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At the Patent Office, 1905

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theoretical physics—and, independently, the Irish physicist George Fitzgerald came up with the hypothesis that solid objects contracted slightly when they moved through the ether. The Lorentz-Fitzgerald contraction would shorten everything, including the measuring arms used by Michelson and Morley, and it would do so by just the exact amount to make the effect of the ether on light undetectable.

Einstein felt that the situation "was very depressing." Scientists found themselves unable to explain electromagnetism using the Newtonian "mechanical view of nature," he said, and this "led to a fundamental dualism which in the long run was insupportable."[7]

Einstein's Road to Relativity

"A new idea comes suddenly and in a rather intuitive way," Einstein once said. "But," he hastened to add, "intuition is nothing but the outcome of earlier intellectual experience."[8]

Einstein's discovery of special relativity involved an intuition based on a decade of intellectual as well as personal experiences.[9] The most important and obvious, I think, was his deep understanding and knowledge of theoretical physics. He was also helped by his ability to visualize thought experiments, which had been encouraged by his education in Aarau. Also, there was his grounding in philosophy: from Hume and Mach he had developed a skepticism about things that could not be observed. And this skepticism was enhanced by his innate rebellious tendency to question authority.

Also part of the mix—and probably reinforcing his ability to both visualize physical situations and to cut to the heart of concepts—was the technological backdrop of his life: helping his uncle Jakob to refine the moving coils and magnets in a generator; working in a patent office that was being flooded with applications for new methods of coordinating clocks; having a boss who encouraged him to apply his skepticism; living near the clock tower and train station and just above the telegraph office in Bern just as Europe was using electrical signals to synchronize clocks within time zones; and having as a sounding board his engineer friend Michele Besso, who worked with him at the patent office, examining electromechanical devices.[10]

The ranking of these influences is, of course, a subjective judgment. After all, even Einstein himself could not be sure how the process unfolded. "It is not easy to talk about how I arrived at the theory of relativity," he said. "There were so many hidden complexities to motivate my thought."[11]

One thing we can note with some confidence is Einstein's main starting point. He repeatedly said that his path toward the theory of relativity began with his thought experiment at age 16 about what it would be like to ride at the speed of light alongside a light beam. This produced a "paradox," he said, and it troubled him for the next ten years:

> If I pursue a beam of light with the velocity *c* (velocity of light in a vacuum), I should observe such a beam of light as an electromagnetic field at rest though spatially oscillating. There seems to be no such thing, however, neither on the basis of experience nor according to Maxwell's equations. From the very beginning it appeared to me intuitively clear that, judged from the standpoint of such an observer, everything would have to happen according to the same laws as for an observer who, relative to the earth, was at rest. For how should the first observer know or be able to determine that he is in a state of fast uniform motion? One sees in this paradox the germ of the special relativity theory is already contained.[12]

This thought experiment did not necessarily undermine the ether theory of light waves. An ether theorist could imagine a frozen light beam. But it violated Einstein's intuition that the laws of optics should obey the principle of relativity. In other words, Maxwell's equations, which specify the speed of light, should be the same for all observers in constant-velocity motion. The emphasis that Einstein placed on this memory indicates that the idea of a frozen light beam—or frozen electromagnetic waves—seemed instinctively wrong to him.[13]

In addition, the thought experiment suggests that he sensed a conflict between Newton's laws of mechanics and the constancy of the speed of light in Maxwell's equations. All of this instilled in him "a state of psychic tension" that he found deeply unnerving. "At the very beginning, when the special theory of relativity began to germinate in me, I was visited by all sorts of nervous conflicts," he later recalled. "When young, I used to go away for weeks in a state of confusion."[14]

There was also a more specific "asymmetry" that began to bother him. When a magnet moves relative to a wire loop, an electric current is produced. As Einstein knew from his experience with his family's generators, the amount of this electric current is exactly the same whether the magnet is moving while the coil seems to be sitting still, or the coil is moving while the magnet seems to be sitting still. He also had studied an 1894 book by August Föppl, *Introduction to Maxwell's Theory of Electricity*. It had a section specifically on "The Electrodynamics of Moving Conductors" that questioned whether, when induction occurs, there should be any distinction between whether the magnet or the conducting coil is said to be in motion.[15]

