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DAVID KAISER: Our last main lecture, at least for quite a while in this class, on our relativity subunit. And today, I want to talk about a project that I've been working on for a long time, probably since-- not since before you were born, most of you, but since many of you were probably, like, literally toddlers.

I've been working on this project for a long time. It's slow. It's crazy slow. But it's also been really fun for me, and hopefully some of it will be of interest for you as well.

So this is a book that I'm just slowly, slowly kind of working on, little pieces here and there. And I think it kind of fits into this part of our class, so I thought we'd talk about this as a kind of wrap-up for this early relativity unit.

And then on Wednesday, we'll launch into yet another crazy new intellectual adventure. We'll start thinking about quantum theory. So today, we'll have our heads squarely in relativity.

So I like to think about this material in the following way. I like to start out this way. If many of us, maybe even before this class had started, had been asked to picture in our minds Albert Einstein, I bet a lot of us would have a picture kind of like this one-- would come to mind. So late, late in his career. He's an old, old man, kind of rumpled in his sweatshirt, near the end of his career.

And more importantly in this picture, he's alone. He's just kind of sitting quietly with his thoughts. All he seems to need are note paper and quiet. He once had famously told a journalist that his ideal occupation would have been a lighthouse keeper. He really, really wanted to be left alone, at least that was the story. That's what it was meant to emphasize.

And yet as many, many scholars have been finding for decades now, this kind of image, this kind of carefully crafted image of Einstein as all alone, as separate or apart from the world, from the world of human affairs, that image doesn't really hold up very well. Once we start doing a little digging, we don't have to work very hard to find a very, very different image of Albert Einstein the person-- not one aloof or apart from the world, but actually as a kind of thoroughly political animal, someone who is deeply enmeshed in political moments, political causes throughout his entire life, very bravely as a young person, right through the end of his life as a very, very famous celebrity.

So you don't have to take my word for it. This is of my favorite examples. The US Federal Bureau of Investigations, the FBI, considered Albert Einstein such a dangerous political radical-- that was their concern-- that they kept him under surveillance, much of it totally illegal surveillance, for 20 years. They thought he was a thoroughly political creature and, as far some were concerned, a kind of dangerous one-- so radical.

So here's one example from his FBI file. It was classified for decades even after his death. It was released in response to a Freedom of Information Act some years ago. So now anyone can get his entire file at the click of a button. Just Google it, and you can find the whole PDF.

So we have primary sources, like the FBI'S own reckoning of this very political figure Albert Einstein. We have lots and lots of really interesting materials by other scholars more recently as well. Einstein's own writings on politics, his essays in newspapers, his speeches before large gatherings, and analysis of the kind of changing political views that he was espousing and debating about.

There's a very interesting book you might enjoy by Fred Jerome called *The Einstein File.* It's actually really based on this FBI file and other materials. So we have lots of examples from early in Einstein's career all the way to the end that he was, in many ways, thoroughly engaged in the political world, very much unlike this kind of stereotypical image, with which I started, of Einstein alone and apart.

So that really has been driving my questions for this book project for a really long time, which is how to think about what is arguably Einstein's most significant scientific legacy, the general theory of relativity, which we'll talk a lot about today. That scientific work has also usually been cast, much like Einstein himself, as this thing apart-- as somehow beautiful, and pristine, and separate from the kind of messy dramas or the human history over the course of the 20th century.

One of my favorite examples of that comes not only in verbal descriptions, but even in pictorial form. This cartoon I'm showing you in the middle of the screen here is a cartoon called the "Temple of Relativity." It was drawn by the very accomplished physicist and cosmologist George Gamow. Some of you might recognize Gamow's name. He helped invent what we now call the Big Bang picture of the cosmos. He was a very accomplished nuclear physicist and cosmologist. He was also an award-winning *Popular Science* writer, and he did his own illustrations. He loved making these whimsical cartoons.

So in one of his popular books from the early 1950s, he drew the "Temple of Relativity". It's meant to bear more than a passing resemblance to the Taj Mahal. It is supposed to be some pristine temple, sort of apart from the messiness. You can see here-- we'll talk about this soon today-- carved into this seemingly marble dome are what we now call the field equations from Einstein's general theory of relativity. We'll talk about those. Here is something called the geodesic equation. These are actually equations taken directly from Einstein's relativity, but meant to be this kind of pristine temporal apart from the messiness of the world.

It wasn't only Gamow. This was reinforced over and over again. Here's another one of my favorite examples in the preface to a relatively influential, very nice textbook by the mathematical physicist John Synge back in 1960, so even after Einstein's death. And he writes in the preface of this book all about general relativity. "Of all physicists, the general relativist has the least social commitment. Let the relativist rejoice in the ivory tower, where he has peace to seek understanding of Einstein's theory, as long as the busy world is satisfied to do its jobs without him. Which seems to me to sound an awful lot like that image of Einstein the person, kind of alone and apart from the hustle and bustle of everyday life.

And so what's been driving this research project for me for, well now, going on 20 years-- the better part of 20 years-- is is this any more accurate for our understanding of general relativity than that earlier portrait of Einstein was compared to the now enormous documentary evidence we have to the contrary? Einstein himself was actually not an anti-social, anti-political person. He was thoroughly enmeshed in the flux of everyday life.

And as I've been working on this book project, some parts with very dear friends and colleagues, but it has that same question about general relativity itself. Is that also part of the kind of flux of the human history and not somehow separated or apart?

So today, we're going to talk for the first part of the class about Einstein's own roots to what became known as the general theory of relativity. And for that, of course, you have two different primers, one of them totally optional, on the Canvas site. One of them I assigned as part of the regular reading is hopefully a helpful orientation, very little mathematics. And strictly as an option for those who might be interested and have a little more time, there's a little more quantitative primer I wrote up some years ago for some UROP students in my physics research group-- totally optional, but for those who are interested.

So we'll sit for a while. What was Einstein thinking about? What became this theory that we now know as general relativity?

Then we'll look at two moments in the kind of expanding history of that work, one of them pretty close to Einstein's own day, where Einstein himself was still a central partner in helping other people think about this new work-- teach them, engage with them, debate with them, and so on. And then we'll jump ahead in the timeline a bit. We'll look at some efforts soon after the Second World War, actually closer to home, some of it handled right here at MIT and associated laboratories. So for that we'll jump ahead in our timeline, and then we'll kind of turn the clock back a bit for Wednesday when we jump into our quantum theory unit. So that's our plan for today, is we're going to sit with general relativity really across a pretty long stretch of time.

Now, the first thing to recognize about the general theory of relativity is that it took Einstein a long, long time to get there. He worked for the better part of a decade, nearly 10 years nonstop. Between the publication that you now are very familiar with is a publication on the electrodynamics of moving bodies, what soon became known as the Special Theory of Relativity. That was published in 1905, perhaps over the objections of referees like yourselves for your paper one assignment. That came out in '05.

He wrapped up what we would now recognize as the General Theory of Relativity fully 10 years later, late in the autumn of 1915. This is an amazing story, where we have unbelievable documentation of many, many, many of these steps along that 10-year intellectual journey. We have, for example, Einstein's own personal notebooks. Here's just a few pages. There are a bunch of these. These are from a critical moment around 1912-13 along this path between '05 and 1915. These have been kind of lovingly poured over by an international team of physicists, and historians, and philosophers of science, transcribed and then translated oftentimes into English. His notes, of course, were in German.

I love these because they show him making mistakes all the time-- crossing things out, starting all over again. He made enormous numbers of mathematical mistakes, which gives me at least a little bit of hope. And we can now see almost day to day for certain critical periods how was his thinking changing?

In addition to his notebooks, we also have this unbelievable resource called the *Collected Papers of Albert Einstein,* which had been edited and put together again by an international team of physicists and mathematicians and historians and philosophers-- a very large team. They've been working at this for decades. And they put out a new volume roughly every year and a half to two years. They've now gotten all the way into the late 1920s, starting from his birth in 1879. He lived until 1955. They have 30 years still to go. I wish them luck.

It's an amazing resource, and they also do regular translations into English as well. It's an amazing, amazing resource. Many, many, many of these volumes now are available entirely for free online, too, which is even more extraordinary. So anyone can now just read through Einstein's mail, even in English, let alone in German. It's extraordinary.

