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Einstein: His Space and Times

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Description
The commonly held view of Albert Einstein is of an eccentric genius for whom the pursuit of science was everything. But in actuality, the brilliant innovator whose Theory of Relativity forever reshaped our understanding of time was a man of his times, always politically engaged and driven by strong moral principles. An avowed pacifist, Einstein's mistrust of authority and outspoken social and scientific views earned him death threats from Nazi sympathizers in the years preceding World War II. To him, science provided not only a means for understanding the behavior of the universe, but a foundation for considering the deeper questions of life and a way for the worldwide Jewish community to gain confidence and pride in itself.

This biography presents Einstein in the context of the world he lived in, offering a fascinating portrait of a remarkable individual who remained actively engaged in international affairs throughout his life. This revealing work not only explains Einstein's theories in understandable terms, it demonstrates how they directly emerged from the realities of his times and helped create the world we live in today. [*From the Publisher*]

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Comments
"Chapter 2: The Miracle Year," of this book is available to download above.

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The Miracle Year

In 1905 Albert Einstein, despite not working as a researcher, planned to transform physics. In a letter to Habicht, who had just moved away from Bern, Einstein refers to elements of his projects for the year as "very revolutionary." Anyone else uttering such words could well be considered audacious, bordering on naïve. Not only did Einstein seem highly unlikely to be the person best positioned to change the course of the oldest and most established field in science, but the field itself did not seem to need changing.

The philosopher Thomas Kuhn argued that scientific revolutions are preceded by a period of crisis in which anomalies force scientists to reconsider the basic concepts, methods, and presuppositions underlying standard practice.[1] Typical scientists, he contended, hate questioning the basis of what they do—they prefer to simply go and do it. So the period before a scientific revolution is very uncomfortable for those in the field who are compelled to think philosophically.

But this was not the case in 1905. There were a few problem areas and a couple of strange results that needed to be accounted for, but no one expected an imminent Copernican-style revolution. Newton's mechanics and James Clerk Maxwell's electrodynamics were entrenched and, by and large, working perfectly well. The boat was in calm waters, and rocking it seemed a waste of time and energy.

Einstein thought what he was about to do was revolutionary because he had a coherent vision of the universe that disagreed with the accepted view in crucial ways. When we understand matter, light, and space differently, he thought, everything would have to change. To make this happen, two things were needed: the details of his picture would have to be rigorously developed, and important people in the physics community would have to take his work seriously, the work of a professional nobody. He knew he needed incredibly strong arguments and irrefutable results, but he also knew that, no matter what he wrote, it would not be considered if it was the work of a mere patent clerk. Shut out of the academic physics community, he knew that if he could not work in the lab of an established physicist he would need to enter by a side door—and for that he would need a doctorate.

Today, if you want a Ph.D., you need to be accepted into a graduate program and satisfy a program of study that includes coursework, exams, and a dissertation process under an adviser resulting in research that expands the field. In Einstein's time, things were less formal and students submitted their work to university faculty, who then determined whether it was novel and important enough to merit the degree.

Einstein's first attempt at a Ph.D. came right after graduating from the ETH. Working in Weber's lab, he explored the thermoelectric Thomson effect.[2] When wires of different materials are connected and electrical current is sent through them, the wires heat up to different temperatures. This did not seem too odd, but more surprisingly, the effect works in the other direction—that is, by heating wires made of different materials joined together one can actually generate electricity. Exploring this connection between heat and electricity was classic Einstein, as he loved looking for insights in the relations between seemingly different subfields of physics. But in 1900, when he first began working toward a doctorate, the effort fell flat.

Einstein next struck out on his own and wrote a dissertation concerning the forces between atoms in a gas in 1901, submitting it to Professor Alfred Kleiner at the University of Zurich, across town from the ETH. No copies of this manuscript survive, but ultimately it was rejected by Kleiner. Some have contended that it was a matter of quality, as Einstein himself would later call it "worthless,"[3] while others have concluded that the problem was "Einstein's attack on the scientific establishment,"[4] especially Ludwig Boltzmann, a very esteemed colleague of Kleiner's. If true, the latter assessment would, in a sense, be ironic because it was Boltzmann's picture of the universe that was the basis of Einstein's revolutionary ideas.

In the preceding generation, a question about heat led to a concern about the nature of physical laws and the structure of the universe. Energy comes in a variety of forms, forms that can be transformed from one to another, but whenever such a change occurs the amount of energy we get out is never quite as much as the amount we put in, because some is always lost in the transfer. Consequently, efforts to create a perpetual motion machine always fail because to get something to move, we need to take some form of energy and convert it into kinetic energy—that is, the energy of motion. This conversion is always incomplete, we always lose some energy, so the machine slows down until eventually it stops. This regularity is expressed by physicists as a principle called the second law of thermodynamics, and is written out in terms of a quantity termed "entropy."

