studying how physical forces could change one into the other or different kinds of effects could impact each other-- electric and magnetic, electrolysis and chemical interactions, and so on. Now, as far as Faraday and really his entire generation was concerned, all of these interconvertible effects, all of these physical forces, were made possible because they were all seated in this all pervasive luminiferous ether.

We looked at this word last time. It's a great word-- lumen- coming from the Latin meaning light and -ferous meaning to carry, the light-bearing or light-carrying ether. So in the course of his investigations of this all pervasive, mechanical, elastic medium of the ether, Faraday introduced lines of force, and then developed from that this idea of fields, these fields that would characterize, as far as Faraday, was concerned the local state of the ether.

What were the stresses, or strains, or tensions in that elastic, bendable, flexible medium in this location at this time, in some other location at that time, at the first location at some later time? And so he introduced this notion of fields to help make sense of the underlying state of the ether.

And so instead of having this action at a distance, he was really emphasizing local effects. Local causes lead to local effects. And this is what we would now consider the birth of field theory. We use field theory all the time across physics, more than ever. It's coming really from work by people like Faraday, in their mind, to understand this particular, physical, real substance that filled the whole universe, as far as they were concerned, the ether.

OK. Then we looked last time at-- whoops, let's see. There we go. We looked at some of the folks who were coming downstream from Faraday, people like William Thomson, later Lord Kelvin, and James Clerk Maxwell. So they shared Faraday's fascination with electrical and magnetic effects. They shared Faraday's fascination with all pervasive ether.

They began to approach those questions with a somewhat different toolkit. So unlike Faraday, who had very little formal schooling beyond something like early middle school or junior high, Thompson and Maxwell became early graduates of this really new, fast-changing system centered largely at Cambridge University, but quickly became common elsewhere.

So by the middle decades of the 19th century, Thompson and Maxwell were approaching Faraday-type questions, but with a new set of tools-- highly mathematical, highly formal tools. And they were both fascinated by these mathematical analogies between electromagnetic phenomena and mechanics. And in fact, they articulated what we call the mechanical worldview. We'll see more examples of that today.

It was in the context of exactly that kind of study, in part because of the importance of things like telegraphy to the emerging British empire-- it was within that context that Maxwell was studying the way in which an all pervasive light-bearing ether would respond to kinds of disturbances. You tweak the ether here, how would that disturbance travel or spread throughout the ether.

And he came to the conclusion, as we saw at the very end of the previous lecture, that light was actually not related to but was, in fact, nothing other than these transverse undulations, a certain kind of wave of disturbance within the ether. The light, in particular, were waves of electric and magnetic fields as they propagated in that kind of mechanical elastic. That was just to get us back up to speed from where we were in the previous discussion.

So now, I want to talk about Maxwell's equations. In some sense, we know Maxwell's equations really well. We still learn them in high school, and college, and graduate school. They're incredibly important. But the way we manipulate them, how we actually handle these equations is-- I would say thank goodness-- pretty different from how Maxwell or Maxwell's immediate circle handled them.

So a lot of Maxwell's work that we remember and make most use of were results that he was working out in the 1850s and 1860s, pretty early in his career. As we saw briefly last time, he bundled all those results together in a very massive, two-volume book published in 1873, totaling about 900 pages between the two volumes called the *Treatise on Electricity and Magnetism.*

And in there is where he lays out a first principle description of electricity magnetism and even much of optics, given the fact that he had figured out or argued that light was nothing other than electromagnetic effects in the ether. So here's where he lays out, for his new readers, what we would now call Maxwell's equations. We had a little taste of that in the excerpt for the last class.

They look like this, this orange box here. They look horrifying, right? Imagine if you had to manipulate Maxwell's equations always in this full component form. As many, maybe all of you know by now, most of the central quantities in electromagnetism are vector quantities. They have both magnitude and direction. So we have to keep track of what's their component in the x direction, in the y direction, in the z direction, and so on.

And so they would write those out component by component. So just writing down things like what's the energy density stored in the field would take half a page. So it's only a later Maxwellian, in this case Oliver Heaviside, who actually invented vector notation precisely to make it easier to handle Maxwell's work. It wasn't to handle any old set of vectors. It was to handle Maxwell's work in this otherwise massive, back-breaking, 900-page treatise.

So nowadays, at the height of fashion, we can each proudly wear a t-shirt that has all of Maxwell's equations, only four lines, because we can use Heaviside's really quite efficient vector notation both to represent vector quantities, like the electric field and the magnetic field, but also these differential operators, like the divergence, the gradient, the curl, and so on.

These were literally invented to handle Maxwell's equations, so we wouldn't all have to do this horribleness for the rest of our lives. So if you proudly have a t-shirt with Maxwell's equations, you should thank Oliver Heaviside. It fits on one t-shirt because of his innovations.

Now, what's really fascinating to me, what I want to spend a little time on for this first part of the lecture, is not just that we now have a more efficient notation to handle vectors, but that what Maxwell's equations seem to mean to Maxwell and his immediate peers is really quite different from what we take those same equations to mean.

So for today's class, you had a reading, a portion of an article to read by the historian Jed Buchwald. That article was later incorporated into this really interesting book called *From Maxwell to Microphysics.* You see its cover shown right here. So I want to follow Jed's lead in walking through a few of these examples of just how different conceptually Maxwell and his immediate circle thought his own equations applied to the world compared to how we use those same equations.

We still buy the t-shirt. We think those equations mean something quite different today. I should say Jed Buchwald is a colleague of mine. He taught for many years here at MIT. He's now a professor at Caltech. But this is stuff that I think is really just amazing.

OK. So to us, Maxwell's equations describe the behavior of fundamental or elementary charged particles, things like electrons, or ions, or even protons, and quarks, and things we'll get to later in this term. So to us, Maxwell's equations talking about objects that have a fixed amount of electric charge that's stapled onto them, doesn't change.

Total electric charge is conserved. You can't change the overall amount of, say, plus or minus charge in the universe. You have a fixed amount of electric charge attached, a constant amount attached to each microscopic charge carrier, like an electron. We would say the charge on an electron is 1 unit. It doesn't later become 1.3 units on one electron. It's a fixed amount per fundamental charge.

And then electrical phenomena, like electric current, is nothing other than those little fundamental charge carriers moving around. So electric current, to us, is nothing but the motion of those elementary charge carriers or fundamental charge carriers. So we have very simple cartoons like this to make sense of things like charge and current.

To Maxwell and even to most of his followers for generations, not one part of that was true. I just want to let that sink in. We use his equations. We put them on our t-shirts. We wear them proudly. I wear them proudly. And yet, what we think those literally exact same equations refer to is almost 100% reversed from how Maxwell himself thought about them or how his peers and students did.

And if you pause for a moment, you say, well, it had to be that way. Some of you may know-- and we'll look at this in a few weeks if this is news to you-- the electron itself wasn't discovered-- or the experimental evidence that would come to be called the electron didn't even coalesce for about 20 years after Maxwell had published his treatise. He writes these 900 pages in 1873.

