directly, there have been high-precision tests of other features of general relativity on the Earth, in the solar system, and in binary systems that contain compact, exotic stars called pulsars. General relativity has come through each test with flying colors.

Over the past twenty years I have participated in the theoretical-physics quest which produced our present understanding of black holes and in the quest to test black-hole predictions by astronomical observation. My own contributions have been modest, but with my physicist and astronomer colleagues I have reveled in the excitement of the quest and have marveled at the insight it has produced. This book is my attempt to convey some sense of that excitement and marvel to people who are not experts in either astronomy or physics.

1

The Relativity of Space and Time

in which Einstein destroys
Newton's conceptions
of space and time as Absolute

13 April 1901

Professor Wilhelm Ostwald
University of Leipzig
Leipzig, Germany

Esteemed Herr Professor!

Please forgive a father who is so bold as to turn to you, esteemed Herr Professor, in the interest of his son.

I shall start by telling you that my son Albert is 22 years old, that he studied at the Zurich Polytechnikum for 4 years, and that he passed his diploma examinations in mathematics and physics with flying colors last summer. Since then, he has been trying unsuccessfully to obtain a position as Assistent, which would enable him to continue his education in theoretical & experimental physics. All those in position to give a judgment in the matter, praise his talents; in any case, I can assure you that he is extraordinarily studious and diligent and clings with great love to his science.

My son therefore feels profoundly unhappy with his present lack of

> position, and his idea that he has gone off the tracks with his career & is now out of touch gets more and more entrenched each day. In addition, he is oppressed by the thought that he is a burden on us, people of modest means.
>
> Since it is you, highly honored Herr Professor, whom my son seems to admire and esteem more than any other scholar currently active in physics, it is you to whom I have taken the liberty of turning with the humble request to read his paper published in the Annalen für Physick and to write him, if possible, a few words of encouragement, so that he might recover his joy in living and working.
>
> If, in addition, you could secure him an Assistent's position for now or the next autumn, my gratitude would know no bounds.
>
> I beg you once again to forgive me for my impudence in writing to you, and I am also taking the liberty of mentioning that my son does not know anything about my unusual step.
>
> I remain, highly esteemed Herr Professor, your devoted
>
> Hermann Einstein

It was, indeed, a period of depression for Albert Einstein. He had been jobless for eight months, since graduating from the Zurich Politechnikum at age twenty-one, and he felt himself a failure.

At the Politechnikum (usually called the "ETH" after its German-language initials), Einstein had studied under several of the world's most renowned physicists and mathematicians, but had not got on well with them. In the turn-of-the-century academic world where most Professors (with a capital P) demanded and expected respect, Einstein gave little. Since childhood he had bristled against authority, always questioning, never accepting anything without testing its truth himself. "Unthinking respect for authority is the greatest enemy of truth," he asserted. Heinrich Weber, the most famous of his two ETH physics professors, complained in exasperation: "You are a smart boy, Einstein, a very smart boy. But you have one great fault: you do not let yourself be told anything." His other physics professor, Jean Pernet, asked him why he didn't study medicine, law, or philology rather than physics. "You can do what you like," Pernet said, "I only wish to warn you in your own interest."

Einstein did not make matters better by his casual attitude toward coursework. "One had to cram all this stuff into one's mind for the examinations whether one liked it or not," he later said. His mathematics professor, Hermann Minkowski, of whom we shall hear much in Chapter 2, was so put off by Einstein's attitude that he called him a "lazy dog."

But lazy Einstein was not. He was just selective. Some parts of the coursework he absorbed thoroughly; others he ignored, preferring to spend his time on self-directed study and thinking. Thinking was fun, joyful, and satisfying; on his own he could learn about the "new" physics, the physics that Heinrich Weber omitted from all his lectures.

Newton's Absolute Space and Time, and the Aether

The "old" physics, the physics that Einstein *could* learn from Weber, was a great body of knowledge that I shall call *Newtonian*, not because Isaac Newton was responsible for all of it (he wasn't), but because its foundations were laid by Newton in the seventeenth century.

