The History of the Twentieth Century
Episode 114
“Beautiful Tightropes of Logic”
Transcript

[music: Fanfare]

In 1905, a theoretical physicist named Albert Einstein earned his Ph.D. and also published four groundbreaking papers on the photoelectric effect, Brownian motion, mass-energy equivalence and his special theory of relativity. These four papers solved some of the most vexing unsolved questions in science, but they more than made up for that by raising many more questions than they solved.

The publication of these four papers took the newly-minted Dr. Einstein into a position of prominence in the scientific world when he was still just 26 years old. He was not yet, however, the household name he was destined to become. For that, he needed to make his fifth and most astonishing theoretical breakthrough: the general theory of relativity.

Welcome to *The History of the Twentieth Century.*

[music: Opening War Theme]

Episode 114. Beautiful Tightropes of Logic.

This week, I want to get caught up on the doings of Albert Einstein, whom we last checked in with back in episode 37, in 1905, his Year of Wonders.

As you know, Einstein had been living in Bern, Switzerland at that time. He was a lifelong pacifist and had left his native Germany and surrendered his German citizenship to avoid military service. He had won Swiss citizenship in 1901, and married his first wife, Mileva, in 1903. Albert and Mileva apparently had a daughter together before their marriage, a fact which did not emerge until decades later. What happened to her is unknown; apparently she either died in infancy or was given up for adoption. Albert was aware of her birth, but it’s not clear he ever saw her.

He had been unable to get a teaching position, and had to move to Bern, the Swiss capital, and settle for a job in the Swiss patent office to support his family. His first son, Hans, was born in Bern in 1904.

After the publication of his four remarkable papers, it got easier for Einstein to find a teaching position. He lectured at the University of Bern for three semesters, then was appointed to a position as associate professor of theoretical physics at the University of Zürich in 1909. The Einsteins moved to Zürich and had another child, Eduard, in 1910.

During this period, Einstein continued to work on relativity. He'd laid out the special theory of relativity in 1905, but there were implications to this work that remained to be explored. If you'll allow me to recap my explanation of special relativity from episode 37, I had said then that the theory combines two principles. One is that observers can't tell experimentally whether they are moving or not. Think of it this way: imagine you are inside a closed room. Is your closed room at rest, or is it moving at a constant speed through the universe? You can't tell from inside a closed room, and there is no experiment you can do, no observation you can make, that will tell you the difference.

The other is that the speed of light always measures the same, no matter how fast the observer taking the measurement is moving, which is what the Michelson-Morley experiment seemed to imply.

From these two principles you can derive the special theory of relativity, and that derivation also produces some really crazy and counterintuitive predictions. A moving object shrinks a little bit in the direction that it's moving. Moving objects gain mass. Time slows down for a moving observer.

But special relativity only considers observers moving at constant velocities, neither speeding up nor slowing down. Not subject to acceleration, in other words. That's why we call it "special" relativity, because it only considers what observers see under certain defined, or special, conditions. What was still needed was a general theory of relativity that would apply under any conditions.

Introducing the concept of acceleration into the mathematics of relativity complicates that math considerably, but there's more to the challenge of general relativity than just working out the math. Remember the closed room I've been talking about? I said an observer shut in a closed room can make no observation that could tell whether the room was moving at a constant velocity or standing still. But an observer in a closed room can certainly tell whether the room is under acceleration. If a room is traveling through space at a constant velocity, the observer inside the room would be weightless, but if the room is subject to some force that is accelerating the room, the observer will find herself pushed against one of the walls of the room by an opposing force. Think of how if you ride in a car or plane that accelerates forward rapidly, you feel yourself pushed back into your seat. There's no way *that* is relative.

So there is a difference between moving inertially, that is, without acceleration, versus moving under acceleration. But Einstein was also pondering the role that gravity played in his theory of relativity. An observer on the surface of the Earth, for example, feels the Earth's gravity as a downward pull, not unlike the pull our observer friend felt when the room she was in was put under acceleration.