It's only in the early and mid-1890s, two decades later, that physicists start to have any kind of empirical evidence that something like an electron is part of the world. So the Maxwellians were not thinking about fundamental or elementary charges that zip around with fixed charge per particle. They were thinking about a continuum, as we've seen many times now, this elastic continuous medium of the light-bearing ether.

So Jed Buchwald calls the Maxwellians inverted atomists. So I think that's a pretty helpful term. They believed in things like chemical atoms. But they didn't believe that there were fundamental constituents that had unchanging properties. So as Jed nicely puts it, instead of building the world out of atoms the way we would imagine, the Maxwellians built atoms out of the world. And by the world, he really means this continuum, elastic medium of the ether.

So things like atoms or charges were coagulations of this more primary stuff, the ether. And that has implications for how they make sense of other electric and magnetic phenomena. So here's an example I want to just take a few moments to walk through that Jed talks about in that article, in fact in that first few pages of the article that I'd assigned for today's reading. It's pretty abstract. So I hope a few pictures might help a little bit.

And this is really just to give a flavor of how the Maxwellians made sense of these things. If every step of this discussion is hard to follow, that's OK. I just want to get across what they thought they were doing. It's more like how did they conceptualize things like charge and current.

So to the Maxwellians, charge could drift in and out of existence because it wasn't a fundamental property attached to fundamental particles. Instead, it was a kind of reflection of the underlying state of the ether. It was a local manifestation of these stresses or strains in the ether.

So to take one example, charge could arise, for example, as a surface effect-- not only this way, but this is one example and one that I think Jed treats pretty nicely, pretty helpfully in that article. So one way you might encounter electric charge building up, according to the Maxwellians, was if you had a change in two different kinds of materials near each other in space. It would be a kind of surface or boundary effect. Let's talk about what they meant by that.

Imagine you had these two conducting plates, these thick black lines on either side. And you put a voltage difference across them. You charge one up with a positive voltage and the other with a negative. So between them, you'd have some net voltage change between the two conducting plates.

So according to Maxwell and his circle, that meant that what you were really doing is putting this elastic ether under tension. The ether that would be in the space between those two plates would now be not at some resting or equilibrium state. You've put it under strain or tension.

In fact, fun fact, I believe it's the case to this day that the French word for voltage is actually tension, like tension. So it really was a notion that you were putting the physical medium under tension when you apply this voltage, this voltage difference.

So now, the potential energy stored in the ether-- I think about squeezing a spring, that mechanical ether. The rate at which that energy would be dissipated, would be relaxed, is controlled by the intervening stuff. So in this case, they imagined they had two different kinds of material filling this space between the two conducting plates that we'll just call the blue region and the green region.

And because they're different kinds of materials, they have different physical properties. In particular, they could store up and/or dissipate this local strain at different rates. This is, again, how the Maxwellians would have talked about it. So in the blue medium, they would have one characteristic elastic capacity. It's what we would call the dielectric constant. We would still use the same Greek letter, epsilon.

To them, it really was like a spring constant. How do you store up potential energy by putting that medium under a strain, like squeezing a spring or stretching a spring? So on the one hand, you have a how easy can you store the potential energy. And the other relevant constant, or characteristic of that material, they called the conducting capacity. We simply call it the conductivity. And we use, again, the same Greek letter, sigma.

And the point was, in these two different kinds of materials, they would have different properties. So the blue material has one characteristic elastic capacity, some other quantitative value for its conducting capacity-- epsilon 1 and sigma 1. And this green region, made of some other kind of stuff, would have different values for those two basically like spring constants.

So the rate at which the tension, the underlying tension of the ether, could be dissipated was a kind of competition between those effects. You store up tension and you dissipate it at different rates, given by, let's say, the ratio tau of that elastic capacity divided by its conducting capacity.

So then what happens at the boundaries-- now, you have different rates of dissipating this underlying tension. So you can build up a surface charge as a boundary effect, as a surface effect. So sure, electric charge could be very important. But it wasn't like vital. To the Maxwellians, it was a kind of accidental effect of the real physics, which you have on the elastic medium of the ether. And it can locally discharge or dissipate that tension at different rates given the material properties of the stuff that fills the region-- the blue region or the green region.

So the surface charge was not very important. It was ephemeral. At some function of time, it's going to float into or out of existence. And it really comes from more fundamental processes involving the ether. That's how they would have characterized it. So let me just say that we can see some similarities.

Perhaps the most important similarity is that for all using field theory, them and us. And we're using it, though the status of those fields is not quite the same. So it's not that quantum field theory is nothing other than a Maxwellian ether. It's certainly not that.

But the notion that there's a way of characterizing how things are spread out through space and changing over time, the basic field notion, that is quite common to how we organize our thoughts today, except that-- with the difference being, even in our modern view-- and again, we'll have chance to look at this in more detail in several weeks-- in our modern view the amount of, say, electric charge is fixed per particle associated with that field.

So we would say, there is a quantum field associated with the electron. And again, we'll come to this. If this is news, that's OK. We'll have time to look at it more carefully. There's a field spread out through space associated with the electron. But the individual particles, the electrons themselves, have a fixed and unchanging amount of charge nailed onto them, attached to them as part of their fundamental properties.

That part had no analogy for the Maxwellians. And I find that amazing. I find that really fascinating. So it's an excellent question. I'd be glad to chat more about it. But for now, let me pause and say some similarities and sense of a field physics, but this notion of fundamental charge carriers, that's actually a pretty important disanalogy.

And so in fact, that's part of what the slide is saying here, this updated slide, that we would describe these properties of these materials, like the blue material and the green material, that they're made up of fundamental objects like electrons, and protons, or even quarks, and so on that we could move around or rearrange those fundamental charge carriers. But we can't change the amount of charge per elementary particle.

We can change their arrangement. And we often call that polarizing them, changing their orientation with respect to each other. We can move around those fundamental charges. And these parameters, like epsilon and sigma that the Maxwellians considered like basic spring constants, to us, those are measures of how readily we can rearrange the fundamental charges. So they're characteristics of a material, but not a characteristic of the stresses in the underlying ether.

So for us, charge comes first-- elementary, unchanging, charge which is fixed to a particle. It never winks out of existence and so on. For the Maxwellians, charge was a secondary effect arising from the state of the medium, even though, as I keep saying, we use Maxwell's equations. We interpret his equations sometimes in really quite radically different ways.

So I'm going to wrap up the Maxwell part. And we'll pause for more questions in a moment. So as I've now emphasized a few times, we still use Maxwell's equations. We really use Oliver Heaviside's very efficient version of Maxwell's equations. So now, it fits on one t-shirt.

But the way we make sense of those is really almost a turned on its head compared to how Maxwell and, indeed, even Oliver Heaviside had interpreted them. And I find that just delicious. I think that's fantastic. We're going to come to that, by the way, many times this semester-- not only Maxwell versus us, Einstein, Heisenberg, you name it.

We're going to see where we use the same equations in many instances. And yet, how we make sense of them, what we think those equations tell us about the world, not fixed, and here's an early example of what's going to be actually a common trend throughout the term.