So with these resources, we can document, to unprecedented precision, this 10-year intellectual work. I'm not going to take you through that in real time. This class won't take 10 years. But I want to give some highlights along the way.

So we know from that body of work that Einstein began working toward what would become the General Theory of Relativity as early as 1907-- not right in 1905, but pretty soon afterwards. He began thinking of it because a different, very prestigious German physicist-- in fact, one who would go on to win the Nobel Prize, named Johannes Stark-- invited Einstein to write a review article. Stark was not an expert on relativity. He was immersed in the behavior of atoms in external electric fields. Some of you might still recognize Stark's name. We still talk about the Stark Effect, or if we're speaking German, the Stark Effect-- same guy.

So things like the impact on the radiation that comes out of certain excited atoms, if the atoms are in some electric field, that was what Stark was immersed in. He was an editor of a different journal, not the *Annalen der Physik,* but a kind of annual reviews journal. And he invited young Einstein, saying this stuff is pretty interesting. People aren't paying attention yet, which was correct by 1907. As we saw last time, very few people had turned to pay much attention to Einstein's work, so Stark very generously invited young Einstein to write a review of his own work to try to get a little more attention in this other journal.

And while working on that review article, Einstein began trying to generalize his work on special relativity. As you may remember, for special relativity, he had restricted attention to observers who moved at a constant speed. They didn't have to be sitting exactly at rest. It wasn't clear what exactly rest would mean anymore if motion was relative. But he would restrict attention to people who were moving at constant speeds with respect to each other, neither speeding up or slowing down-- not accelerating. That's what was meant by this term inertial observers, or inertial frames of reference.

So now, the next obvious question to ask would be can you generalize those results to arbitrary states of motion, not restricted to only constant speeds? What if an observer were speeding up or slowing down? Can you accommodate this framework of relativity to accelerations? And that's what he began thinking about in the context of expansive review article for Johannes Stark's journal.

And as Einstein recalled some years later, he was sitting at his desk at the patent office. He still had his day job. He hadn't even been promoted or whatever. And he looked out the window, and saw across the street a window washer up several stories high, who had an accident and slipped and fell off the scaffolding.

Now, luckily, Einstein said, it had a happy ending. The window washer was caught by a kind of canvas canopy. He did not crash to the ground. He was unharmed. But what Einstein focused mostly on was the experience of that window washer as he was falling between when he left the scaffolding and when he was captured by that canvas awning, the canopy.

During that intervening period, as he was accelerating in free fall toward the ground, his tools were falling at the exact same rate as he was-- his bucket, his squeegee, anything, all his tools that he had with him up there on the high scaffolding. So while he was accelerating, everything with him was falling at the exact same rate, and that suggested to Einstein that that was different from what would have happened if he had stayed at rest and just dropped his can. It seemed that the acceleration had somehow counterbalanced or canceled out the effects of gravity.

If the window washer was standing still and dropping stuff, they would fall further and further away from him. Instead, everything is falling exactly with him, as if they hadn't been dropped at all, as if they were feeling no gravity whatsoever. Relative to him, everything fell at the same rate. It looked very much like acceleration was somehow canceling the ordinary impact of gravity. He starts thinking about this. He calls it, in fact, "the happiest thought of my life" as early as 1907.

He then does what Einstein often did in this part of his career. He begins thinking through very simple sounding scenarios, just like the opening passage in his 1905 paper on the electrodynamics of moving bodies. Now he's not thinking about a moving bar magnet and a conducting coil. He's thinking about people like that window washer in various states of accelerated motion.

So first he considers someone at rest in an elevator, and the elevator has no windows. So this person is sealed, basically, in this small windowless box, and she's sealed in there with two very important scientific tools-- a tennis ball and a stopwatch. No lasers yet, because they weren't invented.

So the person inside the steel box, at rest on the ground floor, no motion, conducts a very extensive experiment. She holds out the tennis ball, lets go, and then times how long it takes until the ball hits the floor.

OK, then unbeknownst to her, her advisor, who's not a great advisor, grad students, raises the entire elevator up to the top floor, and then cuts the cable. And now, knowing that she has time for one last experiment in her unfortunately short career, the grad student inside the elevator does this one more time. She drops the tennis ball and times how long it's going to take till it hits the floor.

It never hits the floor, at least not while she's watching. While she and the entire elevator are in free fall, much like for that window washer, everything falls together at the same rate, which means the tennis ball doesn't really leave its initial position relative to, say, her hand. The ball does not race toward the floor as it had over here when she let go when the elevator was at rest.

While the entire laboratory frame-- while the entire elevator is falling, in fact accelerating in free fall-- then, much like for the window washer, everything inside that laboratory environment falls together at the same rate. So you don't have a relative motion of the ball leaving her hand and racing toward the floor, OK?

Then Einstein takes this to the opposite extreme. Now, imagine that this grad student in the elevator has an identical twin. She's sealed up in a spaceship with no windows, out very far away from any large planets or stars or any masses. So she's out in basically empty space.

She turns on the engine on her rocket ship, so now her rocket begins to accelerate upward at a faster and faster speed while the engine is firing. So now her entire windowless frame is accelerating at a constant rate upward.

She does the same experiment her sister had done. She releases a tennis ball, and times how long it takes to hit the floor. And, in fact, once she lets go it will hit the floor. We would say from outside, if she lets go, the ball hangs still. There's no external forces on the ball, but meanwhile, the floor of the laboratory raises up-- accelerates upwards toward it. But as far as she knows, all she sees is the following. She releases the ball, and some little while later, some time later on her clock, the ball smacks into the floor.

Now she turns off the engine, turns on retrorockets, brings her ship to rest. So now her ship is at rest away from any large masses, away from planets or stars. It's not moving, let alone not accelerating. It's just at rest in outer space. She does the same experiment-- releases the ball, and now the ball just hangs there. It doesn't change its relative position with respect to her hand or the floor. It doesn't crash into the floor.

So now we have these four scenarios. Sometimes when the observer releases the ball, a little while later it smashes to the floor. Other times when the observer releases the ball, it hangs there and doesn't race toward the floor.

Now, Einstein pulls the same trick he pulled in 1905. He says, there's an asymmetry in the explanation. There aren't actually four distinct phenomena, only two. The ball either does hit the floor or it doesn't. Again, it's not like the coil is really in motion-- excuse me, the magnet really in motion and the coil at rest, there's a relative motion, moving magnet induced current. He's pulling the same kind of argument here at the start of his thinking about how to generalize his Special Theory of Relativity-- only two phenomena does the ball hit the floor or not.

However, until this time, physicists had given totally separate, non-overlapping physical explanations for what Einstein argues was really the same thing. They'd given too many explanations for too few phenomena.

So let's take the cases where the ball does crash into the floor. When we're describing the situation where the elevator is at rest on the ground floor here on Earth, we appeal to things like gravity. The massive planet Earth exerts some force on that tennis ball. It exerts a gravitational attraction that pulls the ball downward, and so therefore the ball, under the influence of gravity, smacks into the floor. That's case one.

For the case of the accelerating rocket ship in outer space, we never use the word gravity at all. We never even talk about forces really. The ball is subject to no forces. Once she releases it, nothing is touching the ball. Nothing is exerting a force. But the floor of the laboratory is accelerating upward because of its firing engine. We certainly never need to use the word gravity there.

And so as far as Einstein's concerned, if these are small laboratories with no way of gathering information from the outside world-- no windows, no radios, no telegraph stations, and so on-- then how could anyone ever distinguish which scenario they were in? How would one twin know that she was really, really in an elevator at rest in a gravitational field on Earth and her identical twin really, really know that she's in an accelerating spaceship very far from the Earth or any other planet? All they could do was perform local experiments in their local laboratories. At least that was the argument Einstein had made.

You can still hear the echo of a Ernst Mach positivism. What could become objects of positive experience for them? Conduct tests like drop a ball and time how long until it hits the floor.