Ah! So *here* is a place where we can apply the principle of relativity. An observer in a room can't tell experimentally whether the room is accelerating upward or is on the surface of a planet and subject to a gravitational pull downward. Einstein published a paper in 1911 in which he began to explore what this might mean. He called it his "happiest thought."

At the same time, other theoreticians were working out the implications of special relativity. One such theoretician was the Jewish Austrian Paul Ehrenfest, who offered up this thought experiment in 1909: imagine a cylinder, rotating rapidly. Special relativity tells us that the circumference of the cylinder would become smaller in the direction it's moving. But the diameter of the cylinder would not change, because it's not moving perpendicularly. So how can a cylinder get smaller and not smaller at the same time?

Einstein had an answer to this, but it's a strange one. He suggested you imagine yourself an observer on the surface of the cylinder, with a ring of measuring sticks around the cylinder but apart from it. If you try to measure the circumference of the cylinder, those measuring sticks will have gotten smaller, from your point of view, so for *you* the cylinder's circumference will appear the same, but the ring of measuring sticks around it shrank. From your point of view, it's the space around the cylinder that got smaller and not smaller at the same time. Well, that's relativity for you.

Physicists were already struggling to absorb that special relativity suggests that objects change shape and size when they move at high speeds relative to the observer. But there's something else going on here, something even more fundamental. If the circumference of the cylinder is changing while the diameter remains the same, what's actually happening is that the value of *pi* is different, depending upon the observer. But that can't be right, can it? The only way the value of *pi* can change is if geometry itself is changing. Meaning space is changing. It's bending. Can space itself change shape, depending on who is observing it?

In order to investigate this question, Einstein had to bone up on a new field of mathematics that had developed in the 19th century known as non-Euclidean geometry. It was named that in reference to the ancient Greek geometer Euclid and his famous Fifth Postulate. I don't think it's a good idea for me to delve into Euclid and his Fifth Postulate right here; the thing about geometry is, it's pretty easy to explain with a visual aid, but trying to explain it in words can be very difficult, so I'm just going to skip over that part and suffice it to say that geometers have been pondering Euclid's Fifth Postulate for over a thousand years. It's a rather awkward and inelegant assumption that sticks out like a sore thumb, marring what is otherwise a very simple and elegant picture of geometry. Geometers had been trying for centuries to prove the Fifth Postulate from more basic assumptions, hoping to eliminate that unlovely postulate. They kept failing, and it has to be said that Euclid must have been a pretty sharp guy to realize that the Fifth Postulate couldn't be derived and therefore needed to be set down as a postulate.

By the nineteenth century, mathematicians were beginning to explore alternative geometries where the Fifth Postulate didn't apply. In other words, let's work out geometry by a series of proofs, just as Euclid did, only, let's not include the Fifth Postulate and see what happens. These alternative geometries came to be called non-Euclidean geometries, for obvious reasons. Among the 19th century mathematicians who investigated this branch of geometry were the Germans Carl Friedrich Gauss and Ferdinand Karl Schweikart, the Hungarian János Bolyai, and the Russian Nikolai Ivanovich Lobachevsky, who for better or worse, was destined to be immortalized by the mathematician-songwriter-satirist Tom Lehrer 130 years later.

And then there was the German mathematician Georg Friedrich Bernhard Riemann who not only studied non-Euclidean geometry, but developed a new and sophisticated set of mathematical tools to analyze it. Einstein would have to study Riemann's work in order to further investigate relativity.

Before Einstein came along, though, this work on non-Euclidean geometry was taken merely as a mathematical exercise. It seemed to have no real world application. The physical world around us appears to be fully Euclidean, as least within the limits of the most precise measurements and observations that the 19th century can bring to bear.

The one place where non-Euclidean geometry actually does seem to have some application is when you are doing geometry on a curved surface. The surface of the Earth, for example. If you lay out a large triangle on the surface of the Earth—and I mean large as in, continental size—you can easily see that the angles of the triangle add up to something far larger than the 180º that the angles of a well-behaved triangle laid out on a flat surface always do.

This observation leads to thoughts of what two-dimensional geometry would look like on a curved surface, which in turn invites speculation that a three-dimensional non-Euclidean geometry would be possible in a space that was curved in a higher dimension—a fourth dimension. By the late 19th century, many thinkers were speculating on whether our three-dimensional universe might exist within a larger four-dimensional reality we cannot perceive because of our limitations as three-dimensional beings.