Moreover, for Maxwell much like for Faraday and for William Thomson, the ether came first. We saw a lot of that last time. Here's a few more examples even today. And they develop this mechanical worldview, that this is an elastic medium that we want to analyze-- basically, again, a set of stresses, strains, spring constant-type physics about putting this elastic medium under strain.

It's all about continuity. All of physics came down to the behavior of this evenly spread out elastic medium, which supports contiguous, like nearest neighbor local actions. No point particles-- remember, there's no such thing as the electron, as far as they were concerned, no fundamental charges, , all these time-varying states of the ether. So I'm going to pause there. I'll stop sharing screen, see if anyone else has any questions. That was a great question we had already. Any other thoughts on Maxwell?

Oh, and I see now in the chat Jade also posted an excellent point that, even in English let alone in French, we still call-- we still talk about high tension lines. That's a great example, Jade. I agree, good example. So our course 6 majors, are electrical engineers in particular, are probably not learning how to manipulate the ether. And yet, we're still using Maxwell's equations to do things like to manage things like high tension lines. Great example.

Any other questions on the Maxwell stuff? A momentary disturbance in the ether? There was a great disturbance in the force, we might say. So there was a local tension of the ether because we've acted on it. We've intervened on the ether, they would have said. Because we've set up this conducting plate, and that conducting plate, and probably some big fat chemical battery with big chunky wires, we've done stuff locally.

And we haven't done stuff only to an evacuated region. We're not doing this in a region where we sucked all the other stuff out. We're doing it in a region where it's filled with one kind of maybe rubbery substance or what we now call a dielectric material, like an insulating material, let's say, and some other material.

And so what happens at the boundaries between those materials? Because the ether is trying to dissipate that local tension, the ether is trying to get back to a kind of equilibrium state, you might say, and the rate at which it approaches equilibrium depends on the other stuff that's in that region, so to speak, on top of it.

So how quickly it can dissipate that local disturbance, that local tension, depends on what they would have called the elastic properties of the medium. Take all the stuff that's in that region of space, the ether and any other junk we've thrown on top of it, how quickly can that tension be relaxed? And we have different rates of trying to return to a kind of equilibrium based on these local spring constants.

I think that's right. To be honest, it gets complicated, confusing for me as well because I was trained much more like you than like them. But my best effort, led by scholars like Jed, my effort to get into their head is much more like what you described. There's a local disturbance in the state of the ether.

The ether can't instantly relax to its equilibrium configuration. The rate at which it does is this interplay between how efficiently can you store up the potential energy, and then a separate constant about how quickly you can release that stored tension. And it's that interplay that can be different in different regions of space because we've filled those regions with different kinds of materials. Those are excellent questions.

OK. Let me press on. Let's look at the next part. Right. Oh good, thank you. So again, great questions. So it was really in this time period that something like electrical engineer, as a job title, was just coming into its own, in fact really in the later part of the 19th century.

Maxwell, in fact, hints at that a little bit. If you remember, the preface to his massive treatise-- we had a little excerpt of that in the reading for the previous class. So even in 1873, he called them electricians. That was the word that was often used in English in, let's say, the 1870s and '80s. By the end of the century, the term electrical engineer itself would become more common even in English. But Maxwell talks about there's a demand for electricians. He really meant what we would now call electrical engineers, by and large.

There's a lot of really interesting historical work on sometimes the tensions-- not just the voltage, but the actual tensions between the academic, mathematically trained, natural philosophers, like Maxwell or Lord Kelvin and the electricians who, then as now, sometimes were in institutions of higher learning, sometimes were in private practice, sometimes were in the employment of the government.

And they didn't always agree on theoretical understandings. The electricians, or the engineers, often had, as far as they were concerned-- and they were usually right-- a much better understanding of how realistic materials behaved. What will be electric breakdown? Some dielectric materials really can't be loaded up with too much charge before things go haywire. So there was actually a lot given back and forth-- some of it quite friendly and constructive, some of it a bit of a rivalry.

Now, people like Maxwell and Lord Thompson in particular, some of these fancy university professor types, were actually working quite a lot on advisory boards for more practical engineering, especially around things like government-sponsored telegraphy-- not only that, but including that. The telegraph was a huge driver of this stuff because the British government really wanted to have efficient communication both with its colonies and even for worldwide commerce and so on.

So the priority of telegraphy among other things, soon would be things like street lighting-- we'll look at other examples-- these practical, real world needs for real electrical engineering would often bring together practical engineers, some of whom were trained in advanced mathematics, some of whom weren't, the university natural philosophers who had this mathematical training, and everything in between.

So they had opportunities to interact and learn from each other. And sometimes, then as now, the physicists would say, we understand this and you're all dopes. Some of you might have heard that even today. The engineers would say, we understand this. And you physicists are chasing ridiculous, unrealistic scenarios. That is also often said today and was said then, each of those statements often with good reason.

So if people are interested, some of my friends have written a lot about this. The short answer is there was a growing body of people who were professional engineers of electrical stuff, whether they were called electricians or electric engineers. That was changing.

There were reasons to incentivize getting more of those folks because the government wanted a lot of them. And there were opportunities to learn from each other, sometimes with great-- smoothly and sometimes with some real name calling. It's a good question. Any other questions on this part? Excellent questions.

OK. Let's go to the next part of the lecture. I hope you'll find this next part fun. I find this fantastic, I have to say. This next part is like crazy. OK, let's talk a bit more about how people like Maxwell, and Thompson, and indeed the Maxwellians, how they were encountering this material. For this part, I rely on one of my favorite books ever committed to print-- I'll go on record. I love this book-- called *Masters of Theory* by a colleague of mine named Andy Warwick.

We're going to have an excerpt from Andy's work a little later in the class. It's assigned a few weeks from now. But here's a preview of the kinds of things that Andy writes about in this really quite amazing, I think quite amazing, book. So we saw, of course, a reminder, Michael Faraday had this practical, very modest mathematical training, a little bit of geometry, but not much else.

And then we saw, by the middle decades of the 19th century, a really pretty significant shift in the training of people who cared about things like the states of the ether centered at Cambridge. One of the first things that begins to happen in the 1820s-- so basically, a little bit before William Thompson shows up as an undergraduate-- is a shift to paper. I want to let that settle in. It was weird to go to college and have to take notes on paper.

And that wasn't because they all had iPads, obviously, right? It was weird to use paper because until then, what you did was practiced oral disputation and not in English but, of course, obviously in Latin. What better way to prove your mastery of Euclidean geometry than to bring your own personal chalkboard, a slate, a little personal chalkboard a couple inches big with chalk, and a compass for drawing circles, and so on, and a ruler?

That's what you brought with yourself to your lectures on, let's say, Euclidean geometry. And then to show your mastery of it, you would have a dispute, like a debate, orally in Latin. You would actually debate against usually an instructor or sometimes a fellow student. I miss those days.

