ALBERT'S TIME

Spacetime, relativity, and quantum theory

> Relativity has taught us to be wary of time.
>
> – physicist Wolfgang Rindler, who coined the term "event horizon"

> I see the Past, Present, and Future existing all at once before me.
>
> – William Blake

The city of Bern, nestled between the mountains of western Switzerland, looks much as it did a century ago. Streetcars still wind their way up and down the main streets, while arcades line the narrow lanes of the *Aldstadt*, or old city. The roads are dotted every few blocks with colorful fountains, many of them dating to the sixteenth century. Visitors who climb the gothic spire of the city's cathedral – one of the tallest in the country – are rewarded with sweeping views of red-tiled roofs, church steeples, and the churning blue waters of the Aare River. Apart from the cars and the tourists, in fact, the Swiss capital has changed little since the winter of 1902, when Albert Einstein, aged twenty-two, arrived here – unemployed, traveling on foot, and carrying all his belongings in a single suitcase. Within three years, he would become a husband and a father, and – oh, yes – would develop a radical new picture of time and space that would change the world forever.

Albert Einstein (1879-1955) wasn't born here – that honor goes to the southern German city of Ulm, some 250 kilometers away. Nor did he remain here for very long; in less than a decade, with his genius bringing increased fame, academic positions would draw him to Zurich, Prague, and Berlin, before the rise of Nazism would force him to leave Europe for good. But it was in Bern that the ambitious young scientist got his first real job – an entry-level position examining patent applications in a government office. And it was here that Einstein had his first great insights into the nature of the universe.

A narrow wooden staircase leads up from the street to the small apartment where he once lived, at Kramgasse 49. It is now a museum, and tour guide Ruth Aegler meets me at the top of the stairs. In Einstein's day, she explains in a thick Swiss-German accent, the apartment consisted of just two rooms, though one of them had two large windows looking out onto Kramgasse. (The museum is somewhat larger, having absorbed several adjacent rooms as well as the floor above.) If Einstein had poked his head out of the window and glanced to the left, he would have seen the magnificent sixteenth-century *Zytglogge*, or clock tower, just a block away. Ornate and colorful, if rather squat, it would have greeted young Albert every time he left the apartment.

Visitors now stream through the modest, wallpapered rooms, pondering Einstein's wooden desk from the patent office, dozens of historical photographs, his doctoral thesis, and even his high-school report cards (which show that he wasn't a bad student after all, contrary to popular myth). The patent job brought in just 3,500 francs a year – barely enough to cover the rent and provide the basic necessities of life for the scientist and his wife, Mileva. "Einstein was so happy and so proud that he could, for the first time in his young life, rent an apartment like that," Aegler says. "Only sixty square meters – that's not much, but for him it was absolute luxury."

By day, Einstein pored over the hundreds of patent applications that passed across his desk. His true passion, though, was not gadgetry but the underlying theory – the machinery of the cosmos itself. By the spring of 1905, a new theory of space and time had taken shape in Einstein's mind. At the age of twenty-six – only slightly older than Newton was at the time of *his* great insight – Einstein had his own *annus mirabilis*, producing five groundbreaking physics papers, including the one that gave us the first part of his theory of relativity, known as special relativity.

The Roots of Relativity

At the start of the twentieth century, Newton's laws seemed to explain just about everything – but not *quite* everything. To understand electricity and magnetism, as well as light and radio waves, physicists relied on another very successful description of nature – a framework developed by the Scottish-born physicist James Clerk Maxwell (1831-79).* Maxwell developed a set of equations that describe the relationship between electric and magnetic fields, showing them in fact to be two aspects of the same phenomenon. Just as Newton had linked celestial and terrestrial mechanics, Maxwell showed that electricity and magnetism are intimately connected. Electromagnetism was also found to embrace light, which was now seen to be an electromagnetic wave – an oscillating electric and magnetic field. (Light is just one kind of electromagnetic wave: X-rays, microwaves, and radio waves are all examples of "electromagnetic radiation," differing only in wavelength.)

But Maxwell's equations suggested something remarkable about these electromagnetic waves: they seemed to travel at one particular speed, which physicists denote by the symbol c – the speed of light. (The speed of light was first accurately measured in the 1670s by the Danish astronomer Ole Römer. The modern value for c is about 300,000 kilometers per second.) The notion that light was a wave that traveled at a definite speed raised two rather troubling questions: First of all, *relative to what* do light waves travel at the speed c? Wouldn't the speed of light depend on how you measured it? Surely your own speed, as well as the speed of the light-emitting object, would affect the value that you measured. Did Maxwell's equations apply only in some special reference frame associated with waves of light?

Secondly, just *how* did light waves propagate from one place to another? Everything that scientists understood about waves up to that point suggested that they require some sort of medium in order to move. (Sound waves, for example, require air; waves in the ocean require water.) But light waves had to be able to reach the earth from the sun, across seemingly empty space. What medium supported waves of light?

The best guess that anyone in Maxwell's time had was that light waves vibrate in a substance called the "luminiferous ether" (which I'll refer to simply as the "ether"). The ether, believed to permeate all of space, was presumably the substance that allows light waves to propagate. (It was also said to be the medium by which gravity exerts its influence. Newton never made it clear how the gravitational force of one body was felt by another, distant body; his opponents mocked his notion of gravity for its mysterious ability to reach out across empty space.)

The ether, then, was a convenient solution to both problems: it would give light something to propagate through, and it would define the reference frame of Maxwell's electromagnetic waves. But this still seemed awkward. Shouldn't the laws of physics be the same for everyone? If electro magnetism demands a special, privileged frame of reference, it would seem to violate a very basic principle that goes back to the time of Galileo. Often called the "principle of relativity" (or "Galilean relativity"), it states that there is no "privileged" reference frame: one observer is no better able to measure "true" speeds or distances or intervals of time than any other. Galileo, in fact, described a thought experiment that emphasized that very point: imagine, he said, that you and a friend are cooped up in a windowless cabin on board a moving ship. Suppose you have with you some butterflies and birds, an aquarium full of fish, and a bucket that slowly drips water from a hole at the bottom. You also have a ball that you throw back and forth with your friend. When the ship is tied up at the dock, the animals are equally inclined to move in any direction, the dripping water falls straight down, and throwing the ball takes the same effort regardless of who's throwing it to whom. But – this was Galileo's insight – you would observe *exactly the same effects* even if the ship were in motion at a constant speed. "You will discover not the least change in all the effects," Galileo declared, "nor could you tell from any of them whether the ship was moving or standing still."* Indeed, Galileo had shown that terms like "moving" and "standing still" are merely labels; no observer is in a more privileged position to say that he is at rest (or moving at some particular speed) than any other.