Despite its title as a law, a major dispute arose about the meaning of the second law of thermodynamics. Some, such as Rudolf Clausius and the young Max Planck, argued that as a law it must be both universal and true; that is, it must apply always and everywhere. The second law of thermodynamics says that entropy increases in a closed system (a system where energy is not added), so if the second law of thermodynamics is a real law, entropy necessarily increases. Arguing otherwise were scientists in line with Boltzmann, who contended that we cannot just state these laws as numerical correlations without having a sense of the operative physical factors bringing them about. In other words, we need to pop the hood and see what is happening underneath. Boltzmann was an adherent of the kinetic theory of gases, wherein matter comprises molecules, and heat is the energy of their motion. The second law needed to be worked out in terms of the interactions of these particles.

Many important and respected scientists before the turn of the twentieth century did not accept the atomic view of matter. Atoms and molecules were unobservable, and this group believed it was wrong to try to make sense of empirical results in terms of nonempirical entities—if we cannot see atoms, why would we base our understanding of physics and chemistry on them? But Boltzmann did, and he translated entropy talk into ideas about the statistical distribution of the speeds of the molecules. But when we talk about large-scale statistical relations, unexpected situations must be expected to pop up occasionally. Everyone who buys a lottery ticket should expect to lose, but someone does eventually win. The thermodynamic version of the lottery implies that when we talk about entropy, we should expect at any given time it will increase, but there will be rare cases where on its own it decreases just by luck of the draw. The second law of thermodynamics, Boltzmann held, was a statistical generalization that says that entropy tends to increase.

Einstein shared Boltzmann's picture of a universe full of atoms bouncing around, their behavior governed by statistically derived results. While the details may not have been exactly Boltzmann's, Einstein's second attempt at writing an acceptable dissertation worked along these conceptual lines.

Typical of Einstein, he sent his dissertation to Kleiner, absolutely certain that it would be accepted. Einstein waited and waited, but no word about his dissertation came. Had Kleiner rejected his effort out of hand and not written back? Did he not understand it? The fact was that, several months later, Kleiner still had not gotten around to reading it. So, after expressing some rude words about the man in letters to his closest friends, Einstein went from Bonn to Zurich to see Kleiner, who received him warmly. He wrote to Mileva, "I spent all afternoon at Kleiner's in Zurich telling him my ideas about the electrodynamics of moving bodies, and we talked about all sorts of other physics problems. He's not quite as stupid as I'd thought, and moreover, he's a good fellow. He said I could count on him for a recommendation anytime. Isn't that nice of him? He has to be away during the vacation and hasn't read my paper yet. I told him to take his time, that it's not pressing. He advised me to publish my ideas on the electromagnetic theory of light of moving bodies along with the experimental method."[5] After the visit, Kleiner did eventually make time to read it. He did not like what he read and encouraged Einstein to retract it. Einstein did and was able to recover the 230 franc fee that he had to pay as part of the dissertation submission process, but as a result he became quite bitter.

For a while, Einstein put aside the idea of getting a Ph.D., but then he realized that it would be both useful if he stayed at the patent office and essential if he was to continue pursuing an academic post. Given Kleiner's advice to publish his work on the electrodynamics of moving bodies—that is, the basis for the special theory of relativity—he sent in his work on the question as his third attempt. It, too, was rejected. Recognizing that something safe, conventional, and based on experimentation would be best, Einstein decided to send in part of a larger project, something that was practical and uncontroversial.

At the heart of Einstein's worldview in 1905 were atoms. With his friends in the Olympia Academy, he had read Ernst Mach, the German physicist and philosopher who championed a view called "positivism," in which only that which is observable can be said to be real. Mach used this view to argue that some of the most central elements of physics were, in fact, not real. These included Newton's absolute space, and atoms. Einstein was fascinated by Mach but thought he had to be wrong about atoms. What the world needed was overwhelming experimental evidence, but for this Einstein would need to first build the mathematical foundation. That groundwork was the topic of his dissertation.

The work of physics is to take a situation in the world, figure out which among the infinite elements of the system that could be observed are important, determine how to turn these elements into measurable quantities, and finally set out relations among these quantities whose truth can be experimentally tested. Physicists create equations—that is, mathematical sentences in which the arithmetic combination of terms on the left side of the equal sign yields the same number as the arithmetic combination of the terms on the right side. Those terms either are directly measurable themselves or could be calculated from other measurable quantities using other equations.

In Einstein's work in 1905, we see just such a recurring approach. Einstein's style was to consider a system that can be described in two different ways and figure out how those ways relate to each other. Einstein was a synthesizer; he liked to bring together accounts that seemed to be contrasting takes on the same situation and then argue that they were just different ways of seeing the same thing. Since the accounts are not competing but equivalent descriptions, we can set them equal to each other and find new relations, thereby producing understanding and insight into the nature of that system.

Einstein did just this in his dissertation "A New Determination of Molecular Dimensions." Atoms might not be observable, but this does not discount the existence of macroscopic phenomena that would allow us to discover aspects of their microscopic existence. Einstein's dissertation and the paper that would follow were a two-step process to providing irrefutable evidence that matter is made up of discrete building blocks.