By the late nineteenth century, all the disparate phenomena of the physical Universe could be explained beautifully by a handful of simple *Newtonian physical laws*. For example, all phenomena involving gravity could be explained by *Newton's laws of motion and gravity:*

- Every object moves uniformly in a straight line unless acted on by a force.
- When a force does act, the object's velocity changes at a rate proportional to the force and inversely proportional to its mass.
- Between any two objects in the Universe there acts a gravitational force that is proportional to the product of their masses and inversely proportional to the square of their separation.

By mathematically manipulating[1] these three laws, nineteenth-century physicists could explain the orbits of the planets around the Sun, the orbits of the moons around the planets, the ebb and flow of ocean tides, and the fall of rocks; and they could even learn how to weigh the Sun and the Earth. Similarly, by manipulating a simple set of electric and magnetic laws, the physicists could explain lightning, magnets, radio waves, and the propagation, diffraction, and reflection of light.

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[1] Readers who wish to understand what is meant by *"mathematically manipulating"* the laws of physics will find a discussion in the notes section at the end of the book.

Fame and fortune awaited those who could harness the Newtonian laws for technology. By mathematically manipulating the Newtonian laws of heat, James Watt figured out how to convert a primitive steam engine devised by others into the practical device that came to bear his name. By leaning heavily on Joseph Henry's understanding of the laws of electricity and magnetism, Samuel Morse devised his profitable version of the telegraph.

Inventors and physicists alike took pride in the perfection of their understanding. Everything in the heavens and on Earth seemed to obey the Newtonian laws of physics, and mastery of the laws was bringing humans a mastery of their environment—and perhaps one day would bring mastery of the entire Universe.

All the old, well-established Newtonian laws and their technological applications Einstein could learn in Heinrich Weber's lectures, and learn well. Indeed, in his first several years at the ETH, Einstein was enthusiastic about Weber. To the sole woman in his ETH class, Mileva Marić (of whom he was enamored), he wrote in February 1898, "Weber lectured masterfully. I eagerly anticipate his every class."

But in his fourth year at the ETH Einstein became highly dissatisfied. Weber lectured only on the *old* physics. He completely ignored some of the most important developments of recent decades, including James Clerk Maxwell's discovery of a new set of elegant electromagnetic laws from which one could deduce *all* electromagnetic phenomena: the behaviors of magnets, electric sparks, electric circuits, radio waves, light. Einstein had to teach himself Maxwell's unifying laws of electromagnetism by reading up-to-date books written by physicists at other universities, and he presumably did not hesitate to inform Weber of his dissatisfaction. His relations with Weber deteriorated.

In retrospect it is clear that of all things Weber ignored in his lectures, the most important was the mounting evidence of cracks in the foundation of Newtonian physics, a foundation whose bricks and mortar were Newton's concepts of space and time as absolute.

Newton's *absolute space* was the space of everyday experience, with its three dimensions: east–west, north–south, up–down. It was obvious from everyday experience that there is one and only one such space. It is a space shared by all humanity, by the Sun, by all the planets and the stars. We all move through this space in our own ways and at our own speeds, and regardless of our motion, we experience the space in the same way. This space gives us our sense of length and breadth and height; and according to Newton, we all, regardless of our motion, will agree on the length, breadth, and height of an object, so long as we make sufficiently accurate measurements.

Newton's *absolute time* was the time of everyday experience, the time that flows inexorably forward as we age, the time measured by high-quality clocks and by the rotation of the Earth and motion of the planets. It is a time whose flow is experienced in common by all humanity, by the Sun, by all the planets and the stars. According to Newton we all, regardless of our motion, will agree on the period of some planetary orbit or the duration of some politician's speech, so long as we all use sufficiently accurate clocks to time the orbit or speech.

If Newton's concepts of space and time as absolute were to crumble, the whole edifice of Newtonian physical laws would come tumbling down. Fortunately, year after year, decade after decade, century after century, Newton's foundational concepts had stood firm, producing one scientific triumph after another, from the domain of the planets to the domain of electricity to the domain of heat. There was no sign of any crack in the foundation—until 1881, when Albert Michelson started timing the propagation of light.

It seemed obvious, and the Newtonian laws so demanded, that if one measures the speed of light (or of anything else), the result must depend on how one is moving. If one is at rest in absolute space, then one should see the same light speed in all directions. By contrast, if one is moving through absolute space, say eastward, then one should see eastward-propagating light slowed and westward-propagating light speeded up, just as a person on an eastbound train sees eastward-flying birds slowed and westward-flying birds speeded up.