But in Maxwell's electromagnetism, there *does* seem to be a privileged reference frame – the reference frame of the mysterious ether. It would help, of course, if the properties of the ether could be measured in some way – or even detected, for that matter. Physicists had tried to discern the effects of the earth's motion through the ether as our planet revolves around the sun. As of 1905, however, all attempts to detect the ether had failed.

Most scientists were not losing sleep over this apparent dilemma. In the 1880s, Heinrich Hertz had used Maxwell's equations to predict the existence of radio waves, which he then duly detected; in less than a decade, Guglielmo Marconi was busy building radio transmitters and receivers. But a few physicists, including the young Einstein, were troubled by what they saw as a fundamental flaw in the underlying description of nature embodied in these two conflicting world views. (The French mathematician Henri Poincaré and the Dutch physicist Hendrik A. Lorentz were also grappling with these difficulties.)

One of Einstein's great strengths was his ability to conjure up "thought experiments" – simple mental pictures that allowed him to visualize what otherwise might seem like quite abstract problems. Even as a teenager, he had puzzled over what sounds like a very simple question: What would happen if you could catch up to a beam of light?* Newton and Maxwell offer starkly different answers to this question. In the Newtonian framework, you can catch up to anything; just go faster and faster, no problem. But in Maxwell's picture, light always propagates at 300,000 kilometers per second. If you caught up to a beam of light, its speed (relative to you) would be reduced to zero. Would you then see "frozen" waves of light? (When a surfer rides the crest of a wave in the ocean, he and the wave travel at the same speed; he could perhaps describe his wave as frozen. But what does frozen light look like?) If you *could* observe frozen light, you would have an "absolute" indication of your speed – a clear violation of Galileo's principle of relativity. To Einstein the thought of a stationary beam of light seemed crazy. "There seems to be no such thing," he said, "neither on the basis of experience nor according to Maxwell's equations." Einstein balked at the notion that an observer moving alongside a beam of light might need a different set of equations – different laws – to describe what he saw. After all, motion is relative; echoing the words of Galileo, Einstein asked how the observer would "know, or be able to establish, that he is in a state of fast uniform motion?" And if frozen light had no meaning, what *would* happen as your speed increased, approaching the speed of light?

Historians continue to debate exactly how Einstein arrived at his solution. The job at the patent office – as menial as it seems to us in hindsight – probably gave him valuable mental exercise as he imagined which electrical gadgets would work and which would falter. Historian Peter Galison has argued that the problem of synchronizing Europe's electrical clocks was especially important; many of the patents that crossed Einstein's desk involved electronic devices linked to this problem. Einstein's conversations with a close group of friends in Bern, nicknamed the Olympic Academy, gave him an invaluable sounding board for his ideas about space and time; his wife, Mileva Marič – a former classmate – also played such a role. (In a typical love letter from a few years earlier, Einstein tells Mileva how he looks forward to the hikes they'll take together when he comes to visit her in Zurich: "The first thing we'll do is climb the Ütliberg," he writes, referring to a local hill. "I can already imagine the fun we'll have … and then we'll start in on Helmholtz's electromagnetic theory of light.") Einstein was also profoundly influenced by the philosophical works of such thinkers as David Hume and Ernst Mach, whom he read intently in what little free time he had.

Whatever triggered it, the answer came to Einstein in the first few months of 1905 – seemingly out of the blue, but in fact the culmination of a ten-year period of intense mental focus in which he seems to have thought of little else. The solution, as he told his friend Michele Besso that May, "was to analyze the concept of time." Time, he goes on, "cannot be absolutely defined, and there is an inseparable relation between time and signal velocity."

Einstein had found that Newton's laws had their limitations; they were only an approximation of the true picture. Newton's equations apply correctly as long as the velocities involved are low: at everyday speeds, they're perfectly adequate. But as one approaches the speed of light, they break down. A new kind of framework is needed.

Einstein's paper, titled "On the Electrodynamics of Moving Bodies," was received by the prestigious journal *Annalen der Physik* on June 30, 1905. It was thirty pages long, but Einstein had already overthrown the Newtonian world view within the first few pages, introducing a new way of looking at both time and space, and, for good measure, eliminating the ether once and for all. (The reason no one had detected it, Einstein reasoned, is because it doesn't exist.) At the end of the paper there were no references to earlier work by other scientists, though he thanked his friend Besso "for several valuable suggestions." With his June 30 paper, Einstein had finally shown how to reconcile the mechanics of Newton with the electromagnetic theory of Maxwell.

A New View of Time and Space

The theory that Einstein laid out in 1905 is known as the special theory of relativity, or "special relativity" for short. It rests on two assumptions, or "postulates." The first postulate says that the laws of physics must be the same for any two observers, no matter how fast they're moving relative to one another, so long as they're moving at constant speeds (that is, with no acceleration). Whether you're trying to predict the motion of a projectile, or measuring electrical or magnetic properties, or studying a beam of light, the laws must be the same for everyone.

The second postulate says that the speed of light is always the same, regardless of your own speed and the speed of the object that's emitting the light. In other words, you'll always measure a beam of light as traveling at a specific speed, c.

The first postulate isn't particularly radical. It basically restates Galileo's principle of relativity – the notion that there is no privileged reference frame – and raises it to the status of a fundamental postulate about the physical world.