Before Einstein, atomists focused on the behavior of gases. The measurable quantities of volume, pressure, and temperature had long been related to each other, and in a series of famous papers in the mid-nineteenth century James Clerk Maxwell figured out how to think of them in terms of large collections of microscopic molecules. If gases were really just a bunch of disconnected molecules in motion, then pressure would be the result of the particles bouncing off the wall of the container in which they were held. Since heat adds energy, higher temperature could be thought of as increasing the average speed of the molecules. Maxwell had made a few assumptions about the molecules to make calculation easier—they are spherical and infinitely hard and interact only by contact (in other words, we could think of a gas as if it were a cloud of billiard balls)—and he then derived what we call the "Ideal Gas Law," $PV = nRT$, in which P is the pressure, V is the volume, n is the number of molecules, T is the temperature, and R is the Rydberg constant, a number that makes the units come out correctly. This law makes sense to us intuitively. Blow into a balloon and it expands—meaning that if we allow the pressure on the outside of the balloon and the temperature inside to remain constant, the volume of the balloon increases if we add air molecules. If we blow into the balloon while holding it so that it cannot expand, then the pressure on the walls increases. If we tie the balloon off, thereby fixing the amount of air inside, and put it in the freezer, the balloon shrinks because its volume decreases with the temperature. Maxwell showed that all of this would be expected if we thought of gases as if they were made up of molecules.

Einstein wanted to remove the inference of the "as if." Molecules are not merely a heuristic device, a pictorial tool we use; they are real. To move from "as if" to "are," we need to strengthen the argument. Einstein did this by doing for liquids what Maxwell did for gases by considering dissolved substances in solution. Take a cup of tea and add a teaspoon of sugar. The sugar melts from solid crystals to a viscous liquid that distributes itself through the tea so that after a while every sip has roughly the same sweetness. Liquid flows, so it seems that it is not a set of solid, discrete molecules but rather is something smooth. Einstein set out to show that this smooth liquid really was made up of individual bits by considering how the liquid sugar distributes itself throughout the teacup.

To do this, Einstein makes assumptions similar to Maxwell's —that is, assume that (1) the sugar molecules are spherical, and (2) the sugar molecules are so much larger than the molecules of the liquid that from the perspective of larger sugar molecules the tea molecules can be seen as smoothly surrounding them.

Einstein considers two different ways of looking at the situation in the teacup. The sugar, he argues, would be both pushed and pulled. On the one hand, the melted sugar would be pushed forward by diffusion. All systems seek equilibrium, meaning that over time things become evenly distributed. The sugar would move from the small area it initially occupied to being randomly distributed throughout the teacup. On the other hand, the sugar would be pulled back by the viscosity, or thickness, of the liquid. The gooier the liquid, the slower the molecules move through it and the longer it takes them to spread out evenly. Einstein was able to work out equations for the push and pull in such a way that both were fully determinable by measurement except for two terms, one being the size of the molecule and the other being Avogadro's number, the quantity of molecules in a gram of the substance. Having two equations and two unknown terms, we can do some basic algebra and get values for them.

But notice what these unknown values are—the number of molecules and the size of molecules. These make sense only if there are molecules to have a size and a quantity. When we combine this work on liquids with Maxwell's similar work on gases, it seems that we have even more reason to believe in atoms as not just useful fictions, but real entities.

While the underlying desire is the theoretical goal of proving that matter is atomic, the dissertation itself is actually quite practical in that the equations can be used to tell us how two substances will blend. Whether one is mixing cement or blending flavoring into ice cream, Einstein's paper shows how to do it. As a result, his least famous work of 1905 is actually the most useful and thereby the most cited of all his papers.

Most important for Einstein, Kleiner was happy with it, although years later Einstein told biographer Carl Seelig that at first Kleiner was not happy enough, sending it back to Einstein because he thought the paper was too short. So, Einstein being Einstein, he claimed to have added a single sentence and sent it back.[6] This time it was accepted. Kleiner wrote, "The arguments and the calculations are among the most difficult in hydrodynamics and could be approached only by someone who possesses understanding and talent for the treatment of mathematical and physical problems, and it seems to me that Herr Einstein has provided evidence that he is capable of occupying himself successfully with scientific problems."[7] Einstein was now a doctor and could proceed to step two in the demonstration of atoms.

In his next paper of 1905, "On the Movement of Small Particles Suspended in Stationary Liquids Required by the Molecular-Kinetic Theory of Heat," Einstein takes the work he did in his dissertation and applies it to another case, what came to be called "Brownian motion."

Looking at liquids under a microscope, one discovers something odd. Small particles in the liquid can be seen to zigzag around randomly. Some thought that the motion was evidence that the particles had to be biological, that there were small animals moving about. But biologist Robert Brown showed that the phenomenon was replicable with clearly nonliving particles such as ground glass. So it had to be a physical phenomenon.

Some suggested it was caused by thermal currents in the liquid. Hot flows to cold, and maybe this was pulling the particles along. This was not the answer either, because neighboring particles should share similar motions, but they do not.

Others suggested an atomic explanation. Maybe it was an interaction of the atoms of the liquid striking the particulate matter. But the particles were too heavy. It would be like trying to move a bus by hitting it with balloons. The source of the Brownian motion was a mystery.