So these thought experiments are what help Einstein begin to flesh out that intuition or that insight that he seemed to have gotten watching the window washer fall from his window. The gravity and acceleration become interchangeable, that the effects we might attribute to one could just as readily be attributed to the other, depending on situations that might be beyond our observation. He calls this the Equivalence Principle-- the deep underlying equivalence, as far as he's concerned, between the effects of gravity and acceleration. That's what he calls the happiest thought of his life.

Now, that sits with him for a little while. He goes on to his other work we'll look at quite-- he was busy with many things in the same time period, Quantum Theory, as we'll look at in the coming classes. But these ideas can kind of sit with him. And a few years later, he develops his follow-on thought experiment-- still thinking very simply, not quantitatively really at all, very, very simple kind of pictures and thought experiments.

Imagine that spaceship, now in outer space, really does have some windows. Let's say it has a window near the top hatch and near the floor. So it has windows near the top and near the bottom. Maybe it's all windows, very strong, reinforced Plexiglas or whatever.

And now, let's say that a light beam pierces the ship, enters the ship from near the top-- one of these top windows-- while the ship's engine is firing, so while the ship itself is accelerating upward. The light beam comes in through a top window, and while the light beam traverses that ship, in the short while that the light beam travels across the ship, the ship itself is accelerating upward. So by the time that light beam crosses the spaceship, it exits near the floor. It enters near the ceiling, exits near the floor, because the ship itself has accelerated during the time the light wave has been traversing the ship.

Now, he says, what would that look like to observer inside the ship? Well, she would see the light beam enter by the top hatch and exit by the floor. She would see the path of that light beam bend. What the observer inside the ship would see is oh, the light entered there above my head and left below my feet. Its path has been bent.

Now, if she really believes the equivalence principle, she could say the same phenomenon that we attribute to acceleration must occur in situations when we talk about gravity. If gravity and acceleration are interchangeable-- that's the upshot of this Equivalence Principle-- then this bending of the path of light that we might have attributed to the ship's acceleration, that exact same phenomenon should be happening in a gravitational field as well when the ship is at rest.

So Einstein convinces himself-- so far, no one else-- by 1910 or 1911 or so that gravity must bend the path of light. If we can attribute those effects due to acceleration in a frame that otherwise has an absence of gravity, then what if we had no particular motion? The ship is at rest, but in a gravitational field-- Equivalence Principle says the same thing should apply.

Now, that begins a new train of thought. Remember, for Einstein, he had convinced himself by 1905 that light is special. Remember, that was the second postulate of his 1905 paper on the electrodynamics of moving bodies. Nothing travels faster than light, and we all agree on its speed, at least according to Einstein's second postulate.

So people can use light to chart shortest distances between two points in space. Nothing could possibly have gotten from point A to point B faster than a light beam, if everyone agrees on its speed and nothing can go faster than light. So light becomes a kind of mapping tool. We can use light beams, at least in our imagination as a thought experiment, to map out the shortest possible distances between different locations or positions in space.

So now, if a light beam could be-- if its path could be curved by gravity, due to this argument from the Equivalence Principle, that sounds to Einstein like saying that space through which the light is traveling itself could be curved by gravity, that the path that the light is mapping out is telling us something about the underlying space and not just the accidents of the path of the ship or the presence of this or that planet.

This mapping tool, on which we should all agree, should enable us to map the shortest possible distances throughout space. And if the path becomes bent by this kind of argument then maybe space is bent, or even post-Minkowski space time. This is the first time where Einstein begins to give grudging admiration or respect to the work from Hermann Minkowski that we looked at together last time.

This is where, remember, Minkowski, the geometer, had said the real meaning of Einstein's Special Relativity was that space and time themselves meant very little. There was a union called spacetime that mattered, and we should map that using all the tools of geometry. Einstein, years later now, four or five six years later-- four years later-- comes back to that kind of geometrical view as well. We should think about spacetime and not consider the geometrical properties of that object space and time fused together.

And if spacetime could be bent-- that means the rules of geometry that we apply to quantify relationships in that spacetime-- they might not be the geometry that he learned as a young student. They might not be Euclidean geometry. In fact, they would, in general, be non-Euclidean. They would be the geometry that professional geometers had developed in the middle decades of the 19th century, just before Einstein was born, to generalize what we used to just call geometry. Now we have to specify, oh, we mean Euclidean geometry, as opposed to these self-consistent but different variations.

And, by the way, here I want to pause as well. Again, some of you might be familiar with this. There was a really pretty cool 10 or 11-minute YouTube video that my son shared with me. He's in high school and getting really into computer graphics and computer gaming, unfortunately. That's in a making games, not just playing them. But he found some really cool YouTube videos on visualizing non-Euclidean geometry, and I thought one was pretty cool. So I put that in the Canvas site as well-- totally optional, but if you've got 10 minutes to spare, I think you might enjoy it-- much better dynamic animations than this.

But the idea was what even in Einstein's day, this stuff was well known to the professionals, to the mathematicians who were geometers like Minkowski. If we practice geometry, say, on the surface of a sphere, what comes to be called a positively-curved spatial surface or spatial manifold, then a lot of the regular rules we're used to from ordinary or Euclidean geometry, they no longer apply.

So for example, we can construct parallel lines, two lines that are each perpendicular to the equator, say, of this sphere. So they both cross the equator by making the same angle-- sorry, the same right angle. So they're perpendicular to the same line. That should suggest they're both parallel to each other by Euclid's usual rules.

And yet, they don't remain parallel forever. Those lines that are parallel to each other here converge at the North and South Pole of the sphere. So parallel lines don't stay parallel. In fact, they can intersect. Likewise, we can construct triangles, the shortest possible paths to make a closed, three-sided surface or three-sided shape. We can do that with, say, these two lines that each cross the equator and then converge at the North Pole.

Well, now we've made a triangle on this positively-curved surface. But the sum of the angles inside that triangle, by necessity, have to add up to more than 180 degrees. We have 90 degrees here-- one right angle-- another 90 degrees here-- that's two right angles. We've already hit 180, and there's some angle-- it could be 1 degree, it could be 100 degrees, but some angle larger than 0 up here. So the sum of the interior angles of our triangle exceed 180, and that should never happen in Euclidean geometry. So there are all these ways in which the geometry of space time that Einstein kind of grudgingly begins to think he has to worry about are going to depart from the ordinary rules of Euclidean geometry.

And now he begins to sweat, because he cut almost all of his math courses as a university student. Remember, Minkowski had such a low opinion of him and vice versa. When he was a college student, Einstein used to borrow the notes for math classes from mostly two people-- his girlfriend, who became his first wife, Mileva Maric, and from another friend of his, Marcel Grossman.

Grossman loved the mathematics. He didn't cut any math classes. And, in fact, he went on to a very illustrious career as a professor of mathematics. Grossman's own specialty, in fact, became these non-Euclidean geometries. He loved this stuff, like doing geometry on the surface of a sphere or on a hyperbolic satellite surface.

So as luck would have it, as I mentioned briefly in our previous class, Einstein started getting new job offers starting in like 1909, 1910. By 1912, he'd been hired back to Zurich for a new academic post. In fact, he was at the same university where Grossman was now teaching mathematics. So we went to his friend Grossman, and said basically, can you help me out again, just as you bailed me out in college?

So they began collaborating very actively together. Grossman took on Einstein, his peer. Einstein was a professor of physics. But Grossman began tutoring him in what was to mathematicians by this point pretty familiar geometry, the geometry of non-Euclidean spaces. So together, around 1912 and '13, they began publishing a number of articles together, in particular Grossman teaching Einstein the rudiments of how to do geometry on curved surfaces.

And then Einstein eventually moved to a new position in Berlin. They stopped actively collaborating. But Einstein had learned enough from Grossman during that very intense period of collaboration, around 1912, 13 or so, that he was able to then continue those new mathematical techniques on his own.

And then by November of 1915, two more years still even after connecting with Grossman-- two or three years-- he arrived at what we now call the Field Equations of Einstein's General Theory of Relativity. He didn't get there with Grossman, but using the tools that he learned with Grossman, he got to this expression. This was what was carved into that make believe marble temporal in George Gamow's cartoon.