The second postulate, however, is truly shocking. In Newton's world, the speed you measure for any object depends on its motion and on your motion. A train seems to be whizzing past if you're standing on the platform; if you're on board the train, however, it doesn't appear to be moving at all (while the platform appears to be zooming past in the opposite direction). Throw a baseball off the front of the train, and the observer on the platform sees the ball as being given a "boost": if the train is going 100 km/h and you throw the ball at 80 km/h, an observer on the ground will see the ball moving at 180 km/h. The math couldn't be simpler: the speed measured by the observer on the ground is the sum of the train's speed and the ball's speed. It's just $v = v_1 + v_2$. Sounds obvious, right?

In Einstein's theory, this is still *approximately* true of trains and baseballs and other slow-moving objects – that is, objects moving at much less than the speed of light. But his second postulate says it is *not* the case for light: no matter how fast you're moving, and no matter how fast a source of light is moving, you'll still measure that beam of light as traveling at 300,000 km/s. It doesn't matter if I'm walking slowly with a flashlight or if I've mounted the flashlight on a rocketship, speeding past you at, say, 200,000 km/s (two-thirds the speed of light). It makes no difference; you will still measure that beam of light as moving at 300,000 km/s. This is the final answer to Einstein's thought experiment about catching up to the speed of light: it can't be done. Light can neither be given a boost nor slowed down; and no matter how fast *you* move, the beam of light will still appear to be traveling at its usual speed. (This also has the effect of making the speed of light the ultimate "speed limit" in the universe.)

In fact, whenever speeds are comparable to the speed of light, they no longer add up as simply as they did in Newton's world. The speed v that you measure is no longer equal to $v_1 + v_2$. Einstein worked out the correct formula.* It still gives Newton's result at low speeds, but at high speeds you get a lower sum than you would have expected. (And no matter how large v_1 and v_2 are, the sum will never be greater than c.)

And now the showstopper: in order for the speed of light to be constant, *time and space must be relative*. In other words, if two observers are moving relative to one another, they can disagree about the time interval between two events or the distance between two points in space – something that could never happen in Newton's arena of absolute time and space. And Einstein showed how to calculate those discrepancies precisely.

How can two observers, with perfectly synchronized clocks, possibly disagree about the interval of time elapsed between one event and another? This is perhaps the most counter intuitive implication of Einstein's theory. In fact, it turns out that a clock moving at high speed will appear to "tick" more slowly than an identical clock that's "stationary" (the quotation marks here are just a reminder that either of the two clocks can be said to be the one that's moving). This effect is known as *time dilation*. As an example, consider an imaginary high-speed train carrying a "light beam clock" – a clock made from a pair of parallel horizontal mirrors, one above the other, with a beam of light bouncing up and down between them (page 162, upper diagram). When the train is stationary, a person on board and a person standing on the platform both measure the same interval of time between each "tick" of the clock. When the train moves at close to the speed of light, however, an observer on the platform sees the beam of light trace out a diagonal or sawtooth path (lower diagram). Therefore, the distance the beam of light travels during each "tick" is larger. But – and this is the crucial part – Einstein's second postulate requires that the speed of light is still measured as having the same value. Since speed is equal to distance divided by time, and since the distance is larger, the time between each "tick" must increase. Therefore, an observer on the ground sees the clock on board the moving train as running slow.

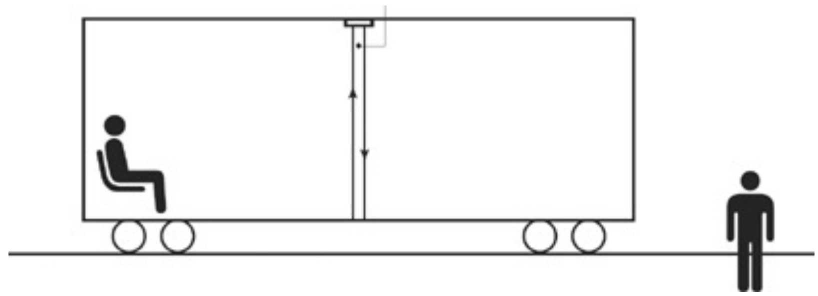
But the observer on board the train comes to the opposite conclusion: he sees a light beam in a similar clock on the ground as tracing out a diagonal path, and concludes that *it* is running slow. In keeping with Einstein's first postulate, there is no special, "preferred" reference frame – both descriptions are equally valid.

The time-dilation effects are negligible at everyday speeds but become significant as one approaches the speed of light. (I won't bother with the formula for time dilation here, but it involves only junior-high mathematics – some subtraction, division, and a square root.) If your friend's rocket is whizzing past at eight-tenths of the speed of light, you will observe her clock to be ticking at only 60 per cent of its usual rate. At nine-tenths the speed of light, it slows to just 43 per cent of its normal rate; at 99 per cent of light speed, it falls to 14 per cent. (Your friend cannot reach the speed of light; if she could, you would see her clock as having stopped altogether.)*

Why Time Is Relative

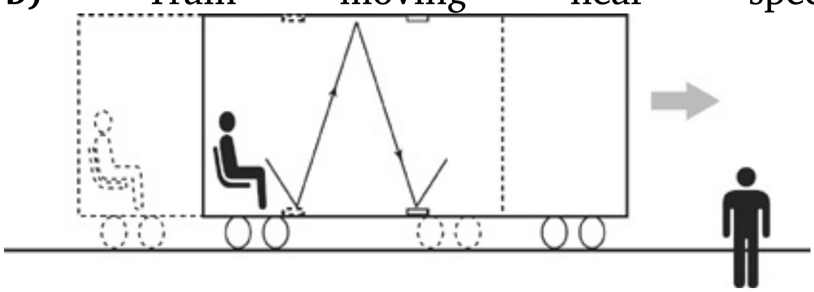
a) "Light beam" clock on board stationary train

Clock measures time by means of light pulse moving up and down between two mirrors.



The passenger in the train and an observer on the ground measure the same interval during each cycle of the clock.

b) Train moving near speed of light



The observer on the ground now sees the light pulse trace out a diagonal path. Since the speed of the light pulse is constant, he measures a greater interval during each cycle of the clock – and concludes that the clock is "running slow."

• He also sees the train (and everything in it) become shorter
– but only in the direction of the motion.