Einstein thought that the atomic explanation was on the right track, but that the phenomenon was more complicated than could be explained by one-on-one collisions—indeed, it is more complicated in exactly the same sort of way the sugar in tea example worked. The larger particles are surrounded by many tiny molecules bouncing off of them. But since the liquid around them is composed of molecules all moving in various directions, on average the molecular collisions from one side of the large particles would most likely be balanced out by the collisions from the molecules on the other side. Only if you had a significantly greater number of collisions from one side than from the other would enough force be generated to cause the large particles to move. If we take the molecular hypothesis seriously and think of the liquid in equilibrium—that is, the same energy of motion everywhere—then there should be no movement of the particles.

But the picture Einstein had of the microworld was much more chaotic. The molecules were not smoothly choreographed; rather, the temperature was an average, with some moving faster, others moving slower, and all moving in random directions. As such, the combined interactions of the molecules with the particles would be a result of chance. There was a possibility that a lot more molecular collisions could occur in one direction, but there was no reason to think it would happen in one direction rather than another. How could one mathematically model this situation?

Einstein realized that he recently had done just that. In his doctoral dissertation, he treated the molecules of dissolved sugar as larger spheres surrounded by a sea of liquid. That is exactly what was happening in this case. Einstein could use the same exact mathematical moves from his dissertation and apply them to Brownian motion.

> It will be shown in this paper that, according to the molecular-kinetic theory of heat, bodies of microscopically visible size suspended in liquids must, as a result of thermal molecular motions, perform motions of such magnitude that these motions can be detected by a microscope. It is possible that the motions to be discussed here are identical with the so-called "Brownian molecular motion"; however, the data available to me on the latter are so imprecise that I could not form a definite opinion on the matter.
>
> If it is really possible to observe the motion to be discussed here, along with the laws it is expected to obey, then classical thermodynamics can no longer be viewed as strictly

> valid even for microscopically distinguishable space, and an exact determination of the real size of atoms becomes possible. Conversely, if the prediction of this motion were to be proved wrong, this fact would provide a weighty argument against the molecular-kinetic conception of heat.[8]

Einstein's carefulness in the first paragraph, hedging as he does on whether the motion he is predicting is, in fact, Brownian motion, is to some extent legitimate in that his lack of access to university resources did leave him without the tools needed for the stronger claim. At the same time, there is little doubt in Einstein's mind that what he is describing is Brownian motion. This makes the challenge in the second paragraph something of a sucker's bet. Einstein sets out observation of the motion that he "predicts" will occur as something philosophers of science call a "crucial experiment"—that is, a result that if observed will justify a theory, and if not observed will falsify it. It is all or nothing, a sudden-death overtime for scientific theories. Einstein seems to be playing it honestly—go check and see if this motion is observable; if it isn't, then the molecular picture will have been defeated and we all need to stop believing in the reality of atoms. Of course, he makes this offer only because he knows that the motion has already been repeatedly observed.

But the wager requires more than generalities, and Einstein ends the paper by throwing down the gauntlet for experimenters. He considers particles 0.00004 inches in diameter suspended in water (he needs to specify the liquid so that the viscosity is known), and predicts that at 62.5 degrees Fahrenheit the particle would move horizontally (thereby neglecting the effects of gravity) about 0.000003 inches per minute. Since this is a displacement that was within the possibility of being observed in the lab, though not easily, Einstein concludes with: "Let us hope that a researcher will soon succeed in solving the problems posed here, which is of such importance in the theory of heat!"[9] The use of exclamation points is not common in scientific papers, and it shows both Einstein's sense of the importance of his work and his lack of concern with the usual marks of professionalism.

Thankfully, researchers did take up this challenge, and the French master experimenter Jean Perrin verified Einstein's calculation, earning the Nobel Prize in 1926. Perrin, with Einstein, was a strong proponent of the atomic theory and, also in line with Einstein, a prolific calculator of Avogadro's number. They both spent much time collecting radically different sorts of phenomena from across the spectrum of subfields in physics, all of which could be used to calculate Avogadro's number. Since Avogadro's number is the number of atoms in a fixed amount of a substance, each approach must give independent and additional support for the existence of atoms. After all, you cannot have a number of things without having the things to be numbered. But even after Perrin's work, which once and for all convinced even the most dogmatic holdouts in the scientific community of the existence of atoms, the two continued to seek out novel and disparate places to find Avogadro's number hiding in the equations of the disparate subfields of physics and chemistry.

Demonstrating the existence of atoms would be a major accomplishment for any scientist, much less one so junior, but this effort is widely regarded as the least important of Einstein's work in 1905. In addition to the structure of matter, he also considered a radical revision of our understanding of the nature of light.

In the nineteenth century, light was considered a wave for both experimental and theoretical reasons. Despite Newton's contention that light was a particle, the French physicist and engineer Augustin-Jean Fresnel and the British researcher Thomas Young produced optical effects that seemed to be explainable only if we consider light to be a wave. Waves add and subtract in particular ways when they flow through each other—"interfere," in technical terms—and there are numerous phenomena where this sort of interference can be seen. In these cases, light behaves as a wave.