For the birds, it is the air that regulates their flight speed. Beating their wings against the air, the birds of each species move at the same maximum speed through the air regardless of their flight direction. Similarly, for light it was a substance called the *aether* that regulated the propagation speed, according to Newtonian physical laws. Beating its electric and magnetic fields against the aether, light propagates always at the same universal speed through the aether, regardless of its propagation direction. And since the aether (according to Newtonian concepts) is at rest in absolute space, anyone at rest will measure the same light speed in all directions, while anyone in motion will measure different light speeds.

Now, the Earth moves through absolute space, if for no other reason than its motion around the Sun; it moves in one direction in January, then in the opposite direction six months later, in June. Correspondingly, we on Earth should measure the speed of light to be different in different directions, and the differences should change with the seasons—though only very slightly (about 1 part in 10,000), because the Earth moves so slowly compared to light.

To verify this prediction was a fascinating challenge for experimental physicists. Albert Michelson, a twenty-eight-year-old American, took up the challenge in 1881, using an exquisitely accurate experimental technique (now called "Michelson interferometry"[2]) that he had invented. But try as he might, Michelson could find no evidence whatsoever for any variation of light speed with direction. The speed turned out to be the same in *all* directions and at *all* seasons in his initial 1881 experiments, and the same to much higher precision in later 1887 experiments that Michelson performed in Cleveland, Ohio, jointly with a chemist, Edward Morley. Michelson reacted with a mixture of elation at his discovery and dismay at its consequences. Heinrich Weber and most other physicists of the 1890s reacted with skepticism.

It was easy to be skeptical. Interesting experiments are often terribly difficult—so difficult, in fact, that regardless of how carefully they are carried out, they can give wrong results. Just one little abnormality in the apparatus, or one tiny uncontrolled fluctuation in its temperature, or one unexpected vibration of the floor beneath it, might alter the experiment's final result. Thus, it is not surprising that physicists of today, like physicists of the 1890s, are occasionally confronted by terribly difficult experiments which conflict with each other or conflict with our deeply cherished beliefs about the nature of the Universe and its physical laws. Recent examples are experiments that purported to discover a "fifth force" (one not present in the standard, highly successful physical laws) and other experiments denying that such a force exists; also experiments claiming to discover "cold fusion" (a phenomenon forbidden by the standard laws, if physicists understand those laws correctly) and other experiments denying that cold fusion occurs. Almost always the experiments that threaten our deeply cherished beliefs are wrong; their radical results are artifacts of experimental error. However, occasionally they are right and point the way toward a revolution in our understanding of nature.

One mark of an outstanding physicist is an ability to "smell" which

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[2] Chapter 10.

experiments are to be trusted, and which not; which are to be worried about, and which ignored. As technology improves and the experiments are repeated over and over again, the truth ultimately becomes clear; but if one is trying to contribute to the progress of science, and if one wants to place one's own imprimatur on major discoveries, then one needs to divine early, not later, which experiments to trust.

Several outstanding physicists of the 1890s examined the Michelson–Morley experiment and concluded that the intimate details of the apparatus and the exquisite care with which it was executed made a strongly convincing case. This experiment "smells good," they decided; something might well be wrong with the foundations of Newtonian physics. By contrast, Heinrich Weber and most others were confident that, given time and further experimental effort, all would come out fine; Newtonian physics would triumph in the end, as it had so many times before. It would be inappropriate to even mention this experiment in one's university lectures; one should not mislead young minds.

The Irish physicist George F. Fitzgerald was the first to accept the Michelson–Morley experiment at face value and speculate about its implications. By comparing it with other experiments, he came to the radical conclusion that the fault lies in physicists' understanding of the concept of "length," and correspondingly there might be something wrong with Newton's concept of absolute space. In a short 1889 article in the American journal *Science*, he wrote in part:

> I have read with much interest Messrs. Michelson and Morley's wonderfully delicate experiment. . . . Their result seems opposed to other experiments. . . . I would suggest that almost the only hypothesis that can reconcile this opposition is that the length of material bodies changes, according as they are moving through the aether [through absolute space] or across it, by an amount depending on the square of the ratio of their velocities to that of light.