Interestingly, the equations that Einstein used in his June 30 paper were not new. They had been known to both Poincaré and Lorentz – but neither man had made the crucial leap of interpretation; neither had seen how the principle of relativity and Maxwell's electromagnetism could be reconciled by thinking about time and space in a new way. Einstein, it seems, had a unique ability to step back and see the big picture.

Perhaps his relative isolation at the patent office – he had, up to that time, failed to secure a job in academia – worked to his advantage; as someone cut off from the physics establishment, he had no particular loyalty to its preconceptions. In other words, he had nothing to lose. "He comes in entirely as an outsider," says Harvard historian Gerald Holton, a leading Einstein scholar. "He has no stakes at all in any of the nineteenth-and the early-twentieth-century physics … He lets his mind wander. He's not endangering his academic position, because he doesn't have one, and he can take those risks … He takes a much more Olympian view than any of the others did."

The physics community (and eventually the world at large) came to see special relativity as revolutionary, but Einstein never saw it that way. His aim was merely to extend Maxwell's theory of electromagnetism to a wider array of phenomena. Stressing the fact that the speed of light was the same for everyone, rather than the fact that time and space were not, he at first called his idea *Invariantentheorie* – "invariance theory." But Poincaré and the great German physicist Max Planck called it the theory of relativity, and that's the name that stuck.

The Problem of "Now"

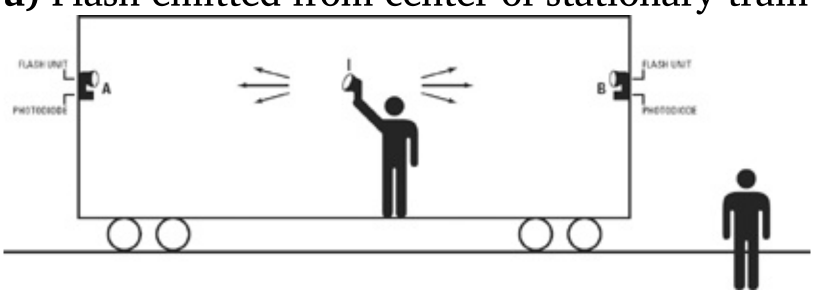
The slowing down of fast-moving clocks is just one of the ways in which special relativity assaults our commonsense view of time. It also forces us to re-think the idea of *simultaneity*. We say that two events are simultaneous if they happen at the same time; in Newton's world, this was a very straightforward idea. But in Einstein's universe, we have a problem: two events that may be simultaneous for me may not be simultaneous for you, depending on our relative motion. This is called the "relativity of simultaneity."

Suppose again that we have a railway car, this time equipped with a couple of simple gadgets: at either end of the car we install a camera's flash unit along with a photodiode, and we wire it up so that when light, from any source, hits the photodiode, it triggers the flash (upper diagram). (We can imagine that the car is dark enough that unless we introduce extra light, the flash units just sit there and do not fire.) Let's call the unit on the left A and the one on the right B. Now I take up a position in the middle of the car, halfway between A and B. I have a third flash unit, which I'm holding in my hand. If I set off the flash, what happens? Light from the flash reaches A and B at the same time, and forces them both to fire. From my perspective, the flashes triggered at A and B are simultaneous.

Now imagine that the railway car is moving along from left to right, at some speed close to the speed of light (lower diagram). Standing in the middle of the car, I set off my flash and again see the flashes at A and B as simultaneous. (Einstein's first postulate demands this; it simply says that I can equally well describe myself as being at rest, with the station and the platform speeding by.) But what does an observer on the ground see? From her perspective, the back of the car (A) is "chasing" the beam of light, while the front of the car (B) is running away from it. From her point of view, the beam travels a shorter distance to reach A than it does to reach B. According to Einstein's second postulate, she sees the beam itself moving at the usual speed, *c* – and concludes that the time needed for the beam to reach A, and trigger its flash, is less than the time needed for the beam to reach B. In other words, she sees the flash at A before she sees the flash at B. The events are no longer simultaneous.

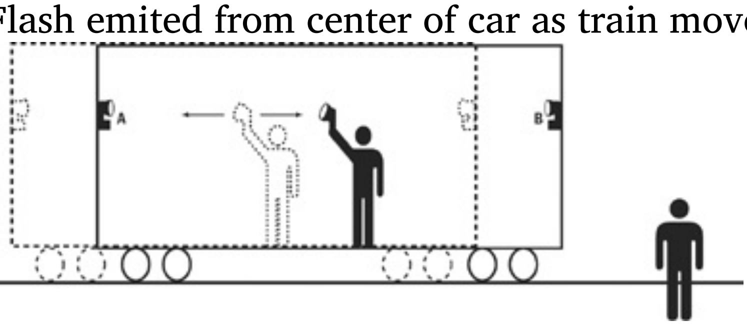
Why Simultaneity Is Relative

a) Flash emitted from center of stationary train car



To the passenger and to an observer on the ground, the light from the flash emitted at the center of the car reaches the two ends of the car at the same time. The photodiodes trigger the secondary flash units at A and B simultaneously.

b) Flash emited from center of car as train moves near speed of light



> To the observer on the ground, the emitted light beam now reaches A first, as the back of the train "catches up" to the beam of light. He sees the secondary flash unit at A fire before the unit at B fires. The events at A and B – still simultaneous for the passenger – are no longer simultaneous for the observer on the platform.

With special relativity, we can no longer declare two events to be simultaneous in any absolute sense. Instead, we can only say that they may *appear* simultaneous from some particular frame of reference. (Physicist Brian Greene calls this "one of the deepest insights into the nature of reality ever discovered.")

It gets worse. What do we mean when we say a particular event is happening "now"? When we use the word "now," we are really comparing two events: I can snap my fingers and then ask whether some other event is simultaneous with my finger-snapping or not. If it is, I say that the event is happening "now." In the Newtonian universe, I can legitimately ask, "What events in the universe are happening right now?" The answer would be a unique set of occurrences, scattered throughout space but lying on a single "slice through time." I can snap my fingers at, say, noon Eastern Standard Time on December 1, 2009, and every event, everywhere in the universe, either is simultaneous with my finger-snapping or is not. That was fine for Newton, but not for Einstein. As we have seen, in special relativity there is no universal agreement among observers as to whether two events actually are simultaneous or not – and thus there can be no universal "now." As Einstein remarked, "There is no audible tick-tock everywhere in the world that can be considered time." (There is an amusing story about a lecture he once gave in Zurich, where he covered a blackboard with clocks to illustrate the concept of simultaneity. After a lengthy exposition, he asked, "What is the time, actually? I don't have a watch.")