Anyway, so it was actually weird, starting in the 1820s and '30s, when they were then told to start showing up not just with their own personal chalkboard, but with paper. It was actually still relatively expensive. They would rewrite and rewrite on it. Paper eventually becomes less expensive and less of a foreign item for a college student's toolkit.

So over the 1830s, '40s, '50s, Cambridge starts going through this massive transformation in how they assess their students away from oral disputations in Latin and toward written exams on paper. In fact, the entire undergraduate study for a Cambridge undergraduate would culminate in a three-day written examination called the Mathematical Tripos.

And so instead of having this scene of people like a debate club about, say, geometry or any part of mathematics, it shifted to this. You sit quietly in a room. This part probably looks a little bit more familiar, like taking SATs or some of the exams today. You sit quietly in a room, working out on paper. Your written responses are then graded by the proctors. And that was how you showed your mastery or your accomplishment of the material.

Now, I made it sound like that might be familiar to us. We use paper. We take written exams not infrequently. I don't want to make this sound too familiar. What happened was a remarkable pendulum swing. So by the middle of the 19th century, it's not just that Cambridge students took this exam on paper. This was literally how they graduated from college.

To get your bachelor's degree in any subject that you were studying, whether you were a philosophy student, or a literature student, or history, or mathematics, or physics, you had to pass through this Mathematical Tripos exam. There wasn't a Literature Tripos exam. This was the only way to the exit door to get your degree from Cambridge University, whether you had actually studied mathematics or not.

It was a three-day exam. And in fact, your score on this one test-- not all your grades along the way, your score on this three-day written exam determined basically your graduation rank. So you go to college for a couple of years. You study a whole bunch of classes. You establish your ranking among all your peers on a three-day written exam in silence taken in the Senate House.

And if that's not bad enough, then they would publish the rank order in the national newspapers. So it's bad enough to have to worry about one high stakes test. It's like the definition of a high stakes test. But then everyone you ever knew and everyone your family ever knew would see just how well or, indeed, how poorly you had done.

So the very top scorers were called Wranglers. And the very top of the Wranglers was called the Senior Wrangler. That would be like any of the Wranglers with high honors, let's say, something like a magna cum laude and above or something like that or maybe cum laude. But the very top scorer, like the valedictorian, was called the Senior Wrangler.

And to show just how competitive this was, both William Thompson and James Clerk Maxwell were actually only Second Wranglers, which is still pretty good. They weren't even best in their class either of their graduating years. So as Andy charts in this really fascinating book, this is a massive overhaul in how Cambridge trained everyone at the undergraduate level. Everyone passed through this Mathematical Tripos.

Now, how would you do that? Very quickly, you would learn to do that not only by attending lectures, but by hiring a coach, a personal private coach. Why would they have used the word coach? Again, it puts us back in the mindset of the early and middle 19th century.

One of the newest and most fascinating technologies of the day was the railroad or the railway coach. This was just coming into common usage both in Britain, and in other places throughout Europe, and the United States, and elsewhere. In the 1820s and '30s, they were called coaches, these mechanized coaches.

The idea of your mathematics coach to help you get through the Mathematical Tripos exam was that, much like the railroad, the coach would literally transport you, the student, from one place to another at an unnatural, breakneck speed. So much like the railroad could go racing down the rails at speeds up to 20mph-- that wasn't very fast by our standards, but it seemed like lightning speed compared to horses.

The railway coaches could transport people from one place to their destination really fast. Your mathematics coach would ferry you along at breakneck speed from your entrance of your studies toward your destination, which was the Tripos exam and your graduation. So they began calling their personal tutors coaches in recognition of the railroad.

And here's one of the most successful of the later 19th century, Edward Routh, shown here with his-- I think that's Routh here, I think. They all look so similar-- with a bunch of his the pupils he was tutoring. Routh was not a professor at Cambridge. Routh was a former student who did very well on the Tripos exam, and then basically was hired out. So students would pay him directly, in addition to and separate from their university fees.

They would hire a personal private tutor. And he'd set them up to work in small groups or one on one. And they would work with Routh around the clock. Now, how would you maintain that kind of discipline and schedule? By a robust program of physical exercise and exertion, like famously rowing or punting on the Cam, if any of you been to visit Cambridge.

So there grows up not only a special kind of tutorial or coaching system, these coaches, but a whole associated kind of athletics program not for the joys of athletics, per se, but really to help you stay physically fit, so you can stay mentally fit, so you can spend all of your time preparing for the Mathematical Tripos exam.

So then they start to call their athletic tutors coaches, right? So why do we have football coaches today? Not just because of the railway but because of the Mathematical Tripos in 19th century Britain. I love that. So the coaching was really new. And it was set up as a para-university way of shuttling these young students all the way to extraordinary mathematical skill in a short time.

So here's an example. Again, I take it from Andy's book. He found some wonderful notes, and diaries, and correspondence from people who went through this system. Here's an example from someone named James Ward, who was a student preparing for the Tripos in the 1870s.

This is a set of rules that he'd written out in his diary that he and his roommates had agreed to. And see which parts of this you want to take up with your roommates once for all back on campus again. The rules were-- they all agreed to this. The entire rooming block agreed to this.

They would each be out of bed by 7:35. Or they could sleep in a bit more on Sundays. They would do five hours of work-- and that meant mathematics work, mathematics problem sets, before lunch. So you get up early and do five hours of math before lunch. So far, I'm interested.

You do at least one hour of athletic exercise after lunch, like rowing. That's to basically help clear your mind, make sure you're ready for more math. Three hours more of math problem sets after that. Finish by 11:00 PM. Be in bed sharply by 11:30 because, the next day, you've got more math to do. And you can stay up a little bit later on Saturday.

Here's the best part. You start paying in fines if you break the rules into a collective little pot of money within the rooming group. So if you break these rules, you have to start paying 3-- I remember that's 3 quid or what it is, but 3 pocket change for the first rule broken on any given day, a little bit more for every other rule broken on the same day.

Now, it gets even more fun. You get paid out of that fund, that roommate kitty jar. You get paid out of that if you wake up your roommates extra early. Can you imagine your roommates being incentivized to wake you up at 6:30 instead of 7:30 so you could get more math done? You'd be so grateful to them that they would get money out of this common little bit of cash.

Any work that you do before 8:00 AM would count toward these other ones. So if you get up extra early and you do work even before 8:00, you can work a little bit less after lunch, for example. You get a little credit for time spent in church society meetings. I love that. And these rules are binding until further notice. I just think that's great. So these are on the slides. You can download those. If you want to set up similar rules with your roommates, I encourage you to.

Now, what do you do if you take all the smart, smart, smarty pants at Cambridge University and put them through this where the only way they can graduate, no matter what subject they're actually trying to major in or study-- the only way they can graduate is by passing through this single Mathematical Tripos exam? What happens if you do that for a few generations?

And I want to just let this sink in for a moment as well. What they would do on this timed exam, a three-day written exam is solved basically a lot of pretty increasingly hard math problems, math and physics problems. So an example that would be a warm-up that they would learn to do very quickly with their private coaches would be how to solve for the motion, say, of a pendulum that's swinging, if you neglect air resistance and it swings with a small amplitude.