Maxwell's equations, the four laws that govern electromagnetism, are named for James Clerk Maxwell, who discovered none of them and in fact made just one change to one term in one equation. But when Maxwell took these individual principles and put them together into a coherent, unified theory, they became incredibly powerful. One of the unexpected results was that these equations, which describe the behavior of electricity and magnetism, could also be used to describe the behavior of light. Maxwell's equations give us a description that has the form of a wave equation, so given the observable evidence light had to be thought of as a wave of electromagnetic radiation.

But now we had a problem. Waves require a medium, something to do the waving. Sound, for example, is a wave in air. No air, no sound. But we receive light from stars that are very, very distant. If empty space is a vacuum, then what is doing the waving to get the light waves from there to here? Physicists called this undetected medium the luminiferous aether and sought to detect it directly or indirectly. That is what Einstein was doing when he injured himself in the lab in college. By evacuating a glass jar, was he pulling out just air or was he sucking out the aether as well? If aether could be moved by physical forces, then the vacuum pump could remove it, causing an "aether vacuum" and making the jar no longer transparent—without aether inside the light waves could not be transmitted through it. These conditions would turn the evacuated jar into the inverse of a black hole: instead of keeping light contained within it, the jar would never allow light to enter.

Einstein grew skeptical of the existence of the aether. But as long as light had to be a wave, the aether was necessary. If physics was to be rid of this unnecessary scaffolding, then a new picture of light would be needed. Hints of such a depiction were emerging. One came to be known as "blackbody radiation."

Objects give off light when heated—think of an iron bar in the blacksmith's furnace. Now, suppose we heat up an empty metal sphere. The light emitted from the interior surface would be trapped inside, some of it reabsorbed by the walls and some reflected inside. The question physicists asked was, "If we poked a small hole and look inside, what would we see?" In other words, how much would be reabsorbed, how much would be bouncing around, and what wavelengths would we observe?

The standard understanding at the time gave the problematic result that as we look at smaller and smaller wavelengths of light, the amount of energy for those colors would get larger and larger, so that in total an infinite amount of energy would flow out of the hole. But this is impossible: you cannot put in a finite amount of energy and get out an infinite amount. From experimental data we knew what actually happened, and it was quite different. This was termed "the ultraviolet catastrophe."

We had a flawed theory and data we could not explain. A lot of effort from the smartest physicists at the time went into trying to solve this problem, but progress was slow at best. We had different models that were correct for different ranges, but no underlying account that held across the spectrum. This meant that no general sense of the underlying mechanism could be developed.

Planck decided to work backward. Instead of finding a model that fit the data, he started with the data and figured out what function would give him the observed energy curve. He found that we could account for blackbody radiation if we think of light as emitted and absorbed not as waves but as individual packets, as particles. For Planck, this was quite disturbing. Convinced that the atomic hypothesis was wrong, that matter is continuous and light is a smooth wave, he held that nature could not come in bits. But here was his finding, and so he declared that we needed to think of light *as if* it was absorbed and emitted in discrete clumps. While it was traveling, the wave description worked perfectly, but to avoid the ultraviolet catastrophe we would treat light as if it were made up of particles when it is given off or taken in. Planck took this not literally but only as a heuristic device, a mental image to help us think about light in certain circumstances.

Einstein's intuitions were the opposite of Planck's. Where Planck was disturbed by anything that was not smooth, Einstein preferred a chunky universe. He had already instantiated this picture with his work on atoms, and now he had his sights set on light. Planck was correct, Einstein thought, more accurate than he would allow himself to be. Planck gave us more than just a way of thinking; he showed us the light.

This idea of turning light into a collection of bits was not an isolated finding. J. J. Thomson and Philipp Lenard had shown that cathode rays were not rays at all, but actually collections of little particles we came to know as electrons. Lenard had also shown that light of the right color could kick electrons out of metal in a fashion that waves could not. Einstein had been greatly impressed with the work of Lenard, writing excitedly to Mileva about it before they were married.[10] If the cathode ray was actually a stream of particles, why not light?

The title of Einstein's third 1905 paper, "On a Heuristic Point of View Concerning the Production and Transformation of Light," is, to some degree, disingenuous. Unlike Planck, who explicitly stated that he was treating light as a particle during emission and absorption as just a heuristic device, Einstein thought he was providing more, that he was in fact showing something "quite revolutionary"—that light is, in fact, a particle.

The argument is classic Einstein. Like his first two papers, in which we gain insight into a phenomenon by considering it in two very different, seemingly inconsistent ways, here too we see Einstein taking seriously the idea that light behaves as a particle without completely surrendering the idea that it also behaves as a wave. Indeed, even after this paper Einstein on multiple occasions will refer to light waves and come up with thought experiments in which he treats light as a wave. This might seem problematic because particles and waves are completely different kinds of things: a particle is a thing unto itself that has a particular spatial location; a wave is a disturbance in a medium, it is a ripple that requires something to be rippled and is spread out in space. For Einstein, the two were complementary; the particulate nature was the underlying picture, but when you put a bunch of them together traveling through space, they move in a wavelike fashion.

Einstein makes his case by considering entropy again. He considers a collection of particles that are taken from a smaller volume to a larger one and calculates the increase in entropy. He then thinks about light that starts in a smaller area and increases in exactly the same way. As it turns out, the entropy equations for light and for particles have the same exact form. A coincidence—or is it? If we think of light as being made up of energetic bits, it makes perfect sense.

