[SQUEAKING] [RUSTLING] [CLICKING]

DAVID KAISER: OK. Welcome everyone. Welcome back to 8225, which is also STS 042, Physics in the 20th Century. Let me start by asking just quickly if there are any logistical questions, any kind of course structure or other questions like that we can try to clear up quickly. And then we'll jump into the first main lecture.

In general, it's good to do the readings, at least to skim the more technical readings before the assigned class. So for today, that was a brief excerpt from Maxwell's treatise on electricity and magnetism, for example, and a chapter from Bruce Hunt's book on the Maxwellians. So in general, it'll be helpful if you keep up-- if students keep up with the readings because it's just going to snowball.

Otherwise, some of the readings, as you probably have noted with the Maxwell in particular, are pretty-- they're not exactly a page turning novel, right? What's going on with that. So I'm going to be talking about what Maxwell thought he was doing, what some of Maxwell's contemporaries-- how they read that book in today's lecture. So today hopefully will exemplify the kind of use to make of readings like that, as we go through the first worked example with Maxwell today.

Other readings, as you'll see, like the chapter from Bruce Hunt for this week, are by physicists, or historians, or sociologists, or other more recent scholars trying to help us make sense of that older work. And for those, I think it does make sense to read them a bit more closely. What's the actual argument the author is making? What are the kinds of evidence that the author brings to bear?

Because what we'll work on together over the course of the semester is actually working on your own written essays, your own analyses, where you will-- we'll help you build up toward it. But you'll be working on articulating an argument, defending that argument with evidence and examples from various sources.

The readings that we would call a secondary source, readings by historians, or more recent physicists, or philosophers, or sociologists, or journalists, or whomever, those are more like the kinds of writings we're going to try to do ourselves over the course of the term. And plus, I think, hopefully they're interesting. I chose them very carefully.

So I do recommend you try to read those a bit differently, let's say, than something like skimming over Maxwell's treatise, which might look both pretty bland, and weird, and a little unusual, given how we do things today. So there are different ways to read the different kinds of sources.

And I guess, hopefully, today we'll actually give a bit of an example of that, as we talk a little bit about that Maxwell reading throughout today. So that's the plan. And if there's no other questions, I think we'll just jump right in. So I'm going to go ahead and share screen. And hopefully, you can see that first slide.

So today, we're going to start our journey in earnest. We're going to turn the clock back about 200 years and talk about some of the leading natural philosophers, some of the leading people who are trying to understand the physical world. And what do they think their job was? What were the settings in which they did it? What were the conceptual tools they brought to bear? And we'll always be asking ourselves, what looks kind of similar and what looks really, really unfamiliar from our vantage point today?

So the discussion today has three main sections. We have a brief warm-up on physics then and now, just to try to prep us to put our minds back into the world of the early 19th century. Then we'll spend a bit of time talking about Michael Faraday, who was one of the most widely celebrated scientists or natural philosophers of his day. And we'll see some of the things that he introduced during his rather unusual career.

And then the last main section for today, we'll talk about some of the folks who are a bit younger than Faraday, who took up his mantle who tried to continue his line of work, but, again, using some different kinds of techniques and tools, in this case William Thompson and James Clerk Maxwell. So that's our goal for today.

So let's just pause and remember that we are entering a kind of imaginary time capsule and going back about 200 years to start. So the assumptions that we might bring in as physics students, as MIT students more generally about how the world works, about what the job of a physicist is, and so on, those won't map on perfectly well to some of these earlier folks when we start talking about.

And I find that that's part of what's so fun for me about working in the history of science, is exactly those moments where things don't look so familiar, as well as the continuity we can trace over time. So one of the biggest questions we might ask about physics today is, what's the world made of? What do we think, as modern day scientists, are the basic building blocks out of which the world is made?

If we were to conduct a survey of most working physicists at MIT or really anywhere around the world at this point, we'd get an answer along these lines. We would hear about something called the standard model of particle physics, which is amazing. And we'll actually talk a bit about the standard model later in the semester.

It describes the world as made up of a very small number of fundamental entities, elementary particles like the quarks, and electrons, and tau mesons, and neutrinos, and even the long elusive Higgs boson. There's a collection, not a very big collection, of stuff out of which we think literally everything else is made.

We hear the physicists today talk about the tools that have been developed to try to study the interactions of those elementary bits of matter, how different particles can interact with each other, can scatter off each other, can transmit the fundamental forces of nature by exchanging certain kinds of particles in a vacuum.

Depending on which physicist, we ask, we might get an earful, maybe more than we invited, saying that actually all those particles are themselves really only the efflorescence of more fundamental entities called strings that live in some abstract space. The point is, we're going to get an answer like this about, basically, particles exchanging particles in a vacuum.

Now, if we were to build our time machine, which I sincerely hope we can complete soon, and we go back 100, let alone 200 years to, say, talk with leading natural researchers in Britain, and we told them this answer, that physicists today said the world is made of particles exchanging particles in a vacuum, they would have thought we were really not with it. I like to think they would have shouted bollocks or at least something maybe more colorful.

Every single part of this modern answer would have looked extraordinarily wrongheaded to the people that we're going to spend some time reading about and talking about at the start of this term. And why is that important? I mean, if we did this exercise with the ancient Mayans, or the medieval Turks, or the Renaissance French, we'd also expect some disagreement.

What I like about this is that we're turning the clock back not so far, compared to the present day. And yet, we already see a huge divergence in the answers. As we'll see throughout today and actually the first several class sessions for the term, we use their equations. We still use Maxwell's equations, for example, and a lot of the ideas that Michael Faraday introduced.

And yet, what they thought those equations meant, what they thought they were describing about how the world is made up are almost 180 degrees opposite from how we start our investigations today. So even though some parts have remained the same going over these 150 or 200 years to the past, how we make sense of those ideas or those techniques have gone through a really quite amazing change.

So what do we think the world is made of? That's not a static set of answers. And we see pretty dramatic change, even over a relatively short span of history. There's another kind of shift that we want to get our heads into, attune ourselves to as well. And that concerns who pursues the study of physics and in what kinds of settings, what institutions.

So during the first half of the 19th century, when we'll start this class, people who worked on what we would call physics-- electricity, magnetism, optics, other phenomena, heat-- they also worked on things that we would call not physics, like chemistry, or mathematics, or astronomy, physiology, even beyond that.

For them, this was all one field of study. It was often grouped under the term natural philosophy rather than physics, or chemistry, or mathematics, per se. In fact, the term for a person who studied these things-- in English, the term we would call a scientist was actually only invented in 1834. It's remarkably new, as far as the English language goes. It was invented after some of the developments we'll actually start talking about today.

So even having the job description scientist or the title is actually relatively new. And what these particular kinds of scientists that we would now call physicists-- what they thought they should do-- again, some pretty broad changes compared to what we're used to today.

Not only do they think their job description was different than what we might imagine for ourselves, but where they did the work and what kinds of settings or institutions, that was also pretty different merely 200 years ago, let alone much further back in human history. So a lot of stuff we'll start by talking about today was not done in schools or universities. They were done in separate institutes or academies.

And the key thing is these were not places where students took classes to get degrees. There was a separation between learning institutions-- universities existed throughout many parts of the world, including Western Europe and the United States. Universities existed. But that was not where people were doing what we would call scientific research.

In fact, some of the most prominent natural philosophers or leading physicists were not only not professors at universities, some of them had never even attended university themselves. And that's true of the first figure we'll look at today, Michael Faraday. So there's a big shift toward a placement of this research that would look more familiar-- things more like what we'd expect to see ourselves.