"But according to the Maxwell-Lorentz theory," Einstein recalled, "the theoretical interpretation of the phenomenon is very different for the two cases." In the first case, Faraday's law of induction said that the motion of the magnet through the ether created an electric field. In the second case, Lorentz's force law said a current was created by the motion of the conducting coil through the magnetic field. "The idea that these two cases should essentially be different was unbearable to me," Einstein said.[16]

Einstein had been wrestling for years with the concept of the ether, which theoretically determined the definition of "at rest" in these electrical induction theories. As a student at the Zurich Polytechnic in 1899, he had written to Mileva Marić that "the introduction of the term 'ether' into theories of electricity has led to the conception of a medium whose motion can be described without, I believe, being able to ascribe physical meaning to it."[17] Yet that very month he was on vacation in Aarau working with a teacher at his old school on ways to detect the ether. "I had a good idea for investigating the way in which a body's relative motion with respect to the ether affects the velocity of the propagation of light," he told Marić.

Professor Weber told Einstein that his approach was impractical. Probably at Weber's suggestion, Einstein then read a paper by Wilhelm Wien that described the null results of thirteen ether-detection experiments, including those by Michelson and Morley and by

Fizeau.[18] He also learned about the Michelson-Morley experiment by reading, sometime before 1905, Lorentz's 1895 book, *Attempt at a Theory of Electrical and Optical Phenomena in Moving Bodies.* In this book, Lorentz goes through various failed attempts to detect the ether as a prelude to developing his theory of contractions.[19]

"Induction and Deduction in Physics"

So what effect did the Michelson-Morley results—which showed no evidence of the ether and no difference in the observed speed of light no matter in what direction the observer was moving—have on Einstein as he was incubating his ideas on relativity? To hear him tell it, almost none at all. In fact, at times he would even recollect (incorrectly) that he had not even known of the experiment before 1905. Einstein's inconsistent statements over the next fifty years about the influence of Michelson-Morley are useful in that they remind us of the caution needed when writing history based on dimming recollections.[20]

Einstein's trail of contradictory statements begins with an address he gave in Kyoto, Japan, in 1922, when he noted that Michelson's failure to detect an ether was "the first path that led me to what we call the principle of special relativity." In a toast at a 1931 dinner in Pasadena honoring Michelson, Einstein was gracious to the eminent experimenter, yet subtly circumspect: "You uncovered an insidious defect in the ether theory of light, as it then existed, and stimulated the ideas of Lorentz and Fitzgerald, out of which the Special Theory of Relativity developed."[21]

Einstein described his thought process in a series of talks with the Gestalt psychology pioneer Max Wertheimer, who later called the Michelson-Morley results "crucial" to Einstein's thinking. But as Arthur I. Miller has shown, this assertion was probably motivated by Wertheimer's goal of using Einstein's tale as a way to illustrate the tenets of Gestalt psychology.[22]

Einstein further confused the issue in the last few years of his life by giving a series of statements on the subject to a physicist named Robert Shankland. At first he said he had read of Michelson-Morley only *after* 1905, then he said he had read about it in Lorentz's book *before* 1905, and finally he added, "I guess I just took it for granted that it was true."[23]

That final point is the most significant one because Einstein made it often. He simply took for granted, by the time he started working seriously on relativity, that there was no need to review all the ether-drift experiments because, based on his starting assumptions, all attempts to detect the ether were doomed to failure.[24] For him, the significance of these experimental results was to reinforce what he already believed: that Galileo's relativity principle applied to light waves.[25]

This may account for the scant attention he gave to the experiments in his 1905 paper. He never mentioned the Michelson-Morley experiment by name, even where it would have been relevant, nor the Fizeau experiment using moving water. Instead, right after discussing the relativity of the magnet-and-coil movements, he merely flicked in a phrase about "the unsuccessful attempts to detect a motion of the earth relative to the light medium."

Some scientific theories depend primarily on induction: analyzing a lot of experimental findings and then finding theories that explain the empirical patterns. Others depend more on deduction: starting with elegant principles and postulates that are embraced as holy and then deducing the consequences from them. All scientists blend both approaches to differing degrees. Einstein had a good feel for experimental findings, and he used this knowledge to find certain fixed points upon which he could construct a theory.[26] But his emphasis was primarily on the deductive approach.[27]

Remember how in his Brownian motion paper he so oddly, yet accurately, downplayed the role that experimental findings played in what was essentially a theoretical deduction? There was a similar situation with his relativity theory. What he implied about Brownian motion he said explicitly about relativity and Michelson-Morley: "I was pretty much convinced of the validity of the principle before I knew of this experiment and its results."