Then as now, we would recognize that the pendulum, if it has a fixed length, capital L, this is what we would call a natural frequency. What's its natural rate of swinging back and forth once we displace it from its equilibrium position and let it just gently swing back and forth? It has a frequency to execute its oscillations.

And in fact, this is an example of a simple harmonic oscillator. There's a very simple equation we can write for the change of, let's say, the height of the pendulum bob above its resting position. We can characterize the height above its equilibrium spot as some amplitude phi.

How will that amplitude of the height change over time? It depends on this natural frequency. And we all know on this call that we can solve this very quickly as a series of sines and cosines. It will oscillate periodically like sines and cosines. OK. What if the length of the pendulum is changing over time?

So now, instead of a pendulum of fixed length, the length itself is raising and-- getting longer and shorter. So this distance changes over time. Well now, it's not actually quite so straightforward. It's no longer a simple harmonic oscillator. Let's assume that the length of the pendulum itself changes periodically, maybe with some distinct period from what would have been the average period of motion.

So now, we're solving a different differential equation. If this is unfamiliar to you, good. That means you've led a healthy and productive life to date. This is the thing that the Cambridge students would learn with their private coaches because they would face these problems on a timed exam that determined their graduation honors.

If you have a pendulum of periodically varying length, then the same problem to solve-- how can we characterize the height at any given moment-- that becomes not the equation for a simple harmonic oscillator, but what's called the Mathieu equation, which miraculously can be solved analytically in closed form. It's kind of amazing. But it doesn't look just like sines and cosines.

And in fact, thanks to modern day computers, we can solve this pretty quickly. And it has much more complicated behavior. Instead of only a simple kind of rocking back and forth like sines and cosines, it has these periodic functions where the period is actually determined by the period at which the length is changing, and then these exponential terms-- sorry, the exponential terms which can lead either to more complicated rocking back and forth or, in fact, could lead to instabilities.

You could have runaway solutions and so on, if these factors, mu, in fact are real and not only imaginary. Complicated, complicated pendulum. We don't have to solve this problem on a timed exam. I emphasize this to show this is the kind of thing you would hire a coach to help you get really good at.

Starting from when you entered as an 18-year-old to when you faced this exit exam, the Tripos, you would learn to solve problems like this in closed form, and then solve 200 more of them on a timed exam over three days. And if you didn't do well, everyone would see just how poorly you did because they'd print the results in the national newspapers.

Now, this came home to me rather viscerally when I was doing my own physics dissertation some years ago. To help the coaches and the students get good at this stuff, there were books written by especially successful coaches that the other coaches would use. And you just practice. It was like compendia of worked examples to help you practice like a practice exam because you'd be facing the Tripos.

And you can see, they would label which Tripos this exact problem had already appeared upon. So you want to make sure you're practicing on realistic Tripos problems. This book was first published in 1902, but drawing on examples from Tripos problems throughout the 1890s.

These are all, in this case, manipulating something called the Weierstrass function, the Weierstrass polynomial, which is one of the things it turns up when you start solving these complicated pendulum problems. So you want to get good at solving them fast, learn the tricks to do a coordinate transformation or see, oh, I've seen that form before. I know what to do next.

Well, before I knew about the Tripos and before I knew about these coaching books, I was also trying to solve problems involving coupled oscillators that changed their fundamental frequency over time. In this case, I was studying the early universe for my PhD dissertation.

And I actually reinvented or rediscovered a lot of these quite amazing analytic techniques, where you can solve for what are essentially coupled pendula, where they can change their length that determines the rate at which one elementary particle can decay into another. And it starts looking just like these coupled oscillator equations.

And you solve them with things like the Weierstrass polynomials. I spent 6, or 7, or probably 8 months beating my head against this trying to solve things like the Mathieu equation and the Lame equation in closed form. It was seen as sufficiently original to warrant publication in the *Physical Review* in 1897.

Then I met my pal, Andy Warwick. He said, oh, that was literally a homework problem for undergraduates in 1897. And so that's when it came home to me that this was basically child abuse. Let's just be clear. What Cambridge was doing was an extraordinary effort to train people in ways that look familiar to us-- timed exams, written paper problem sets-- but are actually not quite what we do either.

So I learned myself the hard way-- months and months, not three days on a timed exam-- just what these undergraduates were capable of doing by the end of the 19th century. So this intense mathematical training, I want to emphasize, was not only for people who liked it. This was the only way to the exit door.

Every single Cambridge student, throughout much of the 19th century, if they wanted to get their bachelor's degree in theology, in philosophy, in history, in mathematics, everyone took this Mathematical Tripos exam. Why would you ever do that to people? Again, it's an indication of the setting in which this was being done in this rapidly changing British empire. So the empire had a great need for what they considered disciplined thinkers, civil servants.

And the thinking was, if you could master things like these crazy oscillator equations on a timed exam, if you could develop the mental discipline and the full-body discipline to keep yourself going for years at a time to conquer these very complicated analytic math problems, then they hoped you could conquer anything in economics, in government, in logistics, any kind of bureaucracy.

This was seen as a particularly efficient way to train civil servants to handle the empire. And so as a size effect, not because this was the goal-- but as a side effect of doing this generation after generation for decades, a critical mass grew of people who went through this Tripos training and actually liked it, actually wanted to use those techniques to further their understanding of nature, like the Maxwellians, like Maxwell himself, and then indeed the generations who studied things like Maxwell's treatise.

So the people who were experts in things like the divergence, and gradient, and curl, and all these great techniques for electromagnetism, they were coming out of this training not because Cambridge wanted to make more experts necessarily in mathematical physics, but because some small portion of folks who went through this increasingly common system wanted to use those skills for what we would call scientific research.

And so the professionalization of this mathematically trained cohort was driven in part by demands of empire, both supplying research problems, like telegraphy or other problems in practical impact of electricity, magnetism, and optics, and also prioritizing this very specific kind of elite educational infrastructure. So let me pause there. Let's get some questions on that.

Let's see. I see one of the questions was, who wrote the exams? Good. So the exams were usually written by the faculty in mathematics and physics, most of whom, at this point, had themselves gone through Cambridge. But the people writing the manuals, the help manuals, were usually recent students who had done very well.

If you were a Wrangler, let alone a Senior Wrangler-- if you were in the Wrangler group, if you had high honors, then you could basically name your price. If you wanted to hang around Cambridge, you could literally make a career collecting direct student fees a dozen or so at a time and coaching these younger students through because you proved you could do it. And then you would sometimes write your own book and get royalties and sale of your training manual.

So the exams themselves were the provenance of the faculty. But all the associated pedagogical materials-- the training manuals, the homework sets, and all that-- those were developed often by these private coaches. Let's see. Another meme on the way. I want to see the meme.

Another question is, prior to the Tripos, had university education always been evaluated by oral disputation? By and large, or at least that was the main pattern-- not only at Cambridge, but including at Cambridge. And that goes back really to the earliest universities in Europe. There's, again, some marvelous historical work by other colleagues going back to the Middle Ages.