That shift begins in the middle of the 19th century, so more like 150 or 170 years ago, rather than 200 years ago or more. There's a shift to where research in fields like physics gets done more often than not by people who are professors in universities who also spend some of their time teaching students, like what we are more used to today. That has a history. It's actually relatively recent.

And it emerges really in the middle part of the 19th century. So the overall theme of this very first warm-up for the class is to put ourselves on guard. We shouldn't assume that our current sense of what's expected, or normal, or familiar either about how we choose to study the natural world, what concepts we use, let alone how we think we should be pursuing that, and what kinds of institutions or job descriptions--

We shouldn't expect that what's familiar to us today is just how people did things in the past. And in fact, we'll see some pretty dramatic changes over a relatively short span of time. So let me pause there and ask if any questions just on that early warm-up. Anyone have any thoughts or questions about that?

If not, then I'm going to press on. Again, feel free to jump in on the chat if things come up. Let's talk about this first figure I already mentioned, Michael Faraday. We're going to spend a little time talking about Faraday. I think he's fascinating. So he became one of the most successful and actually one of the most famous natural philosophers in his lifetime-- in fact, really of the entire 19th century.

He had a pretty remarkable personal story. And I think we'll also see he helps make clear some of the larger social and institutional changes going on as well. He helps us understand his own larger time period. Personally, he had this really inspiring rags to riches story. He was born into a rather poor family. He never attended high school, let alone college or university.

He was apprenticed to a bookbinder at age 13. That means he literally left his family, moved in with his main tutor, and was apprenticed in a kind of trade. So in that sense, his career path started out closer to what we might expect of the Renaissance or even the Middle Ages than to the modern period. It was a time still of guilds and of trades associations. And his role, his way to make a living, was to learn the kind of manual dexterity skills of being a bookbinder, starting early on.

He met the very famous chemist or natural philosopher Humphry Davy when Davy gave a series of public lectures on natural philosophy at the Royal Institution in London. And we'll talk a bit about the Royal Institution. It was not a university. It was a place where research was done and public lectures were given.

So Faraday was just mesmerized by Davy's lectures. He actually took very careful notes on these public lectures. Faraday then bound them into a beautiful, very fancy book. And here's how we know he was so smart. He then gave that fancy book to Davy as a gift. And I have a hint here of what you can do with that information.

He basically bribed his way into a new kind of apprenticeship. Davy was very flattered and impressed by the kind of manual skills, by the dexterity that Faraday had shown. So Davy hired Faraday for basically a new kind of apprenticeship. Faraday had never attended high school or college. It wasn't that he was trained in mathematical physics, quite the contrary.

But Davy figured Faraday could do some new kinds of manual dexterity skills in the laboratory as a laboratory assistant, a continuation of his bookbinder apprenticeship. So that's how Faraday enters what we would now call the world of natural philosophy.

So years and years go by. They worked very closely for a long time. Davy eventually steps down. He retires. And Faraday, in fact, became his successor, now the director of this Royal Institution in London. So much like I mentioned a few moments ago, Faraday worked on really a kind mind-boggling array of topics, mind-boggling from our modern point of view, quite familiar to his own contemporaries.

So he worked on what we would separately classify as chemistry, optics, electromagnetism, electrolysis, and more. To Faraday, these were all elements of a single, unified approach to nature. And he was particularly fascinated, even more so than some of his contemporaries, with this interconvertibility of forces. How could electrical effects make physiological effects happen, like using electric shocks to make a frog's leg jump?

How could chemical effects be catalyzed by electric currents? So the way that one kind of phenomenon or force could have effects in some other domain. Now, Faraday was partly inspired in this interconvertibility view by his own religious background. Some really very interesting work by a number of historians and biographers of Faraday who have tried to understand why Faraday took this notion even further, even more fervently than many of his own contemporaries.

And these other historians make a pretty compelling case. Faraday belonged to a rather small religious minority in England. He was a Protestant, but he was not an Anglican. He was not a member of the official church of England. He belonged to this small sect called the Sandemanians, Protestant but not Anglican.

And the Sandemanians, even more than the standard church of England at the time, emphasized an underlying unity to all of nature-- we're all part of one natural world-- and that people and things are somehow connected to each other. And that was part of what the Sandemanians themselves believed. And it had a theological import for them. And there's a really interesting parallel, at the very least, in some of the ways that Faraday then explored the natural world as well.

He became a beloved, very successful public lecturer. He continued the tradition that Humphry Davy had done at the Royal Institution, giving these very, very well-attended so-called Christmas lectures. These still continue from the Royal Institution to this day. Faraday would really fill the lecture hall and give these dazzling, spectacular demonstrations of electrical effects, and chemical change, and all the rest. That's partly why he became so beloved and well-known in his lifetime.

You can't quite see it in this engraving. It's hard to tell. This really was the definition of popular. The tickets were not too expensive. That's partly how very young and poor Faraday himself was able to attend as a child. It wasn't like attending the fanciest opera performance in high elite London. There'd be cheap seats. You can see how large the hall was.

So the very nice, fancy seats, then as now, were expensive. And tickets would go to the affluent and well-to-do. But there really was what we today would call a kind of outreach. There was a real effort to reach across several social and economic classes-- not all the way, but broader than only the very elite. And they became a really beloved city institution within London.

People would come in from out of town to attend them. It became an annual tradition. And Faraday became especially beloved as a presenter in that tradition. So they really were reaching not only people who had any interest in natural philosophy.

It was really a way of showing a kind of sophistication and a way for members of the so-called aspiring classes, meaning those who weren't so well-to-do, to be able to participate in things that they saw the real elites doing. So it really had an interesting social cross-section to them. Historians have written a lot of interesting stuff about these public lectures. They really were talked about broadly, covered in the broadsheet newspapers and all that.

In this time period, the main mechanisms were largely books. So even scientists, whom we would call physicists, were mostly writing monographs and sometimes writing short articles for fellow specialists. There were scientific journals, including some of the earliest that have been founded in England, going back to the 1660s, similar ones in other parts of Europe.

But the real transfer mechanisms were often through monographs. And it's partly why Maxwell's treatise, that we'll talk about later today, became so widely known and so influential. There were then these lectures. There were also so-called itinerant lecturers, people who made their whole living just giving popular lectures on topics like electricity town to town-- so not just in London, but to the outskirts and likewise throughout provincial France and other places.

So there were popular lectures. In that sense, you can think of it almost like *PBS* television today, like *Nova* specials. But for fellow specialists, there were just the start of professional meetings. The British Association for the Advancement of Science were having annual meetings of the sort that would become so familiar for fellow specialists. Sometimes, those would be covered in the national newspapers.

It was a hodgepodge. Some things would look familiar to us. Some things might seem a little more unusual. But Faraday wrote books and books and some articles, for example. And certainly, some of this would get into the curriculum for universities. And we'll talk more about that actually especially later today and in the next class session.

But the way that kind of fellow researchers interact with fellow researchers, it was largely through books, sometimes through journals, and through these different kinds of lectures. Great, great questions. I'm going to move on. These are great questions. I'll try to answer more that I don't get to as we go further.

But I want to get to one of the topics that was really, really high on Faraday's list of most important because it's really going to set our agenda for several classes to come. And that's what was called the aether, a presumptive hypothetical medium that pretty much everyone that we're going to talk about, Faraday included, just assumed. They knew. They had an extremely strong confidence that this medium was filling all of space, filled every nook and cranny of the universe.

And it was this medium that filled everything that enabled various processes to affect one another. That was the interconvertibility of forces. Why did electrical effects lead to magnetic effects? Because they're both ultimately effects of this aether that connects everything. So what's the aether?