But "making perfect sense" gets you only as far as "heuristic device": it gets you "as if." He then asks what happens when we apply this idea to three cases that the wave theory of light cannot handle. Lo and behold, all three are explained perfectly. The most famous of these is the phenomenon discovered by Lenard that excited Einstein years earlier, the photoelectric effect.

If you take ultraviolet light and shine it on a surface, electrons are kicked out. That is not strange; in fact, with the wave theory of light it is to be expected. Metals have very loosely bound electrons in their outermost shells, electrons that are easily stripped off. That is why metals make such good wires for electrical circuits. If light was a wave, then when it hits the surface of the metal, the metal would vibrate—think of the tuning fork experiment from elementary school in which the struck tuning fork causes the unstruck one to vibrate without touching. These vibrations could liberate the loosely held electrons. No problem.

Except that when you make the light brighter you should be making the wave larger, and the larger wave will give the emitted electrons more energy, meaning they will move faster. It turns out that this is not what we see. More electrons are emitted, but not faster ones. If light is a wave, this should not happen.

But if light is a particle, this phenomenon makes perfect sense. In making the light brighter you are shooting more bits of light at the metal, all traveling at the same speed. More collisions of similar particles will mean more ejected electrons traveling at the same speed. Nice and neat, another anomaly disappears if light is a particle.

So, we have Planck's blackbody case, the entropy analogy, and the three cases including the photoelectric effect. While it seemed clear to Einstein that we needed to adopt the chunky picture of light, his results were so revolutionary that many refused to accept them until other notable scientists including the Americans Robert Millikan and Arthur Compton came up with further experimental support. Eventually it simply became undeniable in the face of mounting evidence, no matter how hard the establishment tried to deny it.

In March, April, and May of 1905, Einstein established the existence of atoms, forever changing our picture of matter, and he overthrew the universally held wave theory of light, forever changing our view of optical phenomena. Not bad for someone without a job as a working scientist. What was left to be done? Einstein had his sights set on the biggest of big game in physics: mechanics. Isaac Newton's theory of motion reigned supreme for three hundred years and was widely considered the greatest scientific advance in human history. The lowly patent clerk had his work cut out for him in no uncertain terms.

The paper that introduced Einstein's most famous work was titled "On the Electrodynamics of Moving Bodies." He begins by considering a coil of wire connected to a circuit. Now, take a magnet and move it back and forth inside of the coil. The result is a current in the circuit. Next, hold the magnet still and move the coil back and forth around it at the same rate. The result? The same current. It doesn't matter which is moving and which is still. All that matters is the relative state of motion between them.

The problem was that the best existing theory at the time, Maxwell's electrodynamics, gave completely different explanations for the two cases. In the case of the moving magnet, you have a changing, or "dynamic," magnetic field. In the case of the moving coil, you have a fixed, or "static," magnetic field, and these are entirely different cases as far as Maxwell's account is concerned.

At least, they were entirely different cases as long as you had a luminiferous aether—an underlying structure filling all of space—because then you could say which one was really moving, and the moving magnet was different from the moving coil because they were moving or stationary with respect to aether. But in the paper on light, Einstein had turned light into particles, and, unlike waves, particles do not need a medium. If light is not a wave, then we don't need the luminiferous aether, and without it we can say that the moving magnet and the moving coil are just different descriptions of the same physical situation reported from different perspectives. Once again we have the classic Einstein move of taking two different ways of looking at something and bringing them together to give us a new insight.

But there was one more problem that sprang from Maxwell's theory. When you derive the equation for light, the one that has the form of a wave equation, and you look for the term that represents the speed of the wave, it turns out to be a constant. And when the value of that constant is calculated from the theory, it turns out to be exactly the observed speed of light.

But the speed of light could not possibly be a constant. Consider parting friends, one leaving on a train as the other watches from the platform. They wave to each other as the train pulls out at two miles an hour. The person on the platform sees his friend on the train moving at two miles an hour, while the person on the train sees her friend moving the other direction at two miles an hour. Now consider someone who just got off the train and is running at five miles an hour past the person on the platform in the opposite direction of the train to greet his waiting family. The person on the platform would see this person moving at five miles an hour, but the person on the train would see the person moving at seven. Velocities add in a simple fashion.

Suppose a brother and sister are playing hide-and-seek in the dark, the seeking brother carrying a flashlight. When the hiding sister is found, the brother initially remains still but then starts to walk toward her at two miles an hour, keeping the flashlight shining in her eyes the whole time. When he was still, the light shining in her eyes was coming at her at the speed of light. When he started to approach, surely she saw the light at the speed of light plus two miles an hour. That is what both common sense and Newton tell us.

In Maxwell's theory, the speed of light is a constant, but a constant for whom? In what frame of reference is this speed constant? If two people are moving relative to each other, the speed surely changes for each. Who has the perspective of perfect rest such that the speed of light is a constant for him? As long as we had a luminiferous aether, there was an answer: the speed of light was constant with respect to the aether. Find the aether frame and you find where the speed of light is constant.