I would like to say I'm not advocating body art, but if you're looking for a new tattoo, you can do a lot worse than this. It's pretty awesome. It's short enough to tweet. This is just an extraordinary expression. What it's doing is quantifying what become the new rules for Einstein's General Relativity.

This side over here, the R's and the G mu nu and all that, that's really what he had learned from Grossman. That's the mathematics of characterizing the curvature or the warping of a curved spacetime, the degree to which it deviates from ordinary or Euclidean geometry. This is doing things like gradients, like rates of change, how much does a surface bend between point A and point B, and how do you quantify that? And again, that was a bit vague. I have a bit more on that in the optional primer on the Canvas site-- totally optional.

This is the mathematics of how to quantify the bending and warping of space and time, mostly with the techniques of which he learned from Grossman. The other side is characterizing where the stuff is. This is talking about the distribution of matter and energy throughout space. Where is this stuff? How densely is it packed here versus there?

And so as the later general relativist John Wheeler famously liked to say, we can read this equation in either of two ways. We can say that warping space tells matter how to move, or matter tells space and time how to bend. It's this incredible union between the geometry of space and time and the distribution of stuff, of matter and energy. And that's what becomes the General Theory of Relativity.

So by the end of this 10-year journey, by no means when he started-- by the end of that, Einstein had convinced himself, albeit, as we'll see, almost no one else-- he convinced himself that gravity was nothing but geometry, that there was no force of gravity at all. There was no need to talk about a big mass like the Earth tugging, exerting a force on, say, the tennis ball in our lab assistant's hand, or on the moon, or the sun exerting a force on the Earth. The entire language of gravitational force, like from Newton, was simply kind of beside the point. It was superfluous, much like Einstein thought the ether was.

What's really happening, according to Einstein, is that objects are following the shortest possible paths they can, but they're doing it through regions of space and time that need not be flat. So things are moving on as short a path as they can through a geometry that might be pretty unusual-- through curved space and time.

So in this regular example you've probably seen before, you can think of warping spacetime as a stretched, taut trampoline-- a kind of rubber sheet. We can plop a large, heavy bowling ball in the middle. That could be like the sun, a very large mass. It will have a larger, quantitative effect on the geometry near it. It'll warp space and time considerably. And then smaller objects, like a ping pong ball, which could represent the Earth-- they're going to skitter around in that now-warped surface, and that warped spacetime.

So the Earth is trying to move on as straight a line as it can. It's just getting constantly deflected from what would have been a straight path because the surface on which it's moving has been bent, has been warped or deformed by the presence of this large mass of the sun. So that's what Einstein convinces himself after this 10 years-- really eight years-- of pretty solid work. That's how we should account for gravitation.

So let me pause there, stop sharing my screen, and ask for any questions. Any questions on any of that? No questions at all? This is totally intuitive, everyone already knew this? Come on. I mean, you're doing better than Einstein by not cutting your classes, so maybe it all adds up that this would be totally sensible for you.

If not, I'm happy to march forward. I want to make sure we have that kind of basic sense of how Einstein, over this long period, has to develop both new tools, or actually has to learn what were by then standard tools, and apply it to what seemed like a very familiar situation.

Aidan asks, were people believing Einstein, or were they still doubting? Very good. So let's talk about that in the next part. So the short answer is, most people hadn't even heard about this yet, for reasons that we'll talk about in the next main unit. And some of those who did hear about it were very, very skeptical, and maybe for understandable reasons. That's even stranger sounding, I think, than all that relativity stuff, right? There's no force of gravity? Every single success from Newton's physics is thrown out? The Universal Theory of Gravity means nothing-- that kind of thing.

The public's perception of gravity at this point-- good question from Silu-- was really, for those who had at least a little formal schooling, even through high school, would have learned about things like the great triumph, as it was seen at the time-- the great triumph of Newton's universal gravitation. It wasn't just that Newton seemed like he got it all right. Newton's work had been subjected time and time again since Newton's own day right up to Einstein's day to increasingly precise quantitative tests, where it passed virtually every known test, from astronomy, from celestial mechanics. It helps astronomers predict where various objects should move in the sky by assuming there was a force of gravity between, say, the sun, and the Earth, or between the Earth and the moon.

There were a few little anomalies that kept people busy, but it was otherwise this crowning achievement. People had used it in the late 1700s, early 1800s-- I can't remember now. I'd have to look it up-- to predict whole new planets, from the wobble in other objects. So the planet-- was it Uranus or Neptune-- was discovered that way. Now, I'm really forgetting.

There was so much confidence in Newton's laws, including his Law of Gravitation, that people could actually find new stuff in the sky that had been literally unknown to the ancients, on the strength of using Newton's law of gravity to go out and find it and make sense of it. So it was a pretty big deal for Einstein to say, oh, there's no force of gravity. That's a lot like saying, oh, there's no ether. And so, not surprisingly, people needed a little more evidence, and more than just his say so, to jump on board.

And as Horace knows from reading ahead, we're going to see a lot begins to change in 1919. We'll come to that real soon. Excellent questions. Any other changes here?

Let's see. Jesus says, what does it mean when we talk about the energy of an orbit? Ah, that correlates to a difference in energy for a different geometry of spacetime. Yes, that's very good.

So it gets actually a bit complicated. Einstein himself didn't even quite realize this at first. One of the first people to really tackle that was actually the extraordinary mathematical physicist Emmy Noether, who was in Gottingen, who began thinking about how can we characterize energy in a self-consistent way in the context of this new framework for curving spacetime?

So how to handle energy, or energy densities in general relativity, was actually really tricky. Einstein himself was certainly not the first to get there. We now have tools, some of them dating back as early as to Emmy Noether from around this time, with which we can actually characterize the energy-- at least within one observer's frame, the energy of, say, a particular orbit. We can compare energy differences. We can certainly talk about the energy density, how much energy per unit volume of space. So the energetics get complicated as well.

And Horace now tells us he wasn't only reading ahead. He actually grew up near where part of the next story is going to take place. So that's cool.

So let's turn to the next part. Actually, good questions, if any more questions come up, of course, as usual, feel free to put it in the chat or wait till our next round. Dia says, how do we move the equivalence principle to the energy density tensor? OK, yeah. So that is a very good question.

So that's really what he learned from Grossman. So Einstein's first efforts on this were long before he'd actually learned any of this fancy math from Grossman. He was trying to do things with scalar functions, potentials-- a lot like the kind of work that William Thompson and James Clerk Maxwell were doing for electrodynamics.

And he was, therefore, trying to generalize the Laplace's Equation. If you remember from your classical mechanics, one can characterize Newton's Law of Gravity in terms of not only forces, but in terms of simpler mathematical quantities like scalar functions-- sort of a vector force, you can have a scalar relationship, so scalar potential phi.

And then you can relate the changes in space, the gradient squared, or nabla, of that scalar function. That would then be sourced by the energy density or by the matter density, by where the mass is distributed per unit volume.

So Einstein began thinking about gravity should still be somehow related to where the stuff is in a kind of density. But then we learn from the mathematician Grossman there are more complicated mathematical ways to characterize these non-Euclidean manifolds, like these mathematical objects called tensors. And you can learn more about those, if that's new to you, in that optional primer. Then to keep a tensor relationship to make the equation self-consistent, Einstein had to relate a tensor quantity for the curvature of space and time to some tensor generalization, no longer a single-scalar field that would characterize where the stuff is. So Einstein began thinking about a very simple single scalar potential, and therefore a single scalar matter density, and he began learning from Grossman how to treat that in a more mathematical generalized way.

Victoria says, if General Theory says objects essentially fall on the shortest paths, what point are they trying to get to? Ah, so they're still trying to minimize a way of characterizing the energy of their path. Einstein didn't know that yet. That wasn't true, and that wasn't on his mind in 1915. But the paths these objects will take still come from minimizing the kind of total energy associated with the path. They're just doing so through a spacetime that's no longer Euclidean. And that's the kind of work that people like Emmy Noether, and David Hilbert, and eventually Einstein himself began to work on in the months and years after November 1915. It's a great question.

Let's take the last one from Sarah, then I'll move on. Sarah says, non-Euclidean geometry is a term describing anything that isn't Euclidean. That's correct. There are indeed several types of non-Euclidean geometries. It's totally right. And there are two very simple kinds, to characterize global spaces, that have a constant curvature.