Some of you may know Oxford was the first University in England. But that wasn't even the first in Europe, let alone other parts of the world. Oxford was founded in, roughly speaking, 1100. Cambridge was founded about a century later in around 1209. So these predate James Clerk Maxwell by centuries, by half a millennium.

And for most of that time, indeed, the way of showing your command of the material was like jousting. It was oral disputes. And think about what kind of student, what kind of skills that kind of accentuates. It's kind of like-- I mean, if you speak a little disparagingly, it's like finishing school. It's like charm school, right?

You want to be very quick on your feet. And you want to be persuasive in oral discussion. Those aren't bad skills to have. They're quite different skills than getting up at 6:30 to do really hard math problem sets till lunch so that three years later you can solve the Mathieu you equation among 200 questions on a timed exam.

So what kinds of skills are deemed most important, those aren't static. They change. They change at MIT. We go through curriculum reform, at least to some small degree, all the time. And I just find that particular transition from the oral disputations in Latin to these paper-based problem sets-- I just find that fascinating. Let's see, other questions in here.

Did it affect what people chose to study? Oh, that's interesting. I'm not sure. The question is-- you can probably see in the chat-- did the Tripos exam and the esteem that came with scoring well affect what people chose to study? I don't know actually how the system had to work. I'm not sure if then, in 1850 let's say, if an undergraduate had to declare a major the way we would have to do in our modern universities.

And if so, if there's information on how many students declared majors in history, or law, or medicine, or philology, and so on. So I'm not sure what the impact was on the distribution of topics studied. It's really interesting. Any would know. I should just ask Andy Warwick.

What I find most striking is that even though there existed, then as now even at the time, many fields of study, or many kinds of fields to delve into more and more deeply, the only graduation requirement was the Math Tripos. I mean, that's just astonishing. Imagine if we tried that at MIT, right? I mean, sure, you can go major in political science or, heaven forbid, biology.

But you have to take the Math Tripos to get out of MIT. Can you imagine the pushback? So that I find really stunning. And I think that the idea was really-- this is demonstrating a disciplined mind, according to what they considered valuable for discipline in general, but in the context of the still expanding British empire.

What happened afterwards? Good. So there was beginning, in this part, in the second part of the 19th century-- there was beginning of fellowships, where if you scored-- especially if you scored very well, if you were a Senior Wrangler, really among the top Wranglers, you would then qualify-- basically get paid to get a fellowship to stay in Cambridge and not only to do so by collecting your own student fees as a coach.

So it wasn't quite a tenure track position. Sometimes, if you did well on your fellowship, then you'd get hired. There was not yet a formal program of PhDs. That's really getting introduced in the very, very close of the 19th century. And that gets more common by the 1890s and forward.

So there was something like a master's degree. And that, in fact, goes back quite a ways. You can get a bachelor's degree, and then get a fellowship, and then have a career at a university. Sometimes, you can get a master's, and then get hired to stay on the faculty or do other kinds of jobs. And then the more formal graduate training leading to a terminal doctoral degree, that gets built up really over the 1880s, but accelerating over the 1890s.

What did pre-university maths education look like? Oh, that's a good question. It was changing slowly. Again, Andy writes about this a bit in his book. A number of the graduates of Cambridge became secondary school teachers as well as tutors and so on. So you see a dispersion effect, where people who have imbibed this program-- gotten drunk on Math Tripos-- some of them do fan out and become very influential high school teachers.

And they bring an appropriate level-- they're not doing Tripos problems, per se. But they bring a more formal schooling in mathematical analysis into other parts of Britain. And it's not only happening in Britain. But there's a cool story to be told there. So it does trickle out. Not overnight, but you do see a kind of spillover effect, again, measured over, say, a few decades, not quite in William Thompson's day-- not in the 1840s, but by the 1860s, 1870s.

And what happens is you can start comparing Tripos exams from the 1840s to the 1890s. You see an extraordinary acceleration of what's expected of these students in still just only three years of undergraduate training. And that's what people like Andy have looked at in detail.

What becomes like a really hard Tripos problem in 1850 becomes a kind of trivial one by 1880 because all the kids have come in and have already trained on those. And so the acceleration of what counts as a legitimate problem is mind-boggling. And again, I love showing that comparison to Weierstrass polynomials of like undergraduates who were doing pretty well in 1890 and me struggling my tail off for months, not for hours, to reproduce what they had learned to do just to get out of college.

So you can imagine, if you build up a community that's used to that, that leads to a certain kind of question. One of the things that Andy does so nicely in the book is then show that how does that then impact on how that group framed their own research questions. When they wanted to ask more about the ether, they were starting from that toolkit. And that affected, as we'll see-- a little preview-- that affected how they made sense of other new work, like Einstein's work on relativity.

That's the piece that I signed from Andy for a few weeks from now. So when they encountered creative work from other scholars in other parts of the world, they would make sense of it from that toolkit. Oh, I how can I bring my tools to that cool set of questions? So it shapes what even counts as a research question.

Let me move on from here. These are great questions. And I'd be glad to chat more about them. But there's a little bit more I want to get through for today's lecture because other countries-- we're going to leave Britain, at least temporarily. And let's start looking at some contrasting developments around the same time, but now on the continent.

So Maxwell's work became popular not only in Britain, not only in the Cambridge circle, but pretty quickly on the continent as well, especially in the later 1880s. Remember, his treatise was published in 1873. Roughly 15 years later, it was becoming much, much more common to be taught and talked about in places like the German states-- Austria, Switzerland, and France, and so on.

One of the things that helped a lot was in 1888, 15 years later, a German natural researcher, Heinrich Hertz, actually succeeded in testing one of the key predictions from Maxwell's work, that these Maxwell waves, that we would now call electromagnetic radiation, could be disturbances in the ether with any kind of characteristic wavelength, not only within the visible spectrum to which our eyes are sensitive.

So in modern terms, what Hertz did was generate and then detect radial waves. He was making Maxwell waves, a kind of disturbance in the ether, but with a much, much longer characteristic wavelength. And that was what Maxwell said should be possible. Hertz was among the first to demonstrate that empirically. And that really drove a lot of interest in this Maxwellian electrodynamics in the 1880s and beyond.

What's really fascinating though, coming back to this theme that we've seen a few times and we'll see again, is that when these German scholars, mostly in Germany, began manipulating Maxwell's equations or their slight variations, they did so, again, by making sense of them in a different way. Even when they used the same equations, the way they interpreted them was not really always the same as Maxwell's.

And here in particular, instead of following the characteristically British approach to thinking about this mechanical, elastic ether, like Lord Kelvin instructed his listeners-- stick your hand in a pot of jelly and shake it around-- instead of that, a growing number of the German electromagnetic experts began turning that on its head.

They would use Maxwell's equations, but to argue that, in fact, the world is made of electromagnetism and mechanics is the after-effect. It was another wonderful inversion not just between how we use Maxwell's equations and them, a kind of distinction over time, but even at one moment in time a distinction across space. So I want to sit just a little bit with these characteristic German approaches-- again, to get the contrast in how the same equations could be interpreted somewhat differently.