So we looked for it. The most famous experiment came from the American physicists A. A. Michelson and Edward Morley, who used light and mirrors to try to measure the Earth's motion relative to the aether. Their experiment detected nothing, which seemed to indicate that the Earth drags its aether along with it. But in an experiment that French physicist Hippolyte Fizeau designed to show that aether gets dragged, he too found no effect, seeming to show that the aether was not dragged but stationary. Either it moves or it doesn't—it cannot do both. What to do?

This question worried the Dutch physicist H. A. Lorentz, especially the Michelson-Morley result, and he worked hard to figure out how to make sense of it. Nothing worked because we seemed to have an irreconcilable conflict between Newton's mechanics and Maxwell's electromagnetism. Every attempt to fix Maxwell in a fashion that would bring his theory in line with Newton's failed. Then Lorentz found something: if we go the other way and fix Newton's mechanics to work with Maxwell, then we can account for the Michelson-Morley experiment on the condition that we treat lengths as if they shrink in the direction of motion. Of course, they don't—that would be too weird. Again, it is a heuristic device not to be taken literally, or so Lorentz thought.

Einstein had been discussing this question all day with his friend Michele Besso, after which he caught the train home to Bern. Getting off the train and walking toward his flat, he looked back at the clock on the station tower to see what time it was. Then it struck him. He was seeing not what time it *is*, but what time it *was*. To read a clock, light must bounce off the face and hands and travel to the observer. That takes time. In observing the time what you are seeing is what time it was when the light left the clock. But if the observer was moving away from the clock, that light would have to not only get to the observer who continued looking at the clock, but catch up as he walked away. As a result, it would seem that the clock was running slow.

What if Lorentz was more correct than he realized and it was not just as if the lengths contracted, but it was the case that they really did? And what if the clock actually is running slower for the person moving as a result? What would such a world look like for such observers? This would be the project he set out for himself.

Einstein started from two axioms, basic assumptions from which everything else would follow. The first is the constancy of the speed of light. Having done away with the need for a luminiferous aether, Einstein contended that we must take as a starting point that the speed of light in a vacuum is always the same for all observers, no matter their state of motion with regard to the source. If we go back to our siblings playing with the flashlight, the sister who has the light in her eyes will see that light coming at her at the same speed whether her brother is still or moving toward or away from her with the flashlight. This seems intuitively wrong, but it is the first claim that Einstein takes as necessarily true.

The second is the principle of relativity,[11] a notion he found in the writing of Henri Poincaré, according to which the laws of physics should be the same for all observers who are moving at a constant speed in a straight line with respect to each other. This constraint comes from the fact that when people accelerate, forces appear in one frame but not in another. Think about riding a roller coaster. Going up, you feel a pull back in your seat. Going down, you feel as if you are being pulled up out of your seat. Turning a corner throws you from side to side. To you, there are forces experienced. Your friend watching from the ground would chalk it up to your momentum going in a straight line and the car accelerating around you as it follows the track. What is a force in an accelerating frame is not necessarily seen as a force from another. This difference in forces requires an adjustment in how the physics accounts for them. But if we consider only frames of reference moving in straight lines at constant speeds relative to one another, then there will be none of these "factitious forces," as Einstein termed them, so the physical description for different observers ought to be the same.

Einstein is careful in setting out this principle to specify that the laws of physics he is talking about are the laws of electrodynamics and optics—this means Maxwell's laws with their specification of the constancy of the speed of light. Newton and Maxwell cannot both be right, and he is making clear that he is buying Maxwell's story and not Newton's. This is what undermines Newton's mechanics and thereby requires a new theory of motion.

That theory of motion is precisely what comes out when we combine these two postulates. Einstein derives what we now call the "Lorentz transformations," which determine how lengths and durations will be measured by different observers and show the relationship between them. Just as Lorentz argued, lengths contract when measured by observers who are moving with respect to the thing being measured. The closer the thing gets to the speed of light when measured from your reference frame, the thinner you would measure something as being. If you were traveling the speed of light, the lengths of all things would squish to nothing, but only in the direction you are traveling. Things would still have the same height and width, but their lengths would disappear.

You are moving relative to other observers, but you remain still according to those things you carry along. No matter how fast you move, the things you hold—because they are moving at the same speed in the same direction—will not squish according to your measurements. But when the other observers measure those things, they will see them as having shrunk. The question of length becomes purely one of perspective. There is a fact as to the length of an object in a reference frame, and Einstein's and Lorentz's equations show how that length changes when measured in different reference frames. Length ceases to be something absolute and universal; it becomes a matter of your relative state of motion when you are measuring it.

Similarly, the faster you travel the slower time passes compared with an observer at rest. If you had a watch and I had a watch, and you were traveling close to the speed of light, then my watch would seem to run slow to you. If you were traveling at the speed of light, then time in my reference frame would be seen by you to have stopped completely. I would never age in your eyes. Similarly, your watch would seem to stop when I view it. As with length, this measure is related to reference frame.