And those can be either positive with the same curvature everywhere, so some non-zero positive value, or some non-zero negative value everywhere. Or anything in between. It could be lumpy and could have a much more complicated surface.

And in that video that I linked to, that YouTube video on the Canvas site, actually, the person who made that video does a really nice job going through some of that stuff in the kind of most symmetrical forms of non-Euclidean geometries that depart from ordinary Euclid. So you might enjoy that short video as well, or a little bit more in my optional primer. I do that chat more. These are excellent questions. Good.

Let me press on. Let's go to the next part of the material. It picks up on some of these questions here, after all. Who took any of this seriously? How did people find out about it?

Now, you might recall I mentioned Einstein got to this form that we now recognize, the Field Equations, relating the warping of space and time to the distribution of stuff to where the matter and energy are. He got there in late November 1915, In fact, it was November 25. We know the exact date. He gave a talk on it at the Prussian Academy of Sciences on Thursday the 25th of November, 1915.

Well, as you may recall, that was not a quiet time in the history of, say, Germany or much of Europe. By that point, the First World War-- the War to End All Wars, so people first thought-- had been raging for more than a year. The First World War broke out in August of 1914 in the midst of Einstein's quite significant struggles toward the General Theory of Relativity.

So we immediately are thrown back into the question of relativity and the very messy, very confusing, chaotic, and bloody state of human affairs by asking the simple question. Who else could work on relativity? We're thrown immediately back into this question of people in real times and places, in these cases in quite dramatic, often very dangerous times and places.

So here's a map of Europe around the time of 1914, around the time of the war. I've shown in the big star here is roughly where Berlin is. That's where Einstein was by the time he was finishing this work.

And we want to ask the question of how did he begin to share working knowledge or information about this exciting new set of ideas with colleagues who were not in Berlin, with colleagues elsewhere in Germany, with colleagues in other countries, both to the East and to the West? And we'll see to begin asking that question, we're immediately thrown into the realities of the First World War.

One of the very first people anywhere on the planet, as we get kind of up to speed on this new material of General Relativity, was a Russian mathematician named Vsevolod Frederiks. It turns out Frederiks was originally from St. Petersburg in northern Russia, but he was very talented, and was doing a kind of post-doctoral appointment, a kind of research position, with the world-famous mathematician David Hilbert in Gottingen within Germany.

So Frederiks, the Russian mathematician, was working with David Hilbert in Gottingen. And we know from Einstein's voluminous correspondence and his diaries and so on that Einstein had befriended Hilbert, Frederik's main sponsor, and would actually make long visits to Gottingen-- in fact, two weeks at a time. Those visits could continue even after war had broken out. After all, Einstein was a German civil servant. By this point, he was working. He was employed by the Prussian Academy of Sciences, so he was certainly allowed to travel within Germany, even after war had broken out. So we know he not only could, he did make multiple lengthy trips from Berlin to Gottingen to visit with friends and colleagues, like Hilbert, like Emmy Noether, whom I mentioned who was also at Gottingen, and other colleagues.

He would often stay for two weeks. Sometimes he'd say as a personal house guest of Hilbert. He'd actually live in Hilbert's house. They were very-- had lots of opportunity for informal discussion. Frederiks met Einstein on one of these visits. He began to learn from Einstein directly and began to pursue the work, even after Einstein had went back to Berlin, with this circle in Gottingen that was studying material.

After war broke out, after these visits had started-- now, Frederiks, this Russian mathematician, was a Russian in Germany after those two countries had declared war against each other. So he was detained almost immediately as a civilian prisoner of war. He was literally locked up. He was imprisoned, because he was a Russian citizen in Germany after the nations had declared war.

He had a very powerful friend and sponsor in the person of David Hilbert. Hilbert was a very prominent kind of local figure. So we know that Frederiks didn't suffer nearly as badly as many others did in these sometimes quite horrible conditions in these prisoner of war camps. In fact, Frederiks could, on occasion, still have visits from people like Hilbert and other members of the Gottingen research group. He could continue thinking about relativity, even while locked up.

After the war had ended, he was released. He was repatriated to his native St. Petersburg, which, by this point, had undergone the Russian Revolution-- was now known as Leningrad or Petrograd. It went through several name changes. And once he was there, he began teaching the first-ever classes anywhere within Russia on General Relativity.

One of his first disciples was a very talented Russian mathematical physicist named Alexander Friedmann. They began teaching a course together on relativity. They taught people like Vladimir Fock, George Gamow. He's the person I mentioned earlier with the cartoon drawing of the Temple of Relativity. They taught Lev Landau, and then Landau taught everyone else in Russia basically-- in the Soviet Union. So he created the first school of relativity, but he couldn't do it right away. And he happened to learn the material and be able to transmit the material, all because the changing dynamics of the First World War.

There was another effort to try to move working knowledge of relativity eastward from Berlin in the midst of war. And that involves Einstein's close colleague, Karl Schwarzschild, shown here. So Schwarzschild was actually an observational astronomer, as well as a mathematical physicist. At the time, that was actually not so uncommon. We'll see several people even just today who did both of those roles. Those roles would specialize and separate over the course of the 20th century. But Schwarzschild was publishing papers in mathematical physics and in observational astronomy throughout his career.

He spent quite a large part of his career in Gottingen. He knew that crowd. By the later time that Einstein moved to Berlin, Schwarzschild was nearby in Potsdam running an observatory close to Berlin. He and Einstein got to know each other. So Schwarzschild got to learn directly from Einstein about this developing work on what would become the General Theory of Relativity.

And then when war broke out in the summer of 1914, Schwarzschild, at age 40, volunteered for the infantry. He was such a patriotic German citizen that he decided he could best spend his time by literally fighting as a soldier, boots on the ground to fight. So he was sent to the Eastern front. He was sent to the Russian front.

Now, he's a German soldier far from Berlin, but still in the German army. So he was still able to exchange mail with Einstein. Einstein was a German civil servant. Schwarzschild was a member of the German army. So even though Schwarzschild was basically in Russia right on the front, he and Einstein could still at least trade letters and postcards, many of which have survived. We have this amazing documentary material.

Einstein mailed to Schwarzschild some of the updates as he was working more and more on relativity through the autumn of 1915, after Schwarzschild had already deployed. Einstein was convinced that no one-- not Einstein, not anyone-- would ever be able to find an exact solution to his new equations. As I explained in that optional primer, the equations are highly nonlinear. They don't have the same structure, say, of Maxwell's equations from electromagnetism.

The gravitational terms can act on themselves. You have a highly nonlinear form of the mathematical equations. And in general, there's no rule that says nonlinear equations can always be solved exactly. Einstein was convinced he'd always have to find approximations of the sort he had already been working out.

So imagine Einstein's surprise when he gets another communication back from the Russian front, from his colleague Karl Schwarzschild, who, on some downtime between fighting, was able to work out the first known exact solution to Einstein's own field equations. Schwarzschild found what we now call the Schwarzschild Solution. We named it in his honor-- the solution for the warping of space and time in the vicinity of a spherical mass like the sun. Let's say you have a large mass sitting still, at rest. How much will it deform the surrounding spacetime in this kind of spherically symmetric way around it?

We still use that to talk about motion on the solar system. It led to later thoughts about things like black holes. We use this solution all the time. Schwarzschild derived the first exact solution to Einstein's field equations literally in the middle of war during a pause of fighting.

Einstein was unable to arrange for Schwarzschild's paper to be published, even though Schwarzschild was away. It came out in the proceedings of the Prussian Academy of Sciences. And just weeks after submitting the mail, after sending the update to Einstein, Schwarzschild succumbs to a rare skin disease on the front and died. Here's effort number two to spread working knowledge of relativity eastward. You have to either wait till the war ends and a prisoner of war can be repatriated, or you have this momentary kind of excitement on the Russian front that has ended the way so many lives were during the wall.

OK, one more effort to try to spread working knowledge eastward. It was yet another astronomer colleague, right in Berlin, who had befriended Einstein. His name was Erwin Freundlich. So Freundlich, much like Schwarzschild, was an expert astronomer. And he used to love hearing Einstein talk about this developing work on what would become the General Theory of Relativity.