And by the late 19th century, writers were invoking the fourth dimension as a way of explaining the otherwise inexplicable. In *The Brothers Karamazov*, published in 1879, Fyodor Dostoevsky has one of his characters explain that understanding the nature of God is inherently impossible for human beings, because of their limited three-dimensional understanding. Oscar Wilde's short novel *The Canterville Ghost*, published in 1887, invokes the fourth dimension to explain how the titular ghost can appear and disappear at will. H.G. Wells used the fourth dimension to explain how the time machine works in his 1895 novel of that title.

But among these 19th century writings there is one singular work that stands apart from and above everything else. I am referring of course to the greatest combination mathematical fantasy and social satire ever written: Edwin A. Abbott's short novel *Flatland: A Romance of Many Dimensions,* first published in 1884.

[music: *Symphony No. 8*]

Edwin Abbott Abbott was an English schoolmaster and theologian. He attended Cambridge University, where we took first-class honors in classics, mathematics, and theology. He spent most of his career as headmaster at the City of London School, where among others future British Prime Minister Herbert Asquith would be a student. Abbott wrote textbooks and works on theology as well as dabbling in biography and philology. But it is *Flatland* for which he is best remembered today.

Flatland purports to be a memoir written by A. Square, a resident of Flatland, a two-dimensional world populated by geometric figures. *Flatland* is as much social satire as anything else. A. Square describes a world where men live in a rigid hierarchy of polygons, from triangles at the bottom to a ruling class of polygons of so many sides that they are effectively circles. Women are line segments and are regarded as inferior for that reason. On New Year's Eve of 1999, A. Square is visited by A. Sphere, a being from three-dimensional Spaceland. A. Square experiences visions of Pointland and Lineland and listens to A. Sphere describe Spaceland, but remains unconvinced of its existence. Finally, a very frustrated A. Sphere knocks him out of Flatland altogether and he experiences three dimensions firsthand. The two eavesdrop on the rulers of Flatland and overhear them acknowledging among themselves the existence of higher dimensions but agree to suppress this knowledge and to punish anyone who attempts to spread it.

Unfortunately for A. Square, when he suggests to his companion that perhaps there are higher dimensions beyond the third, his guide indignantly rejects this idea and returns him to Flatland. A. Square then attempts to convince other Flatlanders of the existence of the third dimension but fails and is imprisoned for his heresy. The reader then learns that A. Square has been writing this memoir from his prison cell, in the hope that it will be read someday, when Flatland society is at last ready to embrace the concept of higher dimensions.

All this talk of the fourth dimension inspired some mathematicians and artists of the time to attempt to visualize four dimensional objects, and this helped inspire early twentieth-century Cubism, which we've already talked about a little bit, as well as Surrealism and Dadaism, which we haven't gotten to yet, but I hope we will eventually.

Einstein, meanwhile, continued to work on the problems of a general theory of relativity: the roles of acceleration, of gravity, and of the bending of space. In 1911, he hit upon another important insight: that if a large mass, like say, our sun, can actually bend space, that would mean it can also bend beams of light. Another way to say this is that light can be affected by gravity, even though light has no mass. This was a wholly new idea.

That same year, Einstein was offered a professorship at Charles University in Prague and he moved to that city in April 1911 and took Austrian citizenship. In 1912, he returned to his alma mater in Zürich.

In 1913, he was awarded membership in the Prussian Academy of Sciences in Berlin, and also offered the post of Director of the newly proposed physics department of the Kaiser Wilhelm Institute. He was by this time also involved in a romantic relationship with his first cousin, Elsa Einstein, whom he had known since childhood. Elsa had since grown up, married and divorced and was now available and living in Berlin, which may have been a factor in Albert's deciding to move there.