Just during Faraday's own childhood, another amateur British naturalist named Thomas Young, building on some work by French scholars from around the same time, right around the year 1800, had advanced a wave theory of light. This was opposite actually to Isaac Newton's theory of light, who had a particle or corpuscular theory.

So Thomas Young, like some of the French scholars as well, suggested that a whole bunch of optical phenomena, like interference, like reflection, and refraction could really only be made sense of if light was a series of waves. And I'm sure you've seen this. There's a very simple illustration.

If two waves are perfectly in sync with each other-- we'd say in phase-- you can get constructive interference. The peaks will become larger than either wave alone. The troughs become deeper. Of course, if those two waves are exactly out of sync with each other, if they're perfectly out of phase, you can get destructive interference. And the resultant wave will vanish altogether and anything in between.

So Young and others were convinced that these interference phenomena were natural indications that light is a wave phenomenon. But then the next question is, well, waves of what? Waves in what? Ocean waves are clearly waves of water. Sound waves or compressions are waves in the atmosphere, in the air. What are waves of?

So they said, well, any wave we know about is a wave in some medium. There must be a medium that carries these light waves. It was called the luminiferous aether, which is a very fancy word. You can see how to parse it here. If you remember either Latin or *Harry Potter,* I find them equally helpful. Think about the Lumos spell in *Harry Potter.*

The lumini- part just means light, referring to light. -ferous means carrying. Think of like a Ferris wheel. So the formal name of luminiferous aether really just means the light-carrying or the light-bearing aether. This was the medium in which light traveled, in which everything, all of the physical phenomena, were immersed, which is why these folks would never have said the stuff of the world is elementary particles traveling in a vacuum. There is no vacuum. Everything at root is filled with aether. That's where they were starting from.

So why would you need a medium for light? Again, even before, around the same time as Thomas Young in England, a number of French scholars had found that the speed of light-- the speed at which light waves travel depends on the medium in which they're traveling. In fact, they're slower in water than in air. That's opposite, by the way, to sound waves sound waves. They always travel more quickly in a dense medium.

And that led to things like Snell's law, the whole set of knowledge about refraction and how light behaves when it crosses from one type of medium to another. You can characterize these media in terms of what became known as an index of refraction. And so everything about the behavior of these waves seemed to depend on the medium through which they were traveling.

So there must be some kind of baseline or reference medium, the aether, with respect to which any of these deviations would then be measured. So water is one type of medium. But even if you take all the water away and have a vacuated chamber, you still have light waves traveling in the remaining aether. That was how they organized these studies. All right, so much for light. What about other things like electricity and magnetism?

So again, during Faraday's early career-- by this point, he was already ensconced at the Royal Institution, still working closely with people like Humphry Davy-- there was a headline-grabbing event not found in Britain, but actually nearby in Denmark. So when another natural philosopher, Hans Christian Oersted was giving a public lecture very much like at the Royal Institution, same kind of format-- these were popular throughout Europe.

Oersted was giving a public lecture. And he accidentally discovered, in the midst of his talk, something that he really didn't expect. He had an apparatus that looked a lot like this, a kind of conducting coil. So this is a conducting wire. And he had nearby a compass, so a magnetic needle. And he found that when current was flowing through the wire, the needle would be deflected. He did not expect that at all. None of his audience expected that. No one else expected that.

Somehow the electric current, the flow of electricity, could affect-- could induce magnetic effects. It could change the behavior of that magnetic needle of the compass. This became headline news. If there had been 19th century Twitter, this would have broken Twitter, #theneedlemoved. I'm sure this was literally what everyone was super excited about, including people like Michael Faraday.

This was, for Faraday, exactly this kind of interconversion of forces that he was so interested in, partly from his Sandemanian faith, partly because he was a natural philosopher of his time. So not only does he quickly replicate Oersted's finding-- he separately finds that he can get electric current to move a compass needle-- he then finds the inverse.

As shown here, he takes a bar magnet and starts moving it in a pattern near a conducting coil from which he can measure the current. He has an ammeter attached. And he finds the inverse can happen as well, that a moving magnet, a changing magnetic effect can induce an electric current.

So he's investigating induction, both electric currents inducing magnetic effects, magnetic fields or magnetic effects inducing electric effects. And he wants to keep track of this stuff. So he starts sketching these helpful doodles that he calls lines of force. As far as Faraday was concerned, these were lines of force to depict the underlying state of the aether.

Remember, everything, as far as he's concerned, is what's going on with the underlying aether. So it must be, he begins to reason with these pictorial aids, that the aether could be put under states of strain or tension. If I have an electric charge that I place within the aether, it's going to have an effect and put a strain on the aether immediately around it.

So he draws these lines of force, emanating outward from positive electric charge or collapsing in toward a negative electric charge. And then he begins using his middle school level mathematics. He'd had a little bit of geometry before leaving formal schooling. And he puts that to work.

He supposes, what if the number of lines that come outward from a positive charge is fixed and is proportional to the amount of that electric charge? So a charge of, say, seven units would have seven of these lines radiating outward, affecting the surrounding aether. A charge of 10 units would have 10 lines radiating outward and so on.

Then you can imagine what would happen if you surrounded that positive charge with a kind of imaginary sphere at some distant radius. Then you can ask, how many lines per unit area will cross through that imagined sphere? The density of field lines will fall out. The lines are dispersing as you get further and further away from the electric charge. So the density of field lines, how many of those lines will intersect a unit of that sphere, will fall off like 1 over r squared?

You take the fixed number of lines, divide by the surface area that you've surrounded that charge by. The area goes by like 4 pi r squared. So the density should fall off like 1 over r squared. That was really exciting to Faraday because he had learned, again, from French scholars like Coulomb, not too long before really, just in Faraday's own childhood, that there was this Newton-like force of attraction or repulsion among electric charges. We now call it Coulomb's law.

The magnitude of the force between two electric charges falls off like 1 over the square of the distance, exactly as Faraday had reasoned toward by thinking about states of tension in the aether and how that strain would be dissipated at more and more distance.

So Faraday went on. Remember, he was so excited not only about one topic like electricity, but also about magnetism. What if you plop a bar magnet down in the aether? Then he could do that with these things like iron filings and trace out the kind of lines of influence around the magnets-- something you've probably done even as a child.

And he realized that he could make sense of this also in terms of lines of force, that these iron filings were helping him map out the magnetic effects, the strain that the bar magnet, with its north and south magnetic poles, could do for the surrounding aether. What's really interesting here is that Faraday starts to say that sometimes forces might not be transmitted only along the straight line shortest path between A and B. That was the rule for all Newton-like forces.

The magnetic lines of force would bend. They'd curve. They would have these looping paths. And so maybe the magnetic force did not always go on shortest distance paths. And more generally, Faraday starts saying, let's keep track of all these states of tension in the aether. He introduces this notion of the field, something that physicists to this day use every single day of our careers. We now call it field theory.

It largely comes as being introduced by Faraday, as he tries to make sense of, with convenient mnemonic devices, these states of strain in the aether. So the electric and magnetic fields, as far as Faraday was concerned, were simply ways of characterizing the local state of the aether as represented by these lines of force.

What were the stresses and strains at that spot in the aether? How do they change if I go to this spot? How do they change at that one spot over time? This is what he says is the notion of a field. It's just shorthand for the state of the underlying aether. But is that real? You might still wonder, is the aether just a helpful thing to think about? Or did Faraday and his colleagues think it was really part of the world?