Einstein would often pepper Freundlich, who was much younger-- he was almost a kind of informal assistant. Einstein would ask Freundlich, could astronomers possibly measure this or that? What might be observationally feasible? And so they would have these kind of informal discussions.

Einstein, by 1912, 1913, had convinced himself from this argument, like I gave before, that gravitation-- the warping of spacetime-- should bend the path of light. And he began to wonder and began to talk with Freundlich, the astronomer, if this could ever be observable. And Einstein hatched a plan, saying maybe you could just barely measure this effect during a total solar eclipse.

And here was the argument. He actually wrote letters to other astronomers. Here's a letter he wrote to the American astronomer George Ellery Hale in 1913 trying to encourage astronomers to really look for this effect.

The idea was that the astronomers would take a photograph of some field of stars, some constellations, some evening when they had clear viewing and a point in the Earth's orbit when the sun was, so to speak, behind us, when the Earth was between the sun and the distant stars being photographed. So photograph a constellation at a moment of the Earth's orbit when the sun was, so to speak, behind us. Then wait roughly six months, photograph that exact same constellation, that same field of distant stars, but now when the sun was immediately between the Earth and that constellation.

Now, of course, if the sun is directly between us and those stars, it'll be too bright. It'll be daytime. We won't be able to see them. So Einstein says, oh, wait for a total solar eclipse. Wait for a time when the moon moves exactly into position to block nearly all of that glare of the sun. During that very brief moment of totality, when it's dark again on Earth, take a photograph again with telescopes of that particular constellation, and compare the apparent positions with respect to still more distant stars-- distant away in the field of view.

And Einstein's prediction was that the apparent positions should shift, should splay outward when the light was bent by passing near the sun, compared to when the sun was nowhere near the starlight's path. This is what would soon come to be called gravitational lensing, that the large mass of the sun should act like a lens deforming the space and time around it, bending the path, focusing the path from the more distant stars. So as we trace back the path we assume that light must have taken, we'll attribute it to a further splayed-out position, compared to reference stars that are even further away that pass kind of nowhere near the sun.

So you have a larger field to set your coordinates and ask, do you see any apparent displacement by a measurable amount? Einstein could now begin to calculate how much he thought it should splay out. Do you measure any displacement of the stars during a total solar eclipse?

Freundlich said, that actually is possible. We could actually perform measurements with the requisite angular resolution. We could do that. They calculate when the next total solar eclipse would be and where the best viewing would be. Einstein now uses his new prestige in the Prussian Academy of Sciences to get Freundlich a grant to do it. Freundlich puts together a small team. They get equipment. They set out for where the best viewing of this new eclipse will be. It's going to be best seen in late August 1914 from the Crimea.

They get there just in time, unfortunately not in time for the eclipse. They get there just in time for the outbreak of war between Germany and Russia, Russia having claimed the Crimea. So Freundlich was now in what was recently claimed to be Russian territory just when the Russians and the Germans had declared war against each other.

He and his whole team were captured, locked up as prisoners of war, their equipment confiscated. They could not conduct the observation. So this third effort to move working knowledge of relativity eastward is once again foiled by the very human situation of the First World War.

Let's take one or two examples trying to move working knowledge westward. Now let's go in the opposite direction from Berlin. Even after war had broken out, Einstein could and, in fact, did make several trips to visit colleagues outside of Germany. He was a German civil servant. He was literally a government employee of the Prussian Academy of Sciences. But he could travel not to countries that were at war with Germany. He couldn't go to France or Britain. But he could go to countries that were still neutral, like the Netherlands.

And that was very good for Einstein, because he had a very, very dear friend shown here. It's a little fuzzy photograph. This colleague here, Paul Ehrenfest, was leading a research group in Leiden. They had been friends for a long time. And Einstein, as we know from his letters and diaries, made multiple long trips to visit with Ehrenfest's group in Leiden, even and after war broke out, again staying for a week or two at a time.

It was during those trips after war had broken out when Einstein first met and befriended another one of these researchers, Willem de Sitter, who, like Karl Schwarzschild, was both a mathematical physicist and an observational astronomer. So he was able to coach de Sitter in person during these long visits about this developing work on general relativity. And, in fact, they could trade mail even afterwards, because de Sitter was in a neutral country the mail could get through. And so de Sitter learned literally directly from Einstein through these coaching sessions, many of them in person, about the ins and outs of this new work as it was being developed.

One thing Einstein could not do was either visit or even trade a single postcard with colleagues in Britain. So the war had choked off all direct contact, even indirect contact, like the mail, between, say, Arthur Eddington, who was in Cambridge, England, and Einstein in Berlin.

Eddington was a third one of these kinds of creatures we've now met. He was both a tremendously talented mathematical physicist and an active observational astronomer. Eddington had been Wrangler. He might even have been senior Wrangler, certainly a very high ranking Wrangler in his student days with the Mathematical Tripos. He was one of the few people anywhere on the planet who was especially well equipped to handle the new mathematics of non-Euclidean geometry and apply it to real questions of astrophysical interest, as any astronomer would want to.

And yet he couldn't learn about the work from Einstein. He couldn't get access to the German journals from the blockade. He couldn't get letters from Einstein, or postcards, or vice versa. So what we now know happened was that he began getting letters from Willem de Sitter, that Dutch astronomer whom Einstein met and befriended in Leiden. The Netherlands was a neutral country. The mail could travel between the Netherlands and England. It could separately travel between the Netherlands and Germany. No mail could travel directly between England and Germany. So de Sitter began writing out English language primers on this not-yet-published work from Einstein, trying to get Eddington up to speed as a kind of correspondence course on this very new, otherwise little-known work on General Relativity.

There's some really interesting work on Eddington, a lot of it by my friend Matt Stanley. Matt and I were in grad school together. He's now a professor at New York University. He's written two books on this. The most recent one came out in 2019, pretty recently. Matt is really an expert on Arthur Stanley Eddington and his work.

So Eddington, it turns out I learned from Matt, was not only a mathematical physicist and astronomer. He was also a Quaker, a very devoted Quaker. And therefore, during the First World War, he became a conscientious objector, meaning he refused to fight for the British army, because he refused to fight on general principles. He was a pacifist conscientious objector in keeping with his Quaker faith.

That was a very, very difficult thing to be in wartime Britain in the First World War. Again, I learned from Matthew's work many British historians have cataloged for a long time. The typical response for conscientious objectors in the First World War in Britain was to lock them up, to jail them, or send them to the front for some ambulance duty, whether they were trained as medical professionals or not. So either they were locked up for the duration of the war typically, or sent directly to the front to work-- not to fight, but to work a kind of first aid ambulance duty, whether or not they had any medical training-- very, very, very difficult to be a conscientious objector in Britain in the First World War.

Eddington, it turns out, had again-- much like the mathematician of Vsevolod Frederiks, Eddington had some powerful kind of senior colleagues who were able to wrangle a different situation. Among them was the astronomer royal Frank Dyson based in London.

Frank Dyson thought this was-- basically arranged a scheme to save Eddington from jail. Eddington was willing to go to jail. He had no objection-- but to save Eddington jail, and at least as important to save Cambridge University from embarrassment. It became more and more bad press to have this young, fit, able-bodied young person, Arthur Eddington, at Cambridge not going to go help out as so many other young men from Cambridge, both faculty and students, had done. So it was at least as much to save Eddington's skin as to save face for this very elite institution of Cambridge.

They worked out a deal where Eddington's wartime service would be spent preparing a new scientific experiment. Eddington would prepare the next version of these eclipse expeditions, none of which had actually been really successful yet. The same exact thing that Erwin Freundlich had tried to do, but was foiled by the onset of war, Eddington would spend his service in honor of the British crown preparing for this eclipse expedition-- quite extraordinary. It's good to have powerful friends.

So the next total eclipse, beyond the one that was spoiled in August 1914, was going to happen in May of 1919, as Horace knows very well. And, in fact, the path of totality-- the path that would be best seen for astronomers-- stretched in the opposite direction, not into Crimea, or Eastern Europe, or into Asia, but instead stretching from the tiny spit of islands off the coast of Western Africa not too far from Morocco, but

in the Atlantic Ocean, stretching all the way toward Brazil. So a swath from basically just off the Western coast of Africa through parts of South America.