It is difficult for us to abandon the idea of a universal "now." We imagine that we can utter the phrase "everything in the universe that is happening right now" and have it refer to a meaningful set of events. But Einstein shows us that such a statement has, in fact, no clear meaning. Each observer has his own list of events that appear to be happening "now," and no one person's list is more authoritative than the next.

There is no “master clock” for the universe that can tell us what happened when. “Now” – one of the simplest and most-often-uttered words in our language – seems to have slipped from our grasp.

Newton would not be pleased, but in the century since Einstein unleashed special relativity on the world, countless tests have confirmed the theory’s predictions. A new benchmark was set in the fall of 2007, when a team of scientists led by Gerald Gwinner of the University of Manitoba confirmed the time-dilation effect to one part in 10 million. Gwinner and his colleagues used an accelerator in Germany to whip lithium ions through a circular tube at 6 per cent of the speed of light. They then used a laser to stimulate the ions, forcing them to give off radiation. Because the radiation is an oscillating electromagnetic wave, it can act as a clock; one cycle of the radiation can be thought of as one “tick” of the clock. At the high speeds involved, the ticks slowed down – observed as a lowering of the frequency of the radiation. In Gwinner’s experiment, the frequency shift was just that predicted by special relativity.

In the fall of 1905, Einstein published a short follow-up paper that showed another surprising consequence of his postulates – a link between matter and energy, embodied in what is now the most famous equation in the world: $E = mc^2$.*

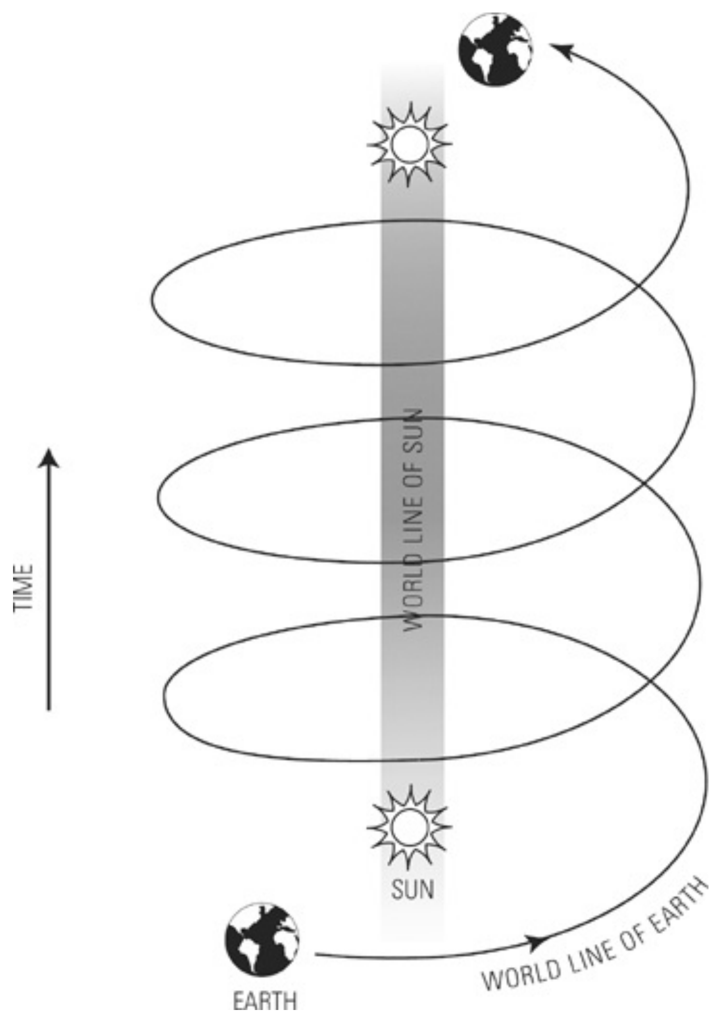
With special relativity, space and time are much more closely related than Newton could have imagined. In the Newtonian world, two events may be separated either in time or in space, or both. A position in space can be given by three numbers (for example, latitude, longitude, and altitude), while a moment in time can be described by a single reference (for example, by giving the precise time and date). With special relativity, however, we have to imagine combining these two sets of information. We must now think of events laid out in a four-dimensional array that we can call “spacetime” – an idea that would be formulated with mathematical precision by Einstein’s former math teacher Hermann Minkowski (1864-1909). In a famous proclamation delivered at a lecture in 1908, Minkowski laid the old, traditional view of space and time to rest: “Henceforth space on its own and time on its own will decline into mere shadows, and only a kind of union between the two will preserve its independence."

It is not easy to picture a four-dimensional scene, but if we ignore one of the space dimensions, then it is not too hard to sketch objects from the perspective of Einstein's spacetime. We can plot the remaining two space dimensions along a horizontal plane, and imagine the vertical axis as that of time. The path of a body through spacetime is called its *world line*. A familiar system, such as the earth and the sun, is now seen in a new light. If we choose a reference frame in which the sun is stationary, then its world line is a straight vertical line, while that of the earth becomes a helix.