And it was unambiguously, for them, part of the world, not just convenient to think about, but really the stuff from which the world was made. And we'll talk about this in some more detail over coming class sessions. Faraday thought he found the golden proof in 1845. And now he's a much more senior researcher.

How could you demonstrate the aether was real? Well, let's study the interaction between magnetic fields and the behavior of light, in particular polarized light. This is now known as the Faraday effect or the Faraday rotation. It's one of these things that's literally still in our textbooks. We use it all the time. It comes from Faraday's efforts to prove to himself and his colleagues that we are all immersed in this elastic, bendable aether.

So Faraday and his peers-- the idea was the following, that if you put the aether under local strain by putting a local magnetic field in some region of space, that magnetic field would have a twisting or curling effect, a kind of torsion on the underlying aether. And then this light wave is traveling through this deformed local bit of the aether. So its behavior will change.

And in particular, what's called the plane of polarization, the direction in which its wave is waving, will rotate. There'll be some angle, shown here as the angle beta. So if the field starts out, the wave starts out waving in one direction, it will literally be rotated by some angle. The amount of rotation depends on the strength of the field and the distance through which this aether is under tension.

This is not just a good idea for 1845. It's how we make sense of the world today, minus the aether part. But it comes from trying to figure out is the aether real. Just last year, I had fun working with a really terrific UROP student. Some of you might know Max Daschner.

He and my friend Joe Formaggio in physics, we used this exact same phenomenon, that an external magnetic field will rotate the plane of polarization of light, not to talk about the aether, but as a way to jam quantum encryption indefinitely. So in this hyper-modern physics of the moment, we're still going back to Faraday rotation. And yet, Faraday thought this was a way of characterizing the aether. I just love that.

We're going to see many examples of that throughout the class. Let me wrap up the Faraday part. I'll pause again for some more questions. So Faraday, as we've seen, worked on a variety of phenomena, what we would call separately chemistry, and optics, electrolysis, even physiology, let alone electromagnetism. He was especially interested in the interconvertibility of forces partly. A compelling case had been made.

This resonated especially closely with his religious minority views, his Sandemanian views and that there was this kind of underlying unity of nature. Faraday was never trained in advanced mathematics. He had really just the rudiments of this pictorial geometry, like we saw with the lines of force. He was an apprenticed tinkerer. He had tremendous manual dexterity skills and also great cleverness.

He became this leading experimentalist based on not formal training at a university, but being apprenticed as a bookbinder, and then essentially apprenticed as Humphry Davy's assistant at the Royal Institution, not at a university. He introduces these things which we still use to this day, like lines of force, and then fields.

For Faraday, these were ways of characterizing the one big prize of natural studies, meaning the aether, the medium within which all these things unfolded, and the reason as far as Faraday was concerned why there could be this interconvertibility and unity. So in place of Newtonian action at a distance that somehow one object could instantaneously affect or exert a force on another one, Faraday starts explaining all physical phenomena--

He has the ambition to explain everything in terms of these local fields there's a local disturbance here at position x equals 1 and it could convey effects to its nearest neighbors point by point. So you have to study how these fields change over time and spread out through space. Everything is now meant to be local fields, not action at a distance. Let me pause there again and ask any questions. I see at least one more item in the chat. Any questions on the Faraday material?

Very good. So it was common to attend the public science lectures. And in fact, it was seen as a way of being elegant. Again, this is really fascinating work on the social class emulation going on, especially heightened, as you might know, in Britain in this time period.

So to be considered a fashionable lady in the terminology of the day, one had to show or at least feign interest in a range of topics, one of which was these elegant demonstrations of the glories of the world. For many people, this, by the way, had a kind of overt religious significance, a kind of natural theology.

Not for everyone, but for many in this period, the idea was that learning about how electric shocks make frogs' legs twitch or how a magnetic bar magnet can change-- can induce electric current, these are ways of revealing the glory of God's creation, as many people argued at the time. So It was seen as actually a function of moral or spiritual uplift.

And therefore, again, according to the assumptions that-- we might say prejudices at the time-- therefore, all the more important for young women to be exposed to this, was the thinking of the time, with their tender, moral souls that needed special care, again to speak in their idiom, not my own.

So there actually was a great encouragement for women to attend these public lectures, not, as you might expect, to move into the laboratory, not to do the work. That was an almost uniquely male enclave in this period, certainly in the Royal Institution. But to be exposed, to be part of the broader, polite discussions, it was one way of showing that you were-- you had an appropriate upbringing.

And again, there's lots of cool stuff I'd be glad to talk more about that or send some references for more readings. The short answer was, yes, to attend the Christmas Lectures at Royal Institute, that was an awesome thing to bring your daughter to. But at the time-- and that's something we'll see change rather slowly, but change over time throughout the semester--

At that time, it was not something that was seen as a kind of acceptable or appropriate day job or a career path. So that was a very, very clear gender disparity, but a great openness to have women participate in that limited way in the public lectures. So very good question. We'll come back to that theme quite a lot.

Great questions. Oh, that's so good. So we'll actually come to some of that in this very next unit right now. So partly, I'll just punt. But the short answer is there was a growing recognition in just this time period among many influential government leaders-- not only in Britain, in many parts of Europe, in fact, many parts of the world-- China and Japan, certainly North America, a growing recognition this during this exact time period that many nation states would benefit from investing in what we would now call science and technology or science and engineering.

So there certainly were hot button issues, then as now. Natural evolution, Darwin's theory of evolution, which comes just around this time first published in 1859, that becomes yet another flashpoint for tension and controversy. But for a lot of this work in what we would now call the physical sciences, as we'll see, there was actually a kind of investment, a new kind of priority in a lot of this work not across the board, not without its own hiccups. We'll come to that.

But it was actually a turning point in a new kind of investment, partly because many of these places were undergoing their own nation-based industrial development. And we'll see that actually even more explicitly in the next class, some of it today with Maxwell and in the next lesson. It was a great question. It's a theme we'll trace throughout the semester.

But even in Faraday's own lifetime, that was beginning to change into a more-- a higher priority in investment in exactly these topics. Great question. Any others? Should we press on? These are great. So keep them coming. These are great historical questions to help us think about what was different back then, what might have been similar. So we're going to keep that kind of back and forth in mind as we enter now just the last part for today's class.

I'm going to talk about William Thompson and James Clerk Maxwell. So as we saw at least briefly, Faraday had very little formal training in mathematics. And he used very little in his own studies, his very voluminous studies. And that's not surprising, given what we know about his own early childhood and education.

There's a really remarkable shift, one that I still find unbelievably fascinating. So we're going to spend quite a bit of time talking about it today and next class as well-- this amazing shift that begins really late in Faraday's own lifetime, in the middle decades of the 19th century. It doesn't only happen in Britain. We're going to look at it because it's especially dramatic or blown out of proportion, we might say, in Britain at places like Cambridge University.

It's happening also in places like France and other parts of the world, even beyond Europe. But Cambridge in Britain gives us the capstone picture of that in its almost pure essence. So there's a real sea change going on between Faraday's early life and even the later years of his own career in the way that people would try to approach natural phenomena like electricity and magnetism.

Two exemplars, two examples of that shift are names that might be familiar to many of you-- and we'll spend a little time today talking about some of their work-- William Thompson, who was later known as Lord Kelvin. That's the same Kelvin from the Kelvin temperature scale, absolute temperature familiar to you, and many other things. So Thompson on one hand and James Clerk Maxwell on the other. Again, I'm sure Maxwell's a familiar name, things like Maxwell's equations and all the rest.