The Einstein family moved to Berlin in April of 1914, which was unfortunate timing. The Great War broke out just four months later, which postponed the establishment of the Physics Institute until 1917. Mileva found out about Elsa and she took the two boys and moved back to Zürich. Albert and Mileva would divorce in 1919. On the plus side, Einstein was drawing a salary from the Academy of Sciences and free to continue exploring his work on a general theory of relativity and presumably spending a lot of his free time with Elsa, whom he would marry in 1919, just weeks after his divorce from Mileva was finalized.

Einstein completed his work on November 25, 1915, and it was published the following spring. The mathematics is positively heinous and I confess I can't really follow it either, so don't expect me to be able to explain in a few minutes what took Einstein years to work out—and even *he* made a few mistakes along the way, as we'll see.

But the fundamental principle that comes out of the theory is simple enough to explain, so here goes. For the entire history of physical science, from the earliest speculations of the ancients to the beginning of the twentieth century, physics has been understood to be about the interactions of mass and energy. Objects move, change direction, and stop again according to their interactions with other objects and with energy. Time and space were understood to be the units by which we observe and measure these interactions.

Think of a football match. The football is a mass, and the players are energy. The football pitch is space, the clock is time. We watch and understand the game by referring to the movements of the ball by the players against the lines on the field and the time on the clock.

When Einstein set down his famous equation $E=mc^2$, he told us that mass and energy were different expressions of the same thing. In our football analogy, it's as if the players sometimes change into footballs and *vice versa*. And if that isn't strange enough for you, hold on, because now Einstein is back with the general theory of relativity, which tells us that time and space are also interacting with mass and energy and each other. So imagine watching a football game where the players not only change into footballs and vice versa, but the plays the opposing team choose to run can bend the lines on the playing field or slow down the clock, and whether the team you're rooting for scored that field goal before or after the buzzer sounded depends on where you were sitting in the stadium.

Come to think of it, that last part is true anyway.

Yeah, that's just a glimpse of how the relativistic universe operates. Another key concept here is that gravity is not a force that reaches out and grabs other objects in the way that, say, magnetism is a force that reaches out and grabs bits of metal. Massive objects bend space itself, and other objects move or change direction because they are influenced by the curvature of the space they occupy.

But the problem with this startling theory is this: the math looks convincing, once you have an Einstein to walk you through it, but is it real, or it just a thought experiment, an intriguing exploration of a weird branch of mathematics, like, well, like non-Euclidean geometry, or Edwin Abbott's Flatland? The way to find out is to test the theory experimentally.

Only, Einstein's advanced thinking has pushed theory about fifty years ahead of observational science. The science of 1914 has nothing fast enough or massive enough to measure, nor the tools to measure it with sufficient precision to determine whether the general theory is true. And indeed, for the next fifty years, there would be doubts about how close a description of the real world was actually contained within Einstein's equations.

But there was one possibility. Astronomers have available one very massive object that's close enough to the Earth that the potential relativistic effects of that object can be observed by Earthbound telescopes. I am referring of course to the sun.

A strong gravitational field can actually bend light, or so says general relativity. That would mean that if you took a photograph of a group of stars at night, when the sun was nowhere near, and compared their positions to their positions in a similar photograph taken at a time when the sun was in front of them, you would find that their positions in the photograph would have changed slightly. Their images would be distorted because the light through the curved space near the sun.

Yeah, Einstein, but how are you going to take a picture of the stars behind the sun? The sunlight is going to wash out the light from the stars. Ah, but not during a solar eclipse it isn't. Einstein had already published a preliminary paper in 1913, predicting how the mass of the sun might bend the light of stars behind it by a detectable amount, and as it happened, there would be a total eclipse of the sun on August 21, 1914 in Eastern Europe, not so very far away from Berlin. A German astronomer named Erwin Freundlich led a team that was dispatched to the Crimea in Russia to observe this eclipse and measure the positions of the stars.

Ha, ha. I bet you already figured out the punch line to this story. Freundlich and his team were in Russia when the July Crisis unfolded, episodes 77 and 78, and as you'll recall, German intelligence was paying German civilians to travel into Russia and report back on evidence of Russian military mobilization, and here was this group of alleged astronomers hundreds of miles inside Russia as the Russian Army was mobilizing, armed with telescopes and cameras and hanging out in the Crimea, where Russia keeps her Black Sea Fleet. These Germans claimed to be there merely to watch an eclipse. Yeah, right. Tell me another one. The Emperor's secret police rounded up these so-called "astronomers" and they missed the eclipse. And it was cloudy that day in the Crimea anyway, so they probably wouldn't have been able to make any useful observations even if they had been permitted to try.