Indeed, all three of his epochal papers in 1905 begin by asserting his intention to pursue a deductive approach. He opens each one by pointing out some oddity caused by jostling theories, rather than some unexplained set of experimental data. He then postulates grand principles while minimizing the role played by data, be it on Brownian motion or blackbody radiation or the speed of light.[28]

In a 1919 essay called "Induction and Deduction in Physics," he described his preference for the latter approach:

> The simplest picture one can form about the creation of an empirical science is along the lines of an inductive method. Individual facts are selected and grouped together so that the laws that connect them become apparent . . . However, the big advances in scientific knowledge originated in this way only to a small degree . . . The truly great advances in our understanding of nature originated in a way almost diametrically opposed to induction. The intuitive grasp of the essentials of a large complex of facts leads the scientist to the postulation of a hypothetical basic law or laws. From these laws, he derives his conclusions.[29]

His appreciation for this approach would grow. "The deeper we penetrate and the more extensive our theories become," he would declare near the end of his life, "the less empirical knowledge is needed to determine those theories."[30]

By the beginning of 1905, Einstein had begun to emphasize deduction rather than induction in his attempt to explain electrodynamics. "By and by, I despaired of the possibility of discovering the true laws by means of constructive efforts based on experimentally known facts," he later said. "The longer and the more despairingly I tried, the more I came to the conviction that only the discovery of a universal formal principle could lead us to assured results."[31]

The Two Postulates

Now that Einstein had decided to pursue his theory from the top down, by deriving it from grand postulates, he had a choice to make: What postulates—what basic assumptions of general principle—would he start with?[32]

His first postulate was the principle of relativity, which asserted that all of the fundamental laws of physics, even Maxwell's equations governing electromagnetic waves, are the same for all observers moving at constant velocity relative to each other. Put more precisely, they are the same for all inertial reference systems, the same for someone at rest relative to the earth as for someone traveling at a uniform velocity on a train or spaceship. He had nurtured his faith in this postulate beginning with his thought experiment about riding alongside a light beam: "From the very beginning it appeared to me intuitively clear that, judged from the standpoint of such an observer, everything would have to happen according to the same laws as for an observer who, relative to the earth, was at rest."

For a companion postulate, involving the velocity of light, Einstein had at least two options:

1. He could go with an emission theory, in which light would shoot from its source like particles from a gun. There would be no need for an ether. The light particles could zoom through emptiness. Their speed would be relative to the source. If this source was racing toward you, its emissions would come at you faster than if it was racing away. (Imagine a pitcher who can throw a ball at 100 miles per hour. If he throws it at you from a car racing toward you it will come at you faster than if he throws it from a car racing away.) In other words, starlight would be emitted from a star at 186,000 miles per second; but if that star was heading toward earth at 10,000 miles per second, the speed of its light would be 196,000 miles per second relative to an observer on earth.
2. An alternative was to postulate that the speed of light was a constant 186,000 miles per second irrespective of the motion of the source that emitted it, which was more consistent with a wave theory. By analogy with sound waves, a fire truck siren does not throw its sound at you faster when it's rushing toward you than it does when it's standing still. In either case, the sound travels through the air at 770 miles per hour.*

* If the source of sound is rushing toward you, the waves will not get to you any faster. However, in what is known as the Doppler effect, the waves will be compressed and the interval between them will be smaller. The decreased wavelength means a higher frequency, which results in a higher-pitched sound (or a lower one, when the siren passes by and starts moving away). A similar effect happens with light. If the source is moving toward you, the wavelength decreases (and frequency increases) so it is shifted to the blue end of the spectrum. Light from a source moving away will be red-shifted.

For a while, Einstein explored the emission theory route. This approach was particularly appealing if you conceived of light as behaving like a stream of quanta. And as noted in the previous chapter, that concept of light quanta was precisely what Einstein had propounded in March 1905, just when he was wrestling with his relativity theory.[33]

But there were problems with this approach. It seemed to entail abandoning Maxwell's equations and the wave theory. If the velocity of a light wave depended on the velocity of the source that emitted it, then the light wave must somehow encode within it this information. But experiments and Maxwell's equations indicated that was not the case.[34]

Einstein tried to find ways to modify Maxwell's equations so that they would fit an emission theory, but the quest became frustrating. "This theory requires that everywhere and in each fixed direction light waves of a different velocity of propagation should be possible," he later recalled. "It may be impossible to set up a reasonable electromagnetic theory that accomplishes such a feat."[35]

In addition, scientists had not been able to find any evidence that the velocity of light depended on that of its source. Light coming from any star seemed to arrive at the same speed.[36]

The more Einstein thought about an emission theory, the more problems he encountered. As he explained to his friend Paul Ehrenfest, it was hard to figure out what would happen when light from a "moving" source was refracted or reflected by a screen at rest. Also, in an emission theory, light from an accelerating source might back up on itself.