So here's a quick example about the origin of mass. So instead of assuming that objects just have some mass based on their mechanical composition, a growing number of these scholars in Germany asked, what if mass itself-- this prototypical mechanical property, what if that was an effect of something even more primary, like electromagnetism? So let's start with a quick analogy.

Imagine you're trying to drag a beach ball under water. So think about hydrogen dynamics. We could describe the kinetic energy of that system. We'll call the kinetic energy T. If the beach ball has a mass outside of the medium, some m0, we drag it with some speed, v, outside the medium, we could very easily write down the kinetic energy for that object-- 1/2 m0 v squared.

We just say the ball has a mass. It's moving at some velocity whose magnitude or speed is v. Kinetic energy-- 1/2 mv squared. We can actually describe the kinetic energy of the combined system when the ball is within the medium, when it's underwater, for an incompressible fluid like water, by using an effective mass.

We still have an expression that looks like 1/2 mv squared. But we adjust what we mean by m. We take into account the mass of the displaced fluid, in this case. But otherwise, the form of the equation is actually still quite tidy. It's still 1/2 mv squared. And we adjust the m to take into account that this ball is displacing some of the fluid. So its motion, its resistance to change in its motion, like its mass, is different from what it would be outside the medium.

So a number of scholars who focused on electromagnetism in the 1880s and '90s in Germany said, well, what if that's a useful analogy for what happens with electric charges? So imagine the motion of a single object that has some charge Q, some electric charge. By virtue of having some electric charge, it necessarily is creating an electric field, some disturbance in the local ether.

Moreover, if that charge is moving with some velocity, it is by necessity generating some magnetic effects. There is an induced magnetic field from a charge in motion. And there is an electric field associated with the electric charge, even if it's at rest. So electric and magnetic fields will affect the motion of an object with electric charge.

So the question was to consider what we might now call the back-reaction or the self-field effects. How can we characterize the motion of an electric charge in its own electric and magnetic fields-- not external fields that we host separately, but by virtue of the fact that an electric an object with some electric charge by necessity creates an electric and a magnetic field if it's moving? And those should act back on its own motion.

So you could consider something like the Lorentz force law. The force, therefore the changes in that charged object's motion, will be due to the electric field and its velocity cross-product into the magnetic field. Now, what if these are the self-fields of that charged object? You can do the same, trick they found quite cleverly.

You can still characterize the kinetic energy of that system as 1/2 mv squared. Just like that beach ball underwater, we make an effective mass. We take into account the extra mass that comes from these field effects that will impact how quickly that charged object would change its motion due to a different imposed force. That's why the mass is a measure of its resistance to changes its motion.

It's just 1/2 mv squared. And there's a different expression for the effective mass that comes uniquely from this kind of back-reaction of its self-fields. And the calculator is a tour de force. You can calculate it based on the properties of that system.

Unlike the beach ball underwater though-- this is the next step that many of them took-- the electric charge can never be taken outside of this medium. You can't turn off its own electric field if it still has some electric charge. If it's moving, you can't stop it from generating some magnetic field.

So unlike the beach ball, you can never take this electric charge out of this medium of these self-fields. As a next step they take, what if there is no mechanical mass? What if this what we might call a bare mass or mechanical mass vanished? What if all mass always arose from these electromagnetic effects? That's what I mean by them turning it on its head.

So all of mechanics, in their estimation, might arise from these complicated effects of electric and magnetic fields, including the self-fields from these objects skittering through space on their own. So one of the very influential proponents of this view, Wilhelm Wien, announced, in 1900, this presents the possibility of an electromagnetic foundation for mechanics. This, again, became known as an electromagnetic worldview.

And I hope you can see that's a kind of inversion from the British mechanical worldview, where all the electromagnetic effects the British folks often were convinced arose from mechanical stresses and strains. Now, a number of these German scholars said, what if actually mechanics, like F equals ma, is actually coming from electromagnetism? So I'm going to pause there. Again, I'll stop sharing screen, just to give a quick taste for how, even in their own day, Maxwell's equations, again, could inspire other interpretations, even when they use the same equations. Any questions on that stuff?

OK. If other questions come up, feel free to put them in the chat or raise your hand. But if not, I'll press on. The last main section for the lecture, almost done. For the last part, I want to get back to some of the institutional questions. Where were some of these German scholars doing their work and why?

So we're going to have another contrast, German and Britain, not only conceptually, but now also in terms of the types of places and the types of priorities in which these folks were conducting their research. So the last main part for today is now this question about institutions.

So what does it mean to have a job title theoretical physicist? When does that become something that people could aspire to, let alone get paid to do? It's not in the age of Galileo or Newton. So some of the folks whose work we would inherit, we would consider part of the theoretical physics legacy was done by people who were never in their own time called something theoretical physicist.

In their own time, in the early and even through the late 1600s, these folks were either called mathematician-- that was a term that's recognized-- or philosopher, or more broadly natural philosopher, as we saw. So the Galileo, Newton, 17th century stuff, there just simply did not exist a person whose job title was theoretical physicist.

OK. Let's move forward in time. What, about in the 18th century? People like Lagrange, or Laplace, or Euler, or any of these other folks whose work we still use so much today? Again, they were doing work that we have folded into the activity of theoretical physics. We couldn't do our work without them, thinking about lagrangians, for those of you who've seen it, or the laplacian operator.

We use their work all the time in theoretical physics. They were, again, called mathematicians or often astronomers. Now, that term was often now in common usage. They were not called theoretical physicists. What about someone like James Clerk Maxwell now by the mid to late 19th century, during the period we've been focusing on in this class so far?

By Maxwell's day, the term physicist had become much more common. That was a kind of job title, not theoretical physicist. And indeed, still natural philosopher was not uncommon either. So a lot of the work that we would recognize as core to the job of a theoretical physicist, to the toolkit, was done by people who did not have that job title and would not probably have even recognized it in their day.

The term and the associated role in society of theoretical physicists comes out of a very particular moment in the middle decades of the 19th century, that same period of these reforms at Cambridge, and these cool things with radial waves, and all that. And here, it really comes out of the German system.

So take just a few moments to think about this very unusual and, let's say, peculiar German university system. And here, I'm drawing especially on the work by a pair of historians. They wrote another two-volume book. This one is only about 600 pages altogether, not 900 pages, a quite fascinating book by Christa Jungnickel and Russell McCormmach.

So one thing to keep in mind is especially after Germany became one unified country in 1871, there was a central education ministry. So within the entire country, there was one basically central government bureau that assigned all the senior professors in every field, in every university, a central bureau that doled out or made the assignments for who would be the full professor in the field of physics, or philosophy, or history, or theology, or chemistry, or anything.

Moreover, in each of these universities, there was one full professor who was called the ordinarius professor in a given field. So it would be one full professor of physics at, say, Wurzburg University. There'd be one full, or ordinarius, professor of physics in Berlin, and so on, assigned by the central bureau, one full professor per subject per university.