And so Eddington and the astronomer royal Frank Dyson put up two small observing teams to go head out to each of those locations. One would set up on the island of Principe, one of the islands not too far from Morocco, and the other would head off for Brazil-- for Sobral, Brazil.

The eclipse would happen in May of 1919. Of course, no one at the time knew when the war would end. They began planning this early in the war. As it happened, the war ended in November of 1918 on November 11. In fact, we still celebrate Armistice Day. In the United States, we often call it Veteran's Day. So the war ended just before the eclipse, but after many of the plans had been set in motion. The eclipse itself happened during continuing wartime privations. It was still enormously disruptive to travel anywhere, let alone through these international steamer trips.

The two teams set out. They performed these measurements. They bring all the equipment and the photographic plates back to London and Cambridge. They boil down the numbers for six more months. And in November of 1919, almost one year to the day after the end of fighting in the First World War, Eddington and Dyson call a special rare joint meeting of the Royal Society of Britain and the Royal Astronomical Society.

Eddington steps up to the podium and says, in effect, Einstein was right. This becomes unbelievable news all around the world. Now you have a British team confirming the work of a German scientist in the midst of a war to overthrow the King of English science, Isaac Newton. This couldn't be juicier international news one year after the end of fighting.

Here's one example, one of my favorite examples, the headline in the*New York Times* coverage. "Lights All Askew in the Heavens. Men of Science More or Less Agog over Results of Eclipse Observations." I always say we don't use the word agog nearly enough anymore. "Einstein Theory Triumphs. Stars Not Where They Seemed or Where Calculated to Be." But nobody need worry. It's not that the sky is falling and so on.

This is what catapults Albert Einstein to worldwide fame. This is why more and more people begin to at least consider the possibility that spacetime is governed by geometry and could be curved. This is when Einstein himself becomes not just a well-known figure among working scientists, but actually literally a worldwide media sensation.

Not too long after this announcement, Einstein sets out for his first world tour. He sails literally around the world, all the way to the United States, to Japan, travels back, and ends up back in Berlin. He's greeted in New York City like a celebrity. He's paraded through the streets. On his follow-up visit, he meets movie stars like Charlie Chaplin. This is why we can buy t-shirts and coffee mugs with Einstein's face on it, because of Eddington's amazing announcement in November of 1919. OK.

So very soon after that, in fact, just while this news was still reverberating all around the world, Einstein gave a follow-up interview for a reporter in the *London Times.* And he wrote in November of 1919, and he said, "Today I'm described in Germany as a 'German servant' and in England as a 'Swiss Jew,'" because the English didn't want to give any credit to the Germans, and the Germans wanted to claim all the credit for him. He goes on to say, "Should it ever be my fate to be represented as a bete noir"-- if it looks like my work is wrong, if the results don't hold up, "I should, on the contrary, become a 'Swiss Jew' for the Germans and a 'German savant' for the English," meaning they'll each claim the other side is responsible for this turkey. They both love me when the work is right. They both want to blame the other side if the work is wrong. Because the English and Germans still don't like each other. And he closes with a flourish. He says, this is yet another application of the Theory of Relativity. He was a pretty good media guy.

Well, it turns out even this prediction turned out to be true much sooner than Einstein had expected. Just months after this interview, months into this worldwide hoopla about the results of the eclipse expedition, events in Germany began to turn very dark, very quickly. There arose what became known as the Deutsche Physik movement. It's usually translated not as German physics-- would be a literal translation-- but as Aryan physics. This was some of the earliest proto stirrings of what would grow into part of the Nazi party.

As early as spring of 1920-- April of 1920-- just months after this November announcement in 1919, groups began holding rallies-- political rallies-- to denounce general relativity, not to denounce Einstein, the Jewish internationalist pacifist who himself had spoken out against the war. It was over determined that these folks wouldn't like Einstein the individual.

They were denouncing the warping of spacetime. It was mostly organized by, as we now know, by political opportunists who were looking for any reason to gin up media attention. Einstein was in the news. He was an easy person, therefore, to have as a target to get your own efforts in the news. That hasn't changed to our Twitter field day today. These folks were also media savvy.

But it wasn't these kind of political operatives who got the spotlight. It was, in fact, these two gentlemen shown on your screen here-- Johannes Stark-- that's the same Stark who had invited Einstein to write the review article in 1907. In the interim, he had received the Nobel Prize in physics for his work on radiation from excited atoms. He was joined by Philipp Lenard, who was also a Nobel laureate, a German experimental physicist. We'll learn more about Lenard's work. Lenard got his Nobel Prize in 1905 for having conducted experiments on the photoelectric effect. Einstein would later win his Nobel Prize for a theoretical explanation of Lenard's results.

These folks should have been able to get along, right-- two Nobel laureates with close intellectual ties to a lot of Einstein's other work. And yet it was not to be. They became the kind of front figures, the faces, public faces, of this Aryan physics or Deutsche Physik movement. They staged these rallies in sports arenas and opera houses-- tens of thousands of people, as early as 1920, to denounce relativity, to denounce this very strange notion of the warping of spacetime.

Lenard became an active author on this topic. Here's a later publication, published now in the midst of the Second World War, 20 years into this effort, called *Grosse Naturforscher* Great Men of Science, it's usually translated, Great Researchers of Nature-- A History of Science in Biographical Form-- [GERMAN].

So what did he do in this book? Here's a sample page from Lenard's book,*Great Men of Science.* He argued in a kind of 2-point strategy. The first part, according to Lenard-- and this is a thick volume with many examples to try to prove his point. The first part is that Einstein's work is disgusting. It is repugnant to the Aryan sensibility. I'll give one example of that. What did he mean by that? That's part one.

Part two, he stole it from us. Key results, argued Lenard, have been plagiarized from properly Aryan researchers. So it's disgusting, and it's ours. It's a very strange form of argument. Then again, he was a Nazi, so what do you want? OK.

Step one, it's repugnant to an Aryan sensibility. There are examples like this that get written up in pamphlets and books all over the place. They would say things like the concept of force, which was introduced by Aryan scientists, by which they mean Newton and Galileo and Descartes-- not exactly Germans or Teutons-- they were introduced by Aryan scientists, obviously arises from the personal experience of human labor, of manual creation, of working the land, a very active rhetoric. This had been and is the essential content of the life of Aryan man, a kind of romantic nostalgia for an agrarian German past, when the pure race, in their terms, had worked the land. They knew the meaning of force in their muscles, because they pushed the plow. Only in their words, only an effete cosmopolitan Jew like Einstein, could ever dispense with the concept of force. Part one, the work is disgusting.

Part two, he stole it from us. There indeed was a little-known German-speaking naturalist-- long before there was a country of Germany, but he was in one of the German territories-- named Johann Soldner. As early as 1803, long before this time, he published an article, which then Stark and Lenard, the Nobel laureates, republished in the Gestapo press in 1921. Soldner had done a very clever calculation. He had used purely Newtonian gravity to calculate the deviation of the path of starlight as it moves near the sun, not because he thought spacetime was curved. He thought there should be a balance of forces. There's a gravitational force-- a universal force of gravity-- that should have an impact on the momentum vector of that light wave. It's a thoroughly classical Newtonian calculation, very clever, and thoroughly forgotten.

Now, it didn't seem to matter to the later Nazis. That soldier's result was exactly one half of Einstein value. It is not what was tested by the eclipse experiments. It was not consistent with the results announced in London. That was a nicety they could dispense with. The point was, everyone in the world is excited about the bending of light by gravity. That was a German, and, to their minds, a properly Aryan result.

To prove that all this work had come from Aryans, Lenard would include these portraits in his book. Here is his portrait of Isaac Newton to show that Newton had this proper-- literally proper racial facial features, like he didn't have a so-called Jewish nose. So he would have these portraiture to use physiognomy-- the external features of the face-- to prove, quote, unquote, "prove to demonstrate" that all the best work had been done by people who were racially pure in their terms. And the work that Einstein was getting famous for had been stolen by others. Let me pause there and stop sharing screen. Any questions on any of that?