[music: *Symphony No. 8*]

In a strange way, their misfortune was a stroke of luck for Albert Einstein and for his reputation as a genius, because his 1913 paper contained a mistake that produced a stronger bending of light from the sun's gravity than it should have. So if Freundlich's team had been able to make their observations as planned, they would have found that the sun's gravity did indeed bend the light from distant stars, but only about a third as much as Einstein's formulas had predicted. That would have forced Einstein to go back to his blackboard to figure out how to modify his formulas to make them match the observed values, which is a place where no theoretician likes to go. But now, Einstein had some extra time to go over his calculations once again, find the mistake on his own, and correct it.

Which he did. But I'm getting ahead of myself. I mentioned in episode 54 that astronomers at this time were puzzling over a small but inexplicable discrepancy in the orbit of Mercury. Some believed it was caused by an as-yet-undiscovered planet closer to the sun. This hypothetical planet had even been given an apt name: Vulcan. But no astronomer had been able to find a planet where the theoreticians were predicting it would be. As Einstein honed and refined his theory of general relativity prior to its 1916 publication date, he found that the theory predicted exactly the observed irregularity in Mercury's orbit without resorting to any hypothetical planet, which was pretty good evidence that he now had it right.

There was one other little problem, though. Einstein's equations didn't seem to allow for a static universe. Instead, the theory implied that the Universe was continually expanding, which was an absurd result. In 1915, the Universe was known to be a clump of a few hundred thousand stars called the Milky Way, with our sun apparently about in the center of the clump. Outside the clump was nothing but endless void, and there was certainly no sign that anything was expanding.

So Einstein added in a finagle factor. The term "finagle factor" is jokingly defined as the amount you have to add to the answer you got to get the answer you should have gotten, which is exactly what Einstein did, although the term "finagle factor" hasn't been coined yet in 1915, so he called it the "cosmological constant," which you have to admit sounds classier.

The publication of Einstein's paper in 1916 initially had little impact. The Great War was on, and most people, even most scientists, had more prosaic things to occupy themselves with than the nature of gravity and the curvature of space. And in the Allied countries, there was intense anti-German propaganda getting slung around, and one component of this derided Germany's commitment to learning and enlightenment, so it was definitely not fashionable at the time in the Allied countries to be watching for the next big scientific breakthrough coming out of Germany, because, who knew, it was probably going to be some new kind of poison gas or something.

But there was at least one British scientist who was not interested in being fashionable. He was the 32-year old Cambridge astronomer Arthur Eddington. Eddington was a Quaker and a pacifist, which may have had something to do with his contrarian interest in German science, and he was in regular communication with the Dutch mathematician Willem de Sitter, who was in turn keeping tabs on the latest work of Albert Einstein. Eddington became an ardent booster of Einstein's work and was instrumental in translating and disseminating it in the English-speaking world.

And Eddington went further than just translating it. After the Great War ended, Eddington traveled to the Portuguese-controlled island of Príncipe, off the coast of Africa, to observe and photograph the total eclipse of May 29, 1919. At long last, the general theory of relativity would be tested experimentally. Einstein's theory passed the test with flying colors, as Eddington announced to the world in a 1920 paper where he published the results.

In the post-war world of 1920, there was something appealing about a German theoretician's work getting experimental confirmation from an English astronomer. It could be seen as a metaphor for the end of the war, and the hope for a new era when the former enemies would work together in more peaceful and enlightened pursuits. But the reality was that this was just one small test of general relativity; most of the theory's startling conclusions were still beyond the reach of science to test and measure.

Albert Einstein would pass away in 1955 at the age of 76; ironically, it would not be until the next twenty years following his death that observational science would finally develop the tools to give general relativity a rigorous testing. But those twenty years would see the Big Bang Theory, research into subatomic particles, black holes, space travel, and the development of atomic clocks that could measure the passage of time with unprecedented accuracy. These new tools would offer many new opportunities to test the conclusions of general relativity, and the theory would pass the test every single time.