So these two folks were about two generations younger than Faraday. They were coming of age when Faraday was already a well-known natural philosopher. They pick up on Faraday's work. They were avid readers of Faraday's books, often monographs, not just his articles. And they begin to translate it into a very powerful mathematical formalism of the sort that Faraday had had no inkling of whatsoever.

It turns out both Thompson and Maxwell were born in Scotland. They were not from London or the immediate English surroundings. They were both Scottish-born. They both moved to Cambridge for their formal university training in the middle decades of the 19th century.

So both Thompson and Maxwell became deeply involved coming exactly to the question that was raised just in that last question period. They became deeply involved with what we might call engineering aspects or applications of natural philosophy, all around the physics of the aether.

They had both had very long, illustrious careers, not only when they were university students. They were pursuing these very fancy, sophisticated mathematical, formal mathematical approaches to electricity, magnetism, and the physics of the aether not only for the sake of pure mathematics. As we'll see, they were deeply involved in very practical ways with things that governments wanted to pay for, like telegraphy and other practical electro-technical devices.

So among the most important in their own careers was indeed telegraphy. So as you know, Britain, then as now, was an island. It's still an island. Back then, it had lots and lots of colonies. That's what's changed. It was a period of still rapid acceleration of the British colonial adventure. So distant outposts or so-called possessions, territorial possessions, really all around the world.

Again, many of you might recall the old quip, that the sun never sets on the British empire. In that time period, there were colonial holdings or territories that spanned really the entire globe. So at any given time of day, the sun was shining on some British outpost.

So what do you need if you're going to try to administer a world-spanning empire? You need ways to have efficient communication. And that was an enormous impetus for things like telegraphy. Even with some of the former colonies, like the United States or Canada, some kind of formal colonial holdings, there was still an effort in this same period, the middle decades of the 19th century, to have efficient, long distance communication for things like commerce and diplomacy.

So there were all kinds of reasons why electromechanical investigations were given a very high priority in Britain in this time period. So we get a taste. Here's our first quotation from that little bit of the Maxwell that I assigned. Maxwell published this voluminous treatise, a two-volume treatise in 1873. The two volumes together run to about 900 pages. It makes for fun beach reading.

But in the very opening of the preface, we get this really interesting observation. He tells us partly why anyone should read this book. And he says here, the important applications of electromagnetism to telegraphy have reacted on pure science by giving a commercial value-- and indeed, a governmental, diplomatic value-- to accurate electrical measurements and by affording to electricians, as say experts in the field, the use of apparatus on a scale which greatly transcends that of any ordinary laboratory.

They're getting huge investment to conduct very large investigations with very elaborate apparatus. The consequences of this demand, this government and commercial private interest demand for electrical knowledge and of these experimental opportunities for acquiring that knowledge have already been very great, both in stimulating the energies of advanced electricians and in diffusing among practical men a degree of accurate knowledge which is likely to conduce to the general scientific progress of the whole engineering profession.

PS, buy my 900-page book. It's literally worth something. That's what he's announcing in the opening pages of his treatise. So let's go a little bit into some of how William Thompson and James Clerk Maxwell start treating Faraday's intellectual legacy. So Thompson began reading Faraday's books, as well as some articles, as an undergraduate. Thompson was still basically 18 and 19 years old at Cambridge when he starts devouring Faraday's work or continues to do so.

He began to realize that he could put Faraday's work-- he could translate it, on the one hand, and also Newton's work on mechanics within the same mathematical structure. This was the stuff that only in the middle decades of the 19th century was what university students at Cambridge, like William Thompson, began to really be immersed in. We'll talk much more about that in the next lecture.

So he realized that could make this bridge. You could treat all these disparate phenomena within electricity and separately all these disparate phenomena within Newton's mechanics-- blocks sliding down planes, the attraction of gravity-- introduce one similar mathematical construct, the potential, a scalar potential, which is often just labeled by the Greek letter phi.

If this is brand new to you, don't worry. If it's very familiar to you, great. The idea is that a scalar function, a scalar field like this potential, it has values at every point in space. Those values can change over time. But it doesn't have direction. It only has magnitudes. You can think of making representing the temperature in the room at every location in space, and then tracking how those temperature readings change over time at each location in space.

That's a scalar function. Temperature is scalar. It has magnitude, but not direction. That's hopefully review. Other things, like these fields that Faraday had introduced for electricity magnetism, those have direction as well as magnitude. Those are vector quantities.

Well, as Thompson was learning to just devour in his undergraduate studies, you could create a vector quantity by taking rates of change of a scalar quantity, what we now call the gradient. So the gradient, often with this upside down triangle or nabla symbol, the gradient of a scalar function gives a vector function. And in particular, one could represent these vector field-like quantities of either electricity or gravitation by first writing down a simpler mathematical object, the scalar function, scalar potential.

So he first reviews what had already been worked out by a bunch of 18th century savants throughout France, so French scholars throughout the 1700s downstream from Newton himself. They had really translated Newton's own work into this language of directional quantities, like fields, like forces in the gravitational field, and then introduced this simplifying mathematical structure of a scalar potential.

And then you could study not just how the field is related to changes in that scalar function, the gradient. You could see how the field would diverge, the divergence of that field related to where the stuff is, the density of sources of gravitation, like the mass density.

This was basically a translation or retranslation of Newton's work from the 1680s, translated into this more modern language throughout the 1700s by the French scholars of directional vector quantities being related to derivatives, to rates of change of simpler scalar quantities. That was literally textbook stuff. That's what Thompson is learning as an undergraduate.

It's now Thompson, not those French folks in this case, who says, can we make a one-for-one map? He's absorbing this cool Faraday stuff. He says, what if we represent an electric field as a state of strain in the aether, exactly as Faraday had begun groping toward pictorially? Those electrical forces can be forces related to an electrical field, the state of disturbance of the aether. Sorry, how did that happen? Sorry, gang.

OK. You can then relate the electric field again to rates of change of a simpler quantity, a scalar potential, exactly analogous to the gravitational case. You can then ask how the electric field is diverging throughout space and time, like those lines of force getting more and more spread out from each other in Faraday's simple pictures. And that's related to where the stuff is, to the sources of this electrical disturbance-- the charge density, how many electrical charged objects are distributed throughout space per unit volume, say.

So he makes a one-to-one map. And he says there's really a precise mathematical analogy between electrical phenomena and mechanics, like Newton's laws. And the mapping is done by this a little bit more formal, more fancy mathematics. So far, that's not so shocking. Thompson was among the first to take this textbook side and start doing new things with the Faraday cool E&M stuff.

Within one year of when Faraday introduced what we now call Faraday rotation-- remember that thing about the external magnetic field rotating the plane of polarization for light-- Thompson does the same thing. He says, oh good, Faraday has some new cool stuff. Let me put that through my very fancy universe of mathematics.

So now, he's still an undergraduate. Thompson is now making brand new stuff-- not just rewriting the known regularities among electrical phenomena, but in fact formalizing the brand new stuff, like Faraday rotation. He introduces a new kind of mathematical object, the vector potential. That was not known even to the French savant. We still call it the vector potential A.

And he introduces a new operator, a new way of manipulating that quantity, which we call the curl. Thompson invents curl as an undergraduate. Just let that sink in for a second. So the new semester is early. You all can invent all kinds of new math before, let's say, November. Thompson is literally doing this for fun on the weekends because he can't get enough math.

So he introduces a vector potential and this curl because, as Faraday had intuited, the effect of a magnetic field on the surrounding aether was a turning or twisting strain, unlike the straight line strain of an electric field. And so Thompson wanted to formalize what that curl, what that twisting torsion would be like as a different kind of strain in the aether.