So Einstein rejected the emission theory in favor of postulating that the speed of a light beam was constant no matter how fast its source was moving. "I came to the conviction that all light should be defined by frequency and intensity alone, completely independently of whether it comes from a moving or from a stationary light source," he told Ehrenfest.[37]

Now Einstein had two postulates: "the principle of relativity" and this new one, which he called "the light postulate." He defined it carefully: "Light always propagates in empty space with a definite velocity V that is independent of the state of motion of the emitting body."[38]

For example, when you measure the velocity of light coming from the headlight of a train, it will always be a constant 186,000 miles per second, even if the train is rushing toward you or backing away from you.

Unfortunately, this light postulate seemed to be incompatible with the principle of relativity. Why? Einstein later used the following thought experiment to explain his apparent dilemma.

Imagine that "a ray of light is sent along the embankment" of a railway track, he said. A man standing on the embankment would measure its speed as 186,000 miles per second as it zipped past him. But now imagine a woman who is riding in a very fast train carriage that is racing away from the light source at 2,000 miles per second. We would assume that she would observe the beam to be zipping past her at only 184,000 miles per second. "The velocity of propagation of a ray of light relative to the carriage thus comes out smaller," Einstein wrote.

"But this result comes into conflict with the principle of relativity," he added. "For, like every other general law of nature, the law of the transmission of light must, according to the principle of relativity, be the same when the railway carriage is the reference body as it is when the embankment is the reference body." In other words, Maxwell's equations, which determine the speed at which light propagates, should operate the same way in the moving carriage as on the embankment. There should be no experiment you can do, including measuring the speed of light, to distinguish which inertial frame of reference is "at rest" and which is moving at a constant velocity.[39]

This was an odd result. A woman racing along the tracks toward or away from the source of a light beam should see that beam zip by her with the exact same speed as an observer standing on the embankment would see that same beam zip by him. The woman's speed relative to the train would vary, depending on whether she was running toward it or away from it. But her speed relative to the light beam coming from the train's headlight would be invariant. All of this made the two postulates, Einstein thought, "seemingly incompatible." As he later explained in a lecture on how he came to his theory, "the constancy of the velocity of light is not consistent with the law of the addition of velocities. The result was that I had to spend almost one year in fruitless thoughts."[40]

By combining the light postulate with the principle of relativity, it meant that an observer would measure the speed of light as the same whether the source was moving toward or away from him, or whether he was moving toward or away from the source, or both, or neither. The speed of light would be the same whatever the motion of the observer and the source.

That is where matters stood in early May 1905. Einstein had embraced the relativity principle and elevated it to a postulate. Then, with a bit more trepidation, he had adopted as a postulate that the velocity of light was independent of the motion of its source. And he puzzled over the apparent dilemma that an observer racing up a track toward a light would see the beam coming at him with the same velocity as when he was racing away from the light—and with the same velocity as someone standing still on the embankment would observe the same beam.

"In view of this dilemma, there appears to be nothing else to do than to abandon either the principle of relativity or the simple law of the propagation of light," Einstein wrote.[41]

Then something delightful happened. Albert Einstein, while talking with a friend, took one of the most elegant imaginative leaps in the history of physics.

"The Step"

It was a beautiful day in Bern, Einstein later remembered, when he went to visit his best friend Michele Besso, the brilliant but unfocused engineer he had met while studying in Zurich and then recruited to join him at the Swiss Patent Office. Many days they would walk to work together, and on this occasion Einstein told Besso about the dilemma that was dogging him.

"I'm going to give it up," Einstein said at one point. But as they discussed it, Einstein recalled, "I suddenly understood the key to the problem." The next day, when he saw Besso, Einstein was in a state of great excitement. He skipped any greeting and immediately declared, "Thank you. I've completely solved the problem."[42]

Only five weeks elapsed between that eureka moment and the day