In 1920, general relativity was explained to the world as the greatest advance in the understanding of physics since Newton, which is fair enough, but if you look at the press accounts of the time, you'll find that scientists and journalists mostly just threw up their hands and told the public that relativity was too complicated to explain. It's taken as long to find the right metaphors to explain general relativity as it took to confirm it.

I talked previously about Einstein's reputation as a genius; how his very name has become synonymous with genius. It was at this moment, in 1920, with the confirmation of general relativity, that his reputation was made as the scientist whose ideas were so complex it was all but impossible even to explain them.

It's one thing to gain an insight through intuition. Our intuition is based on our everyday experiences though, and relativity describes something so far beyond our day-to-day lives that intuition is no help. That's the real reason relativity is so hard to explain and so hard to grasp. To do this kind of science requires special skills, lots of math, and a disciplined way of thinking. As the physicist Richard Feynman would put it, "Trying to understand the way nature works involves a most terrible test of human reasoning ability. It involves subtle trickery, beautiful tightropes of logic on which one has to walk in order not to make a mistake." And there is no better example of this than Einstein and his general theory of relativity.

We'll have to stop there for today. As always, I thank each and every one of you for being a listener. I'd also like to thank Joe for his donation, and thank you, Iurie, for becoming a patron of the podcast. If you have some lucre to spare and would like to become a donor or a patron, I'd invite you to visit the website, historyofthetwentiethcentury.com and click on the PayPal or Patreon buttons.

And I hope you'll all join me next week, on *The History of the Twentieth Century* as we turn our attention back to Mexico and take a look at the latest goings-on in the Mexican Revolution. Let Them Raise Hell, next week, on *The History of the Twentieth Century*.

Oh, and one more thing. Edwin Abbott's book *Flatland*, originally published in 1884, did not make much of a splash at the time and might well have been forgotten, were it not for the English physicist and educator William Garnett who called attention to it in a letter to the British science journal *Nature,* published in 1920, 36 years after the original publication of the book and just at the time Arthur Eddington's eclipse observations were providing experimental confirmation for general relativity. Garnett argued in his letter that Abbott had in some sense anticipated Einstein's four-dimensional view of the Universe and laid out an elegant analogy which could be useful in helping modern readers understand general relativity.

And thus *Flatland* gained a whole new life as the little book math and physics teachers could recommend to their students as an introduction to Einstein's rather impenetrable theories, while the little book's brevity and charm made it one of those rare reading assignments that were entertaining rather than onerous. As science fiction established itself as a niche literary taste in the 1920s, its adherents would cite *Flatland* as an early example of the virtues of the new genre: how it could delight and expand the mind at the same time.

And for the rest of the twentieth century, science fiction writers would invoke the concept of higher dimensions as a way of explaining, well, pretty much anything they wanted to put in their stories. Sometimes the existence of higher dimensions and travel into or through them was a central element of the story itself, one obvious example being Madeleine L'Engle's 1962 novel *A Wrinkle in Time*, which explicitly references Einstein and relativity, in a book intended for young people, no less. In 1965, a Dutch physics teacher named Dionys Burger published a sequel to *Flatland* called *Sphereland: A Fantasy About Curved Spaces and an Expanding Universe*. Burger's sequel introduces relativistic concepts of curved space and an expanding universe by setting out a tale in which A. Square's grandson, a mathematician named A. Hexagon, discovers that his world of Flatland actually exists on the surface of a huge and expanding sphere.

But in the realm of science fiction, curved space and higher dimensions are most frequently invoked as a way of justifying faster than light travel, *Star Trek's* warp drive being merely one easy and obvious example. I could name a hundred more, but instead I'd rather call your attention to the striking irony of science fiction writers using Einstein's esoteric theories on the curvature of space as a loophole to get around the much simpler principle that matter can't travel faster than the speed of light, which was also bequeathed to us by Albert Einstein.

[music: Closing War Theme]