In the case of physics, the ordinarius, or the single full professor, was in charge of all the apparatus in the department, all the experimental work. Here's an example of Wilhelm Rankin's laboratory in the 1890s, for example. Rankin was the ordinarius. This stuff was often treated as if it was the personal property of that one head professor. This was basically Rankin's property until Rankin retired or died. And then it would bequeathed to the next ordinarius professor of physics.

So the one head full professor was in charge of all the experimental equipment. What it meant to be a physics professor was to be an experimental physicist. And the way you demonstrated that was by being the ordinarius in charge of all the equipment. After Germany became one unified country, after its war with France, the country really accelerated a very rapid period of industrialization, very large scale industrialization.

They thought they were behind both Britain and France. They began investing very heavily in what we might consider many areas of engineering. For that, they needed a large, large number of physics teachers-- not only for universities, but especially for things like the high schools. They needed many folks who could go into and help design and improve these massive public works projects. They needed lots and lots of people who could teach physics at the high school level.

So the classrooms grow very rapidly. So then you have to hire lots of people to teach all those would-be high school teachers. So there's a huge growth at the universities throughout Germany in extra faculty. They were called extraordinarius not because they were extraordinary. It's like a false cognate. These were extra, in addition to, the ordinarius. So these were lower rank. These were like junior faculty in our modern parlance. They were not tenured, many of them. They certainly were not the single full professor.

You staff up lots of extra to the ordinarius, lots of junior faculty at universities to teach lots of physics because you need to get lots of high school teachers who could teach even more people basic physics, math, and even engineering. Now, these younger faculty, these extraordinarius faculty, only have access to pencil and paper. They're not in charge of the equipment. They're not the ordinarius. It's not their personal property.

So all they can do is push pencils around on paper. Here's an example of one of them at one stage in his career, Einstein, a person we'll spend quite a bit of time talking about. Well before Einstein was scribbling in his Zurich notebook in 1912, really starting in earnest in the 1850s, '60s, and '70s, you have lots and lots of people who are now joining the faculty ranks at this lower level, this extraordinarius level.

They don't have access, in general, to the experimental equipment, unless they're in the good graces of the full professor. They can't control it. So they spend most of their time in research doing pencil and paper work, mathematical work. Once you build up lots of folks who have done that for one or two generations, there becomes a kind of norm. There becomes a kind of community that's really good at mathematical or theoretical physics.

It starts sounding like the Cambridge story. If you push lots of people through the Mathematical Tripos, some portion will get very good at mathematical analysis for physics. A similar thing for different reasons is happening around the same time, especially in the united German university systems now because this quirky university structure, where you have a very tightly controlled, full professor rank.

You have extraordinary people who can't do as much experimental work as they might like. But they get really good at showing their own command of theoretical physics because they spend all their time with pencil and paper. So only by the end of that 19th century do some universities begin to recognize this is now a new thing. And there are finally ordinarius professorships, full professorships made for theoretical physics.

So increasing numbers of universities within this German system would then have two full professors of physics-- the ordinarius in charge of the experimental work and now a second ordinarius in charge of theoretical physics. The very first to be assigned to in that role was Gustav Kirchhoff, whose work is still well-known to us from things like thermodynamics and statistical physics.

A few years later, Max Planck became one of the earliest ordinarius professors of theoretical physics in Berlin. They start their own journals because there's now a kind of specialty community, their own editors of their specialist journals. So again, we start getting a job title of theoretical physics not because there's an aim to make let's make more theoretical physicists. There's an aim, in the German case, to have a very rapid acceleration of nationwide industrialization.

And partly how that plays out, in this very unusual university system, is to bloat the early or middle ranks of faculty. And that diverts them, more often than not, to one kind of research rather than another. Do that after a while, and there coalesces a recognized set of standards and even a kind of job title for the strange thing called a theoretical physicist.

Now, the last few slides to wrap up, then we'll have time for some more questions. So in place of this British empire building as one of the main roots to building up this community of mathematically trained mathematical or theoretical physicists-- we think about that Tripos exam-- in the newly unified country of Germany, the field of theoretical physics takes root in a pretty different context. The timing is similar. But the drivers are actually a bit different.

There's this very centrally controlled university system, very tight limit on the highest ranking positions. And for the field of physics in particular, the ordinarius, or full professors, was coextensive with experimental physics. That's what it meant to be a physics professor.

Changing industrialization changes the priorities. You need lots of people who can do at least rudimentary physics and mathematics to help with their engineering. You need lots of people who can teach them in high schools. Therefore, you need lots of people who can teach the teachers at the universities, and so on.

So within a generation or two, you create this spillover effect, where you have ordinary professors, and journals, and specialists in this new thing called theoretical physics. Why do I emphasize all that? Because it's in that very particular institutional context, within Germany in the later decades of the 1800s and early 20th century, that's where a lot of the stuff that we're sitting with for the next few weeks of our class, the emergence of what we come to call modern physics, like relativity and quantum theory-- a lot of that is being crafted in that particular institutional context.

We want to understand why there was suddenly an ordinarius chair in theoretical physics in Berlin and so on. So I just want to give us an indication that theoretical physics intellectually has a many centuries lineage. We can trace back why we still use the Galilean transformations or Newton's laws. And yet, the job title, or the description, of the theoretical physicist is actually much more recent vintage. So I'll stop my screen sharing there. We have a couple of minutes for some questions, if people have other questions on that.

Great question. Thank you, Fisher. So you're very much correct. There was a lot of tension factors. Of course, we now know what's on the horizon-- the First World War. And of course, there were many, many quite bloody skirmishes and wars even before that.

So on the one hand, there was a lot of nation-based rivalry. The Germans looked over their shoulders, the German bureaucrats at least, German government officials, and were scared out of their wits that they beat the French in 1870, '71, but they'll lose the next time. Or the British Navy is second to none. So they're always comparing themselves in terms of industrial output and military strength, mostly in this period with Britain and France, also increasingly Russia and other neighbors.

So there's a lot of the rivalry. That spills over not infrequently among the scientists. This is also, however, the first period of international scientific conferences. The natural researchers, the professional researchers, starting in the 1870s, would begin to meet once a year, or twice, or three times a year for conferences in what we would now consider quite familiar. That was new, mostly in the 1870s.

They would work out things like nomenclature. That's why so many things were actually still named in Latin, even though no one was speaking Latin. They wanted to find some way to share ideas and terms for things and work it out. So it was sometimes a kind of friendly rivalry. Sometimes, it wasn't so friendly.

So you see elements of both. And you're quite right, Fisher, this was becoming not uncommon. And we'll see this really literally explode in ways that matter even to us, when we think about the history of physics, narrowly, let alone world history. It really becomes a tinderbox right around 1900 thereafter. That's a great question. Any other questions?

I'm running a little bit late. I know some of you might have to run off to a 2:30 class. So I'll stop there. Great questions and discussion. And I'll see you on Wednesday. And stay tuned. We'll post the paper 1 assignment real soon. Stay well, everyone.