And he formalizes this new operator, which we now know, and love, and use every single day. It comes out of Thompson trying to treat mathematically formally what he was still learning very actively from people like Faraday, pretty amazing. So far, following Faraday's lead, Thompson begins to interpret this mathematical result mechanically. Remember, we saw that one to one bridge between the Newton mechanics stuff and the electricity stuff.

He says, if the same mathematics applies, maybe it's the same physical explanation undergirding all of it. He had learned from people like Michael Faraday and others, the aether seemed to be this inelastic, physical medium. It was literally a kind of stuff spread out everywhere. And that medium could be put under local states of tension or strain with twists, with directional properties described by these vectors.

So these new mathematical techniques like curl could quantify this physical, mechanical medium's response to pressures like electric and magnetic fields. He really took that to heart. In a famous set of public lectures, much like these London ones, he actually came to Baltimore in the United States and gave very, very well attended popular lectures in Baltimore.

Thompson basically tried to give his audience a feel for what these kind of experts were doing. This is a direct quotation. So again, people in their fancy opera gloves, like out for a night on the town, hear the great Lord Kelvin by this point, the great, ennobled Lord Kelvin describe about the latest advances.

And he tells his fancy audience, stick your hand in a bowl of jelly, OK, and see how it wiggles and vibrates as you move your hand around. That's what it was to do physics because the jelly is just like this elastic aether. It's everywhere. And the job of super smart, ambitious people like William Thompson was to quantify the wiggles and vibrations of that aether, much as you would if you disturbed this pot of jelly. I love that.

This becomes known as a mechanical worldview. If the mathematics was the same, make this one-to-one mathematical map, then maybe you could model electromagnetism literally on mechanical models. You have an elastic stuff under states of strain with directional properties.

And if the models reproduce all the relevant phenomena, like Coulomb's law and all the rest, all the electromagnetic phenomena, then maybe these aren't only analogies or models. Maybe the aether really was merely a mechanical system just like that jar of jam. So it becomes a mechanical worldview. All of the things of the world are to be understood on mechanical vibrations or responses of this space-filling aether.

The last part, then I'll pause for more questions, almost done-- we're going to turn to Thompson's slightly younger colleague, James Clerk Maxwell. I mentioned they had a similar upbringing a couple of years apart-- both Scottish, both come to Cambridge for their undergraduate studies.

Maxwell is a couple of years younger. I don't think they actually overlapped in Cambridge. They came to know each other later. Maxwell, like Thompson, becomes steeped in this new Cambridge mathematical training. We'll talk a lot more about the Cambridge training in the next class.

And Maxwell develops further analogies between these electromagnetic aether-based systems and mechanical systems. Here's a famous example. In this, by the way, you get some more description of this in that chapter by Bruce Hunt in the reading for today.

So to model the effects of a magnetic field on the aether, Maxwell imagines this elaborate system. Basically, it's like a contraption of pulleys, and conveyor belts, and gears. We don't have to worry about the details so much. The ambition is what I want to convey, that there's a physical model of an actual system, a mechanical system of gears, levers, and straps that he thinks is what's really going on in the aether when we do things like put a little patch of aether under local strain from a magnetic field.

So between these vortices, as depicted here, are these idle wheels. They stay in place, but can change the rate at which they turn. It really is like these conveyor belts. If an external force changed the rate at which one of these vortices was spinning-- you could change it by imposing one of these external fields like a magnetic field-- you change the rate at which this unit cell is spinning.

That changes the rate at which the immediately nearest neighbors are going to be behaving. It's all this Faraday field idea of local neighbor to local neighbor, not action at a distance. So this unit cell starts to change its rate of rotation. That changes the speed at which these intervening, these so-called idle wheels spin. That then changes the rate at which their nearest neighbors spin because they're literally connected. So it's all local effects.

So all effects are local. And the way that a magnetic disturbance affects something over there is by these local effects propagating through the medium in this gears and straps conveyor belt sort of way. And again, he gives us hints about this even in the brief excerpt from Maxwell's treatise that I assigned for today.

So he talks about how the action of one electrical system on another is affected not by direct action at a distance, not the way Newton had said, but rather by means of a distribution of stress in this medium, this elastic medium, or the aether extending continuously throughout space.

Likewise, he says a few pages later in the excerpt, the distribution of stress in this medium, this aether, is precisely that to which Faraday was led in his investigation of induction, of the fact that a moving magnetic-- moving magnet can induce electrical effects, like an electric current.

At every point of the medium, there's a state of stress. Every part of the aether is under some kind of stress, such that there's tension along the lines of force, pressure at right angles. He's really building a mechanical model, almost sometimes a kind of hydrostatic one and other ones more like the gears of a factory.

This became how the Maxwellians-- not just Maxwell, but even his nearest followers, and students, and proteges-- that's what they thought it was to study the natural world, to build more and more articulated mechanical models of the aether with which they could model and even predict more and more features of the natural world, like electromagnetic effects.

So one of his acolytes, Oliver Lodge, who himself went on to a very, very distinguished career in physics himself, he wrote a book a few years later than Maxwell's treatise called *The Modern Views of Electricity.* And it was all about this Maxwellian approach within this mechanical worldview to account for states of strain in the aether using this much more articulated mapping, the fancy math that people like Thompson, Maxwell, and soon the whole Cambridge group would articulate.

Well, this didn't impress everyone. I love this book review. This is the nastiest book of view for a long, long time. Here's a review by the French mathematical physicist Pierre Duhem, reviewing Oliver Lodge's book, this Maxwellian book. Duhem hoped he would like it. He also was very interested in electromagnetism. But he just sniffs in this wonderful sneering, French way. It's worth quoting.

Duhem says, here is a book intended to expound the modern theories of electricity. And there are nothing but strings which move around pulleys, which roll around drums, which go through pearl beads, which carry weights, and tubes which pump water while others swell and contract. Toothed wheels are geared to one another and gauge hooks. This is the real kicker. We thought we were entering the tranquil and neatly ordered abode of reason. But we find ourselves in a factory.

This was not high praise. He was like, I thought I was going to learn something edifying for my soul. Instead, this is literally low class stuff. This is the most obnoxious takedown book review that I could think of. So this Maxwellian British approach doesn't please everyone. And yet, as we'll see in the last little bit, they're starting to make some pretty remarkable strides nonetheless. Last little bit, then we'll pause for questions, the last part for Maxwell.

So while working out this mechanical model, how would local disturbances propagate through this elastic medium of the aether, Maxwell starts putting in some quantitative values for the way to characterize the response of the aether. These are really like spring constants. How stretchy is the aether? Or how much stretchiness or tension do you get per unit applied external field?

When we apply an external electric field to this part of the aether, how much does the tension change or likewise the magnetic fields? So really, like spring concerts, analogous. And that's what he and his colleagues are measuring in their local laboratories and studying.

Then he goes back to these mechanical models to ask how quickly would a mechanical disturbance begin to propagate within this mechanical aether. And he finds, really to his surprise-- he didn't see that coming-- these disturbances in the aether, the moment by moment local effects would move at a speed he already knew very well, the speed of light. Here's a direct quotation from his very famous paper from 1865.

And he says, the velocity of transverse undulations in our hypothetical medium-- I just love that phrase, transverse undulations in our hypothetical, meaning the speed at which these waves of aether are traveling. That speed agrees so exactly with the velocity of light that's calculated from optical experiments-- and actually, most of the astronomical tests-- that we can scarcely avoid the inference that light consists of the transverse undulations of the same medium, the aether, which is the cause of electric and magnetic phenomena.