Yeah, great, thank you. And thank you to Horace and others in the chat. Very good.

So astronomers have been conducting eclipse expeditions with great precision-- I mean, really precise scientific expeditions-- to measure very precise photographs of the fields of stars since the late 19th century. And that's important. I learned this, by the way, from a few colleagues. But it's also true. And if you're interested in one of the books whose covers I showed you-- you can find it on the slides-- the recent book by my colleague Dan Kennefick, which is on one of the slides, called *No Shadow of a Doubt,* also a fantastic book, also just came out in 2019.

And so I learned from Dan and from another colleague, Alex Pang, that there was a tradition of eclipse expeditions, especially by British astronomers. In fact, there was a division of the Royal Astronomical Society called the Joint Expedition Group or something like that. And Frank Dyson had had a lot of experience with that.

So they were used to lugging equipment around to often difficult, out-of-the-way places to conduct tests, often of the sun itself. It was already seen as a way to try to learn more about the sun, the outer corona of the sun, when you could see the outer part-- was usually obscured by the much brighter glare. So there's lots of reasons to try to photograph the sun or the field of stars right around the sun during an eclipse. So people like Frank Dyson especially had a lot of experience of that.

The effort to try to actually measure light bending in particular was really not on most people's radar screens, so to speak. Einstein began writing letters in 1912, 13 to astronomers all over the world, asking them to look for it. As I had that one little excerpt from his letter to the American astronomer George Ellery Hale, he was talking a lot to Erwin Freundlich.

To my knowledge, the reason eclipse expeditions prior to the 1914 attempt, which was scrubbed by war, were not actually to measure light bending per se. They were in this existing tradition of measuring all kinds of things you could learn from things like stellar astrophysics, by photographing the sun very carefully during an eclipse. So there was the equipment and the know how-- different questions. I think that's important, and that tradition goes back quite a bit earlier.

So in some sense, Frank Dyson could kind of build on existing knowledge, teams, equipment, and infrastructure, keep Eddington out of prison during the wall, and think about doing the same kind of experiment now in a different way. And there's more to say. I'd be glad to send more references to other work, but that's what I've learned in general about these eclipse expeditions.

And Horace also had asked, was it difficult to get there? It was indeed very difficult in general. Most people were still operating under kind of wartime deprivations. Food was still rationed. There was often not available medicine in many places. The supply chains had not sprung back to action. Global commerce was still very, very disrupted. Sea travel was very, very uneven. So even just getting the teams to either Principe or to Sobral was highly difficult. And again, you can learn a lot about that in both Matt Stanley's and Dan Kennefick's recent books. Amazing.

Einstein's view on the war, Silu asks-- very good question. And again, there's a lot of that in Matt Stanley's most recent book, the one I mentioned called *Einstein's War.* The short answer is he was against it and very bravely vocal about his opposition, which was unusual at the time.

So there was early, after the outbreak of fighting, 93 leading German academics, including people like Max Planck, who we'll hear a lot about soon, signed a manifesto a kind of proud declaration that was saying the reports of atrocities by German troops when they invaded other countries were mistaken, basically saying what we now call fake news, that it can't be true. These German soldiers were upstanding gentlemen was the claim. And that they had been provoked, and that no matter what happened, they had not been burning libraries or raping women, which it turns out, in fact, they really were doing.

So there was this manifesto from 93 very highly prestigious German academics in favor of defending the German war effort, and saying, in fact, the Germans should conquer all of Europe, because they were in their own minds. They kind of had reached the apex of learning and culture. The rest of Europe should be glad to serve under German rule, because they were the best at everything. Just ask the Germans-- not a very strong argument to non-Germans.

Well, this only further impassioned the anti-German sentiment in places like Britain and France, for maybe understandable reasons. Einstein, as a kind of mid-career academic in Berlin in the heart of the leadership of Germany, was one of three people-- not 93, only three-- to sign a counter-manifesto that was, in fact, so explosive no newspaper would even publish it until after the war. Because they figured-- they feared the newspaper would be bombed.

His counter-manifesto said Germany is to blame, war is terrible. We should all find out other ways to handle international disputes. He was already very bravely by 1914, 15, 16 an outspoken pacifist internationalist, not only in letters to his colleagues, but he tried at least to be outspoken. Sometimes it was seen as so radical the newspapers wouldn't even print it. And again, there's lots and lots of stuff on that. But that's the not-so-short version.

Yeah, and Jesus says, it's crazy that science was so politicized by the Nazis. Yeah, and we're going to see even more examples of this throughout much of the next several weeks of the course. I agree with you. I mean, it is crazy. It's sad. It's also, unfortunately, a recurring pattern for better or worse. Humans have this ability to do horrible things to each other in a whole range of settings, and this brings out some examples that we hopefully can try to learn from historically.

So I think it's a great point, and Tiffany asked me to elaborate on this as well. Let me just say a bit more about what they're referring to for the later measurement.

So for the 1919 one, the one that was done in Sobral, Brazil, it turns out, maybe not surprising to Horace it turned out to be-- it was May-- an unusually hot day. So before the eclipse, the sunshine was even brighter than they expected. And so they actually messed up their calibration. It literally began to warp some of the lenses or mirrors. It was that hot on their equipment, that they saw things getting out of this very careful alignment. And they hurried to try to recalibrate, but they couldn't take all the time, because they knew totality was coming.

So the team in Brazil was dealing with at least one instrument. The larger, more precise in principle of the two telescopes they brought was physically deforming before their eyes because of the hot Brazilian sun-- Horace may tell us if that's typical or not. And so it was falling out of alignment, and they couldn't change it. They took photographs, but they couldn't trust that, because they had no longer a proper calibration.

They had a smaller telescope that was not nearly as warped. It was maybe in the shade, or I don't know how it worked. And they took a bunch of photographic plates with that one, too.

And so it turns out one of the things that Frank Dyson wound up doing, and in his book by Dan Kennefick, he goes through this in great detail-- was Dyson, who had all this experience with these eclipse expeditions, basically kind of discounted the data from the visibly-warped, no longer properly calibrated larger telescope from the Sobral from the Brazil expedition. When they're boiling down their data doing this statistical analysis, he basically tossed a bunch of data, because he used his experience. He drew on his experience to say, I can't trust that, because it no longer had met-- the systematic error would be too large, we'd say today.

That later caused a lot of controversy. People made it sound like people who wanted Einstein to win were massaging the data. If you included that data, it would look more like a tie. It would be kind of a wash between the Newtonian prediction and the Einsteinian one. I think Dan Kennefick's analysis is really quite watertight, saying this was both proper of the standards of its time, not done by the people who were biggest fans of Einstein's work. In fact, done by the one person who is most vocally skeptical about Einstein's results, meaning Frank Dyson, and seems not to have been a conspiracy at all, but, in fact, an understandable technique. The fact that we would do things differently today-- we would weight data differently to calculate systematic error-- doesn't mean what he was doing was a conspiracy.

The 1912 one I think is saying that if they had tried to measure the deflection, which is an if-- if they were actually trying to do that kind of measurement, they were set up, I assume, to do solar physics, I'm guessing. We can look it up. But if they had tried to do this further star deflection experiment, and if they had good luck and measured the right answer, the answer now would be one we'd expect. Then it would not have matched Einstein's prediction at that time, because, as you rightly say, Einstein's own calculations were changing this period.

In 1912 and 1913, he did not yet come to the form of his equations that we would now recognize. That comes in November 1915. And indeed, his earlier predictions were off by exactly that factor of 2 to make them look like the same answer that one could get from a purely Newtonian calculation. No one knew that at the time, and it was only 1921 that the Nazi Nobel laureates republished that much older, very different calculation.

I'm going to pause there. I won't bother, of course, going through that last part of the talk. I'll try to talk about it later. It's on the slides. I'll be glad to chat about it during office hours. But that gives us a pretty good taste to wrap up our Relativity unit. And then on Wednesday, we'll jump in to the Quantum Theory unit.

So I'll pause there. Please remember to work on paper one, which is due this Friday. Thanks, everyone. Stay well.