This alteration in our measurements of spatial distances and temporal durations plays havoc with our understanding of motion. Velocity, after all, is the distance something moves in a unit of time, so changing measurements of distance and time will change how speeds are measured from one reference frame to another. Think back to our parting friends at the train station. We have one person on the train pulling out at two miles an hour and her friend watching from the platform, while someone who just got off the train walks in the opposite direction from the train at five miles an hour. The woman on the train would see her friend fading away from her at two miles an hour while the person walking past the friend would seem to be moving at seven miles an hour. According to Newton, velocities simply add. Similarly, when we considered the case of our kids with flashlights, if velocities add as Newton demands, then when the brother is walking with the flashlight toward his sister, the speed of the light she observes should increase by the speed of his walking.

But by the first postulate this cannot be true according to Einstein. We need a new way to add velocities to make sure she sees the light moving at the same speed no matter how fast he moves with flashlight toward her. Einstein derives this and shows that it too depends on the speed of the observer relative to the speed of light. The woman on the train will see the person walking past her friend moving at slightly less than seven miles per hour, yet the difference is so small at those speeds that the change is not detectable. But the closer to the speed of light you go, the more that difference matters. At the speed of light, the contribution from the motion disappears so that any velocity plus the speed of light turns out to be the speed of light again.

In the second part of his paper Einstein says to his readers, OK, I've given you a strange new way to see the physical world, but now here's how to test if it works. Just as in the light paper, Einstein sets out several different physical effects that could be explained only by the new theory. He considers the optical Doppler shift and the effects of reflected light, but it is in thinking about moving electrons that something new and strange is predicted by the theory. Not only do we find that observers in different states of motion measure a difference in length, time, and velocity—things we thought with Newton were absolute facts of the world—but they would also measure differences in the mass of the electron.

The faster it goes, the heavier it gets. At the speed of light, the electron would be infinitely heavy. This would give it an infinite amount of kinetic energy. This cannot be, of course, and so Einstein is led to assert that "velocities greater than that of light have—as in our previous results—no possibility of existence."[12] The speed of light is not only a constant, it is also a limiting velocity. Nothing can move faster than this speed. It is not an engineering problem; it is not that we have yet to figure out how to do it. If Einstein's theory is correct, then moving faster than the speed of light would require an infinite amount of energy, and that is not possible. Nothing can move faster than light in a vacuum.

This last result about mass led to Einstein's final revolutionary paper of that miracle year, "Does the Inertia of a Body Depend upon Its Energy Content?," in which he sets out no new theory or conceptual framework. It is just a short note, yet it contains his most famous result. In a few paragraphs he summarizes the first relativity paper and then goes on to point out what would have to be the case with respect to a body that emitted light when viewed from different reference frames. It turns out, for reasons related to the change in mass of the moving electron, that the energy of the body that gives off the light is reduced by an amount that has nothing to do with the composition of the body.

Einstein writes that "*if a body gives off the energy L in the form of radiation, its mass diminishes by* L/c^2."[13] But this wrongly seems to be related to the fact that the emitted energy is light. "The fact that the energy withdrawn from the body becomes energy of radiation evidently makes no difference, so that we are led to the more general conclusion that 'The mass of a body is a measure of its energy content.'"[14] Since the energy need not be in the form of light, we can change the L to its usual E and assert that $m = E/c^2$, or doing some basic algebra allows us to put it in its iconic form, $E = mc^2$.

The mass of the body, of anything that has mass, is a measure of its energy content. This means that mass is a form of energy. On one hand, we know that energy comes in many forms—such as light, heat, motion—and we have long known that we can change one form into another. But energy was seen as a particular physical quantity quite different from mass. The two notions are in different categories in the same way that something has both size and color, but to say that something is blue is to say nothing about how big it is. Here is Einstein arguing that as part of the fundamental structure of the universe, the two are the same sort of property.

The world as we thought we knew it was constructed by Isaac Newton from basic concepts: space, time, motion, mass, and energy. In his masterwork *The Mathematical Principles of Natural Philosophy,* Newton begins by defining these notions or, in the case of space, time, place, and motion, giving a brief discussion of them since they need no defining, "being well-known to all."[15] From these basic notions, Newton developed three elegant laws of motion and a law of universal gravitation that explained the falling of apples and the orbits of planets, the motion of comets and the rising of the tides. It was so successful that it was thought the highest expression of the human mind in all recorded history.

Yet here was a mere patent clerk, a civil servant who could not secure even the lowest ranking research position, claiming to have a new set of concepts that must replace those that had served us so well for hundreds of years without fail. In one year, this scientific nobody had contended that observable facts will force us (1) to radically change how we understand the nature of matter, establishing the atomic hypothesis around since classical Greek times, and establishing a controversial picture of heat, (2) completely change our understanding of the nature of light, thus eliminating the luminiferous aether that seemed essential both to the standard understanding of Maxwell's theory of electricity and to magnetism, and (3) reject the Newtonian concepts of space, time, motion, and mass, all of which sit at the foundation of the most successful theory in scientific history, and replace them with counterintuitive notions that give rise to weird, unobserved effects. In other words, there was virtually no single part of the study of physics, the oldest and most established science, which Einstein did not seek to completely overhaul in 1905. As far as Einstein was concerned, after his work of that miracle year, *everything* was different.