Translated into how we might say today, light waves were literally nothing, but traveling disturbances of electric and magnetic fields within this light-bearing, all pervasive aether. He gets that-- he gets this unification of electricity magnetism and optics by thinking very, very hard and very quantitatively about the mechanical response of this all pervasive aether.

So let me wrap up, and I'll pause. I see a bunch of comments coming up in the chat. So I want to make sure we have time to chat. So let me just wrap up. And then we'll get to discussion. Leading natural philosophers of the 19th century were really quite convinced-- and they had very good reasons-- that the world is made up of just different kinds of stuff than how our contemporaries would answer that question.

That opening question, what's the world made of? The folks back then, world-leading, rightly celebrated scholars-- Faraday, Thompson, Maxwell, and for that matter people like Pierre Duhem and his contemporaries as well-- they were convinced that the world was not made of elementary particles that skitter around in a vacuum. But rather, there was no vacuum.

And particles were a kind of afterthought-- we'll Come back to that in next class-- that the world is filled with elastic, physical medium, the aether. And everything that matters is a response to that aether to various kinds of mechanical disturbances. As Lord Kelvin says, stick your hand in a bowl of jelly. See how it wiggles. That's what the world is made of.

Up until the middle decades of the 19th century, many leading, highly accomplished, and very influential natural philosophers, like Michael Faraday, could enter research careers based on this apprenticeship model closer to the Middle Ages or the Renaissance than to today. They often worked in institutes, which had no formal teaching function. They were not, for the most part, based at universities. That's what begins to change in the middle decades of the 19th century.

So Faraday, Thompson, and Maxwell, in their own different ways, pursued these analogies between this light-bearing or luminiferous aether and mechanical systems-- Faraday with his rather rudimentary geometrical arguments and his very clever pictorial aids, Thompson and Maxwell with this increasingly sophisticated mathematics. We'll look at that some more next time.

They all became convinced of what became called a mechanical worldview. The electromagnetic effects were literally nothing but mechanical effects, mechanical effects on this all pervasive aether. Moreover, this is the birth of what we now call field physics. Local causes yield local effects. There's no action at a distance, unlike Maxwell's description-- excuse me, Newton's description of gravity.

A can affect B But it'll take some time for the effects to propagate. And certain kinds of propagating effects, like these electric and magnetic transverse undulations, they'll show up as nothing other than what we call light. Let me stop sharing the screen there, open it up for questions. There's a huge set in the chat. I think I won't get to them all today.

Great, great question. Thank you. So you're right. So there was a spectrum, even among what we now call the Maxwellians. They didn't all have exactly the same ideas, but they shared a lot. And so indeed, some of them wondered, is this a useful analogy? And if so, should we nonetheless keep pursuing it and see what we get out of it? Others were convinced that it's more than that. It's not merely an analogy. It's a helpful analogy precisely because of some deeper similarity.

And individuals views changed over time. And the whole group would have a, let's say, evolving center of gravity. They were more like each other in the Cambridge scene than like, say, the French, or the Germans, or indeed communities further afield, as we'll look at.

So I don't want to make it sound like they all exactly had the same notion. They were pretty similar, compared to-- actually, we'll see a really interesting contrast next class-- I think interesting-- with some leading scholars within the German states. So there was maybe the strongest contrast.

But you're right that some of these, even within Cambridge or the close Maxwellian colleagues, they were all delighted to pursue the mathematical analogies. And they were getting trained in these very, very elaborate mathematical machinery, as we'll talk more about next time. They shared that.

And They. Were impressed by what the analogies would bring them, either to explain something or to prompt new questions to then try to go investigate in the laboratory. It was a productive set of analogies. That was already what they agreed on. Some then said, it's not just analogy. The world is filled with jelly, effectively. It's a great question.

It looks like Julia has very kindly compiled a bunch of questions for me. Let me answer some that Julia has private chatted to me. And if I miss some others, we'll have time for some more. So someone asks, by way of Julia, if university and research institutions were separated at the time, who used to teach at the universities? Oh, very good.

People would teach at the universities who had gone to university. So it was self-replicating. Now, that's still true today. But we've achieved a kind of monopoly, whereas back then it wasn't such a monopoly. That is to say, people who would teach at universities had indeed been trained like William Thompson, or James Clerk Maxwell, or their own students. And in fact, we'll talk quite a bit about this in the next class and something that I find really interesting.

And that was still separated from people who could enter really elaborately, amazingly prestigious careers, like Michael Faraday or even Thomas Young before him, or Hans Christian Oersted, or many other names we encountered today, without going through that kind of formal university setting. So the apprenticeship model-- get your hands dirty on effectively an elaborate internship and just like never leave-- that was still a viable path in to conduct really world class, cutting-edge research.

Then you'd often write your monograph, your whole book about it, maybe deliver some fancy lectures. Maybe some of the scholars at the university would be interested, and maybe write a textbook, and maybe lecture on it in their classes. But they were separated. The separation begins to be reduced, starting in the roughly 1850s-- 1840s, 1850s.

And they become much, much closer associated-- not automatically, not without some switches back and forth. But the trend really sets in, starting in the middle of 19th century. And again, we'll look at that a bit more directly next time. Very good question. So another question is, why do we go from the convention used in Maxwell of denoting a potential as psi to now using a phi? Oh, very good.

Are they different? No, they're not different. So I guess I skipped ahead to the modern-- I showed my prejudices in my slides here, just using the Greek letter phi for potential. The short answer is I don't know what that particular letter changed. What I do know-- and we'll talk about, , again next time-- is that as you got a taste of it again in the reader today, Maxwell was not using any of this fancy pants vector stuff, right?

Maxwell was writing everything out in explicit Cartesian coordinates. That's probably why-- I joke-- why his book was 900 pages. If he just used vectors, I think it would have been a 20-page pamphlet. We'd be done. And so I talk a lot about that, actually, in the coming class. So the particular question, how did psi become phi, it's interesting. And I actually don't know.

But the larger question about Maxwell's notation-- and in particular, how it could become so valuable for people like us when he writes these incredibly clunky, pain in the butt kinds of things, partly why I gave you those excerpts from his reader, from his treatise-- it doesn't look just like our favorite textbooks today, even when we're using, quote unquote, "his equationss."

So it's a great question. The conventions actually show a lot of interesting stuff, even the particular question about psi and phi. I admit I don't know. Regarding the wheels pulleys as analogies to physical reality, how is continuous rotational symmetry of the physics explained? Oh, that's interesting.

I think the idea-- oh, that's good. Yeah, that's good. So I think they gestured toward it by those molecular vortices. That's the two-dimensional slice. And they certainly were aware of things like spheres. So a lot of it, they talked about ball bearings. So you actually have spherical symmetry. And so they constructed even more elaborate of pulleys and gears.

So they were certainly very attuned, especially thinking about these mathematical, fancy mathematicians, like Thompson and Maxwell. They were very attuned to what we would now call symmetry arguments in real space. Could I rotate the system around x, y, or z?

And so a lot of their models were actually, frankly, spherical, like billiard balls or ball bearings, as opposed to only circles. So we'll come we'll come to that as well. These are all good questions. Other questions here from the chat? Or from not the chat, anyone else have any questions that they want to pose for the group? Feel free to just raise your hand at this point too, now that we can see each other.

I like the comment about putting your hand in jelly, now your keyboard is sticky. My apologies for your keyboard. I'm just trying to catch up on the chat here. Ah, there's a really interesting comment here from Sabrina. I like this. So Sabrina writes that I don't know what a GUT is or grand unified theory. But it seems like we're moving back towards everything being the same thing again with a smile emoji.