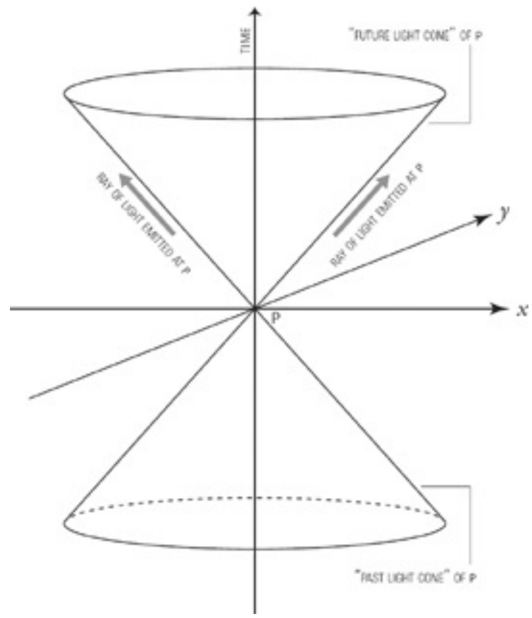
There is another useful concept that will aid us in picturing how events in spacetime relate to one another – what physicists call a *light cone*. Again we imagine space extending along the horizontal plane, and time extending vertically. Suppose a flash of light is emitted at some particular time at a point *P*. (Actually, we should call *P* an "event" – a point isolated in space *and* time.) The rays of light, traveling outward from *P* at the speed of light, trace out a cone-shaped region in spacetime, with *P* at the bottom. This is called the "future light cone of *P*."

Remember, nothing can travel faster than light – so the light cone encloses the entire region of spacetime that a person at *P* could "visit." Indeed, the event *P* cannot have any influence of any kind on the region of spacetime outside the cone. In the same way, we can draw another cone extending downward – that is, backward in time – from *P*. This is *P*'s "past light cone." Only events from within this cone can have had any influence on *P*. Again, this view is in sharp contrast with the Newtonian picture: in the classical view, with no speed limits, you can influence events in any region of spacetime, so long as they lie in the future – and you can *be influenced* by events in any region of spacetime, so long as they lie in the past. Relativity, in contrast, places much of the universe off limits.

In four-dimensional spacetime, what are we to make of notions such as past and future, or before and after? The situation is a bit messier than we might imagine from the clean lines of those light cones. Thanks to the relativity of simultaneity, an event that lies in my past may yet be in your future, and vice versa; all that is required is that the event be far away, and that you and I be moving relative to one another. Many physicists, and quite a few philosophers, have come to see the four-dimensional spacetime of special relativity as evidence that past and future events are just as "real" as present events. Everything seems to be laid out all at once in a kind of block – very similar, in fact, to the kind of "block universe" that we looked at in the previous chapter in connection with the B series described by McTaggart. With special relativity, it seems the block universe now has the backing of the greatest physicist of the twentieth century.



Picturing spacetime: We can't draw four-dimensional spacetime – but if we ignore one space dimension, we can imagine a three-dimensional scene in which time is the third dimension. In this sketch of the Earth-sun system, time runs along the vertical axis, while the Earth's "world line” is seen as a helix.



The “light cone”: only events in the “past light cone” of P can have had any influence on P; and only events in the “future light cone” of P can be influenced by P. (In this spacetime diagram, only two space dimensions are shown. The vertical axis represents time.)

What did Einstein make of this idea? His writings suggest that, much like Parmenides, Augustine, and McTaggart, he viewed the idea of time – or at least the “flow” of time – as something that resides not “out there” in the universe but rather within each of us. “The primitive subjective feeling of time flow,” he once said, “enables us to order our impressions, to judge that one event takes place earlier, another later.”

Many philosophers seem to agree. The American philosopher Hilary Putnam used the absence of a universal “now” to argue that future events are fully predetermined. Let’s say that an event – an election, for example – is in my future, but in your past. (Again, though it may seem odd, this is quite plausible in special relativity, depending on our speeds and the distances involved.) Putnam argues that at the moment when we pass, I am obligated to consider “real” everything that you consider real – including the results of the not-yet-held election! (Not yet held from *my* perspective, that is.) This clearly plays havoc with our traditional ideas of free will and the “openness” of the future. And it’s not just the future that gets an overhaul: by a similar line of reasoning, I am obligated to regard as "still real" events that seem to lie in my past but that may be in the present from your perspective.

The philosopher Michael Lockwood appears to be persuaded by Putnam's argument. "To take the spacetime view seriously," he writes, "is indeed to regard everything that ever exists, or even happens, at any time or place, as being just as real as the contents of the here and now." The "block universe" picture, with its peculiar blurring of past, present, and future, continues to hold sway with both philosophers and physicists. To be sure, each point in spacetime has a past and a future, defined by those light cones, but *every* point has such cones – there is no "overall future" and no "overall past." As physicist and writer Paul Davies has put it, "The very division of time into past, present and future seems to be physically meaningless."

Einstein's Masterpiece

Einstein's paper of June 1905 was just the beginning. Special relativity worked only for bodies moving at a constant speed – not those that are accelerating. It also ignored gravity. He struggled in pursuit of a more complete theory, until one day in 1907 he had a breakthrough based on another simple mental picture: "If a man falls freely, he would not feel his weight," Einstein mused. "This simple thought experiment made a deep impression on me."

Einstein was drawn to a profound conclusion about accelerated motion, analogous to what Galileo had deduced about motion at constant speed. Galileo had said that if you're in a windowless vehicle, you have no way of knowing whether you are at rest or moving at a constant speed. Einstein realized that if you're in a similar vehicle and feel a force pulling down on you, you could be accelerating upward *or* you could be experiencing the pull of gravity – the two are exactly equivalent. (Think of how you momentarily feel heavier as an elevator begins to move upward.)

This link between acceleration and gravity turned out to be the key to developing a new framework for describing both phenomena. It took great mathematical prowess, however, to work out the details. Instead of the “flat” geometry of Euclid, Einstein needed the “curved” geometry developed only recently by the German mathematician G.F. Bernhard Riemann (1826-66). “In all my life I have laboured not nearly as hard,” Einstein said to a colleague. “I have become imbued with a great respect for mathematics … Compared with this problem, the original relativity is child’s play.”

By the end of 1915, Einstein had worked out an entirely new mathematical description of gravity. This work became known as the general theory of relativity, or “general relativity,” to contrast it with the earlier theory of special relativity. The theory depicted gravity in an entirely new way: for Newton, gravity had been a force acting over a distance; for Einstein, it was a warping or curving of space itself. (The most popular analogy is that of a large rubber sheet: When a heavy bowling ball is placed on the sheet, it warps the sheet in proportion to the mass of the ball. Any marbles rolling nearby will be deflected by that curvature.) The sun holds the earth in its orbit by means of just such a warping. In Einstein’s world, matter distorts the very fabric of the universe and we experience that distortion as the force of gravity. For Newton, space and time are a kind of static background or stage on which physical events unfold; for Einstein, space and time are themselves dynamic players in the cosmic drama.

General relativity’s first success involved the orbit of the planet Mercury. Since the mid-1800s, astronomers had noticed that Mercury didn’t trace out a perfect ellipse as it revolved around the sun. Instead, the planet’s orbit shifted by a small amount each time it rounded the sun. The effect – astronomers call it *precession* – is very slight, amounting to less than a hundredth of a degree per century. Yet Newtonian physics could not account for it. Einstein’s theory, however, correctly described the phenomenon.

Three years later, the theory would be put to an even more crucial test. Because the sun distorts the space around it, it should deflect a ray of light emitted by a star if the ray happens to pass nearby. In other words, when the sun passes in front of a distant star, the star’s position – as seen from the earth – should appear to be slightly shifted. The sun is normally too bright to allow such an observation, so astronomers had to wait for a total solar eclipse, in which the moon blocks out the sun’s light. Einstein's predictions were confirmed during an eclipse on May 29, 1919; the images of distant stars were indeed displaced, just as the theory predicted. When the results were announced at a meeting in London in November of that year, it made headlines around the world. *The Times* of London declared a "Revolution in Science"; a few days later the *New York Times* buzzed, "Lights All Askew in the Heavens." Einstein would remain a celebrity – albeit a reluctant one – for the rest of his life.

Time, Gravity, and Black Holes

When we think of a heavy object warping the space around it, and imagine the bowling ball on the distorted rubber sheet, we are overlooking something very important: the massive object is warping space *and time* in its vicinity. (Indeed, as general relativity builds on special relativity, we can simply say that it distorts spacetime.) It turns out that, according to general relativity, time slows down in a gravitational field. The stronger the field, the greater the effect (which is known as "gravitational time dilation"). If two hikers with perfectly synchronized watches take a stroll through the hills of Scotland, the one who takes the high road will find his watch running ahead of that of his friend who chose the low road. (In this example, of course, the difference would be far too small for a store-bought watch to register.)

Gravitational time dilation has now been observed in many different kinds of experiments. One of the more dramatic tests was carried out in 1971, when scientists took atomic clocks around the world on board commercial jetliners; they later compared them to identical clocks that had remained on the ground. The experiment is more complex than it seems, because it tests not only general relativity (the clocks on board the planes were higher than those on the ground, and thus in a weaker gravitational field) but also special relativity (the clocks on the plane were moving at a high speed). The scientists were able to disentangle the two effects, and the results were in agreement with Einstein's theory.* Various terrestrial versions of the experiment have also been carried out. For example, an atomic clock in a U.S. lab in Boulder, Colorado – some 1,600 meters above sea level – has been measured to gain about 5 micro seconds each year compared with an identical clock in Greenwich, England, which is just 25 meters above sea level. So far, every experimental test of general rela tivity has confirmed Einstein's predictions. (In fact, GPS devices – Global Positioning Systems – have to take into account the effects of both special and general relativity in order to function.)

In most cases, gravity's warping of spacetime is very subtle, which is why it went unnoticed for so long. (The sun is 300,000 times heavier than the earth; even so, its gravitational field only deflected those light rays during the 1919 eclipse by a meager 1/2,000 of a degree.) But general relativity predicts that more massive objects can warp spacetime much more severely. Black holes are the most extreme example: these exotic structures warp space and time so drastically that they cut themselves off from the rest of the universe.

A black hole can form when a massive star exhausts its nuclear fuel and can no longer support its own weight. It then begins to collapse. If the star is big enough – more than three times the mass of our sun, roughly – then there is nothing that can stop that collapse. Gravity shrinks the dying star, and when it contracts below a certain critical threshold, known as the "event horizon," something peculiar happens: it becomes invisible. A ray of light emitted from within the event horizon can never escape; the gravitational pull is simply too strong. Objects inside the event horizon are effectively cut off from the outside world. (Although black holes cannot be seen, there is very strong indirect evidence that such objects do, in fact, exist. There may even be a "supermassive" black hole at the center of most galaxies, including our Milky Way.)

If an astronaut were falling into a black hole, a distant observer would see her wristwatch slow down almost to the point of stopping. If she were to reach the event horizon, we would see her watch stop altogether. From the astronaut's point of view, time would continue to pass normally as she fell into the hole and, in all likelihood, into a nasty death. (Actually, the intense radiation from the region just outside the black hole, as well as the tidal effects of the gravitational field,* would almost certainly kill her long before she actually crossed the event horizon.) But for us, observing from far outside the black hole, she would remain forever poised on the event horizon, frozen in time.

The entire field of astrophysics has been transformed by general relativity – and so too has cosmology, the study of the origin and evolution of the universe itself. Our understanding of the birth of the universe has been completely overhauled thanks to Einstein's theory – and we will explore this new perspective in more detail in Chapter 9, when we look at the question of how time, and the universe, began.

How should we picture time as described by Einstein's general relativity? There are still world lines and light cones – but the cones can be slanted and the world lines twisted as spacetime itself is distorted by gravity. Even so, many philosophers believe that the framework of the theory is compatible with the block universe we considered earlier in connection with special relativity. (In general relativity, for example, simultaneity continues to be relative.) We should also note that the equations of general relativity are time-symmetric, just like Newton's equations; nothing in relativity directly addresses the question of time's apparent flow.

The Quantum Revolution

It must be a good feeling to know that you're going to win a Nobel Prize. By 1920, now an international superstar and a household name, Einstein knew he was overdue for the prize. (He had in fact been nominated many times, beginning in 1910, but had been passed over for a variety of reasons, some involving politics and some involving science. Many considered relativity too abstract and theoretical – at least before the eclipse of 1919 – to deserve the prize.) He also knew he would not keep the money: he had already promised it to his wife, Mileva Marič, as part of the divorce settlement. (Einstein divorced Mileva in 1919 and married his cousin Elsa Lowenthal later that year.) When he finally won the Nobel in 1921, the citation did not mention relativity – but it did mention one of the other papers he had written during his miracle year in 1905. He was awarded the prize "for his services to theoretical physics, and especially for his discovery of the law of the photoelectric effect."