So one of the things that maybe it comes back to [? Iabo's ?] question. So for some of these folks, the aether was a word for something that you didn't really know what it was-- a subject, a topic they figured had to be everywhere because they could infer its effects. If I wiggle something here, something happens there. There must be some medium that transmitted the influence from A to B.

How could a moving bar magnet possibly affect an electric current? Because they're both immersed in the shared medium, this all-pervasive medium. And so they gave it a name. They gave it a name long before they had any articulated descriptions or analogies of it. They called it the light-bearing aether, luminiferous aether decades before they had any more specific ideas about it.

And so in that sense, I think it is kind of like we're in a similar situation today-- and we'll talk a bit about this near the very end of this semester-- with our quest to understand what's the world made of. And we have some other-- we have very finely articulated models, like the standard model, and this kind of neutrino, and that kind of electron, and up quarks and down quarks, and gluons, and Higgs boson, all this very specific stuff.

And that amounts, as you may know, for not more than 5% of the kind of mass balance of the universe. We've explained 5% of the universe with unbelievable precision, out to 12 decimal places. Thank you very much. And we know Nothing with a capital N, Nothing about the other 95% of the energy balance.

So we give it names. We call it dark matter and dark energy, again as we'll come to near the end the very, very end of the term. And I think, in some sense, I have some sympathy with either my present colleagues and myself and/or with the people of Faraday's and Maxwell age. They didn't know what the aether was, but they knew it had to be there. It was conveying all these effects. They could measure the effects of disturbing the aether, as far as they were concerned.

So they gave it a name, a kind of placeholder name, partly to help organize their studies. Oh, I'm studying the luminiferous aether as well. That helps get scholars on the same page. They would give their best estimates of what they thought the thing was like and how it would behave. But they didn't know, right? They had better or less well compelling responses.

And I think we're in a very similar situation today-- not by design, not by our hopes-- because we have been stymied now for decades to get any more carefully articulated knowledge about what specifically is dark matter that seems to be filling every galaxy much, much more so than ordinary matter. And what particularly is this other separate kind of stuff that we now call dark energy?

So I think, again, I don't want to say we've learned nothing since 1820. But we can see some maybe humbling, humility-inducing parallels between our best efforts today and the efforts of very, very earnest, talented folks from long ago. That's a great-- again, we'll keep that in mind as we march forward throughout the term.

Julian asks, why were they so reluctant to accept action at a distance? And how did we come to accept it? Oh, good. Let me take the first part first. Action at a distance, that's a great topic. Newton famously says, when it comes to the phenomena of gravity, I feign no hypotheses. Hypotheses non fingo was the Latin.

He says, I think that quantitatively the effect of one mass exerting a force on the other goes as the product of the masses divided by the square of their distance is the law of universal gravitation. What's the underlying reason for that? He says, for that, I feign no hypotheses. He actually had a lot of hypotheses. He just knew not to write them down.

A lot of scholars have argued that he was actually convinced, at least by analogy, that gravity was a kind of alchemical effect, even at a time when alchemy was in poor repute. So he said outwardly and publicly, I don't know what it is. But he seems to have at least been inspired in part by these very-- what we would now call occult forces, where something can somehow have an influence on something else instantly across time and space.

So Newton was comfortable with the notion of action at a distance, that somehow the Earth could instantly tug on the moon and vice versa without having to wait for some influence to travel between here and there. That, even in its day, was criticized by a number of scholars, even in Newton's own day because they thought it did sound occult. It sounds like witchcraft.

How could this thing possibly affect something over there if everything else I see-- I throw a pond-- excuse me, a rock into the pond. I see ripples spread out. The distant edges of the pond aren't affected by my rock until the ripples get there. There were all kinds of common sense observations that suggested to people like Leibniz-- I mean, like Newton's very smart contemporaries-- that the physical world seemed to convey influences by requiring some time for influence to travel from A to B.

So Newton's action at a distance already at least had a curious reputation among the savants who cared. And then you get to someone like Faraday, and Oersted, and Thomas Young. And now, they figure they have a reason to finally give up or to finally reject that action at a distance because they have separate reasons based on this wave theory of light saying, oh, there's a seat.

There's a physical explanation available to us for how all these physical phenomena are transmitted from A to B across space. They're all sitting in this elastic medium, this aether. And that can have a local disturbance that propagates. So there was, so to speak, an added reason to pile on and say, not only did people wonder about Newton's action at a distance in Newton's own day.

Now, roughly 100, 110 years later, we have new inputs. We have new evidence from our investigations that suggest that Newton hadn't known about it or hadn't taken into account at all, all the more reason to try to find out a local causes yield local effects kind of response. So that starts getting more and more compelling to this next generation.

Now, Julian asks, because he knows what's coming, why do we now accept action at a distance? We do and don't. We have a love/hate relationship with it. I assume, Julian, that you're referring to quantum entanglement or so-called quantum nonlocality.

If you're not referring to that, I'm going to hijack this. And I'm going to talk about it because I just love it. So we're going to talk about that actually in a few classes, a little bit later this term. So how have we made our awkward peace with a very certain kind of action at a distance, not easily, not right away, and thanks to a lot of hard and contested thinking? That's a preview for lecture 12, I think.

So we're going to talk about quantum nonlocality because it's one of my favorite topics in the universe. So we'll get to that, too. But for a long, long time, between let's say 1800 and the 1960s or '70s, people were quite content to say that action of distance is always, always bad. We never want it. We never want it in our physics. And they had a range of reasons why they thought that was going to be an acceptable approach.

Aiden and asks, how accessible were the lectures and later universities' research? I mentioned that Faraday did not have much money when he was younger. But was he the exception to the rule? Or did class discrimination prevent-- oh yeah, very good. So in Britain, in British history, I mean, the rough shorthand is we're always talking about class discrimination, so including in Faraday's time. Faraday was absolutely the exception who proved the rule.

It was, as I say, this rags to riches story. It wasn't that there was no social mobility. And you can read any Charles Dickens novel to see some characters who have a breakthrough and rise above their station in the language of the time. But in natural philosophy, Faraday stands out as a pretty unusual case.

And the universities as well, there were scholarship students at places like Cambridge, then as now. So it wasn't only very, very rich children of very rich families who could go to university. But it was tilted very strongly that way. And in fact, it's only in Britain in the middle decades of the 20th century, like 100 years after the days of Thompson and Maxwell, when there's a very large university reform throughout Britain to make much more accessible colleges, universities for many, many more for people from many more backgrounds.

That large scale national university reform comes really, in earnest, like 100 years later. So there were students on fellowship. In fact, Isaac Newton was a scholarship student when he went to Cambridge in his own lifetime in the 1600s. Often, they would have to be basically like a butler or a maid for their roommates. Not an ideal situation, right?

This was not like work study. It was like, you have to go clean up for your rich roommate, not what I recommend today. So there were ways to be a student at some of these elite British universities from more humble backgrounds, not great. This was well outside the reach of someone like Faraday. So again, the latter didn't extend arbitrarily low.

But there was a range of social classes in universities in this time, not a full range. And that begins to change pretty slowly all over the world, including in Britain, including, frankly, in the United States. And of course, we still have challenges even here. So that's a great question. Faraday was, indeed, the exception who proves the rule within natural philosophy. Yeah, great question.

Any other questions there? If not, I realize we're pretty much at the hour. Those are great questions. Thank you so much. I hope it's not too clunky. I'll try to get better at flowing in the questions and discussion throughout these Zoom lectures. Anyway, thanks, everyone. Great, great questions. I'll post the video as soon as it's done processing. It'll go to the Canvas site. And we'll pick it up there for next week. Everyone stay well. See you soon.