That paper, written just a few weeks before the one on special relativity, dealt with the way that light interacts with metals, known as the "photoelectric effect." It was a key contribution to a new scientific framework called "quantum theory," which had its roots in a paper by Max Planck from 1900. Planck was struggling to explain the spectrum of the radiation emitted by hot objects.* The mechanics of Newton and the electromagnetic theory of Maxwell, he found, were inadequate. He was ultimately led to the idea that heat energy is emitted not in a continuous stream but in discrete bundles of a particular (very small) size. Planck called each of these energy bundles a *quantum* (plural *quanta*), from the Latin word for "how much."

We will not wade too deeply into the early development of quantum theory. It will be enough to note that, over the next few decades, quantum theory blossomed into a new system of mechanics that would replace Newtonian mechanics whenever small distances are involved. Newton's mechanics were fine for baseballs and planets (so long as they moved at slow speeds compared to the speed of light), but the atomic and subatomic world could only be studied by means of quantum theory. (The old Newtonian picture would come to be known as "classical" mechanics.)

Quantum mechanics is radically different from Newtonian mechanics. It is, first of all, inherently probabilistic. In classical mechanics, a particle is either at position x or it is not. In the quantum picture, we cannot be so precise. We can only say that when we measure the particle's position, we have some particular probability of finding it at x. In fact, quantum mechanics says that, until we measure it, a particle can be in many places at once; more generally, a quantum system can be in many "states" at once – a phenomenon known as *superposition*. It is only when we observe a quantum system – when we make a measurement – that the system "collapses," and we obtain a single, specific result. (At least, that's how the collapse is viewed in the traditional "Copenhagen interpretation" of quantum mechanics. There is another interpretation known as "many worlds," which we will encounter in the next chapter.)

Time and the Quantum

What is the fate of time in the quantum world? One often hears that the probabilistic nature of quantum measurements leads inexorably away from determinism and (allegedly) allows for an "open" future. However, things are not that simple. It turns out that the equation that describes how a quantum state will evolve, known as the Schrödinger equation, is deterministic; it says that quantum systems do, in fact, evolve in a perfectly predictable way. (And the equation is, once again, time-symmetric.) The system evolves in a predictable way *until* we intervene by making a measurement, at which point the wave function collapses. The collapse of the wave function appears to be irreversible, and thus suggests a link to the arrow of time. As Paul Davies puts it, "In the act of measurement, a single, specific reality gets projected out from a vast array of possibilities … The possible makes a transition to the actual, the open future to the fixed past – which is precisely what we mean by the flux of time."

While quantum theory may eventually point the way to a deeper understanding of the arrow of time, is also threatens to overturn some cherished ideas about cause and effect. In the classical world, every event has a cause, even if we cannot deduce what that cause is. In the quantum world, some events – the decay of a radioactive atom, for example – can just "happen." This is a radical departure from the idea of cause and effect that we were used to from classical physics. But we may just have to accept it: like relativity, the predictions of quantum theory have been borne out by countless experiments. Every time we use a semiconductor-laden gadget, we bear witness to quantum theory's reach.

"Anyone who is not shocked by quantum theory has not understood it," the great physicist Niels Bohr once said. Einstein himself, in spite of being one of the theory's founders, was never able to fully accept the quantum picture of the world. Had Einstein fully embraced the theory, perhaps he would have been the Person of the Millennium and not just the Person of the Century – but that is idle pondering. In a few weeks in early 1905, he overturned our view of the universe in a single swoop of the imagination, and that is a feat that never ceases to impress. “Newton, forgive me,” he wrote many years later, acknowledging that he, too, was standing on the shoulders of giants. “You found the only way that was available at your time to a man of the highest reasoning and creative powers.”

In Bern, visitors stroll through the modest apartment where Einstein lived at the height of *his* creative powers – the rooms where he shared simple meals with his young wife, rocked his newborn son to sleep, played the violin, and imagined a new universe. His friends would drop in after dinner, and linger for long conversations. They talked about mechanics and electricity, clocks and reference frames, physics and philosophy. From those swirling discussions, fueled by cigarettes and Turkish coffee, the seeds of relativity took root in Einstein’s mind.

Few of today’s visitors are professional scientists. Instead, they come from all walks of life, drawn by Einstein’s universal appeal not only as a figure of otherworldly intellect but also as a man of enormous compassion, a kind of secular saint for the scientific age. Children sometimes draw sketches in the museum’s guest book. Ruth Aegler, the tour guide, mentions a nine-year-old boy who left a note to “Dear Albert,” telling of his desire to become “a scientist like you are.” Adults can be just as awestruck, she says. Some of them plead for permission to stay past closing time, just to breathe the air that Einstein once breathed. “You can’t explain that,” Aegler says. “That is something you have to feel.”

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* A more detailed look at Maxwell and an overview of nineteenth-century physics can be found in Chapter 4 of *Universe on a T-Shirt*.

* For most of us today, a jetliner at cruising altitude is probably the most vivid example. As long as the pilot avoids any turbulence or sharp turns, a passenger who closes the window shade might hardly be aware of the plane’s motion.

* Einstein first pondered this “thought experiment” at the age of sixteen, but it is clear that it continued to influence his thinking in the years leading up to his 1905 paper on special relativity.

* The new formula is $v = \dfrac{v_1 + v_2}{1 + \dfrac{v_1 \times v_2}{c^2}}$

* Two other effects are worth mentioning: the length of a fast-moving object will appear to shrink, and its mass – its resistance to further acceleration – will increase.

* In the equation, *E* is energy, *m* is mass, and *c* once again is the speed of light. Because *c* is so large – and c^2 is even larger – even a small amount of mass can be converted into a large amount of energy.

* In fact, there was a third effect to disentangle: the earth's rotation causes its own time dilation effect!

* "Tidal effects" refers to the difference in the strength of gravity's pull on different regions. If the astronaut were falling into the black hole feet-first, gravity would pull on her feet more than her head, with disastrous consequences.

* The *spectrum* of a body refers to the intensity of the radiation given off at different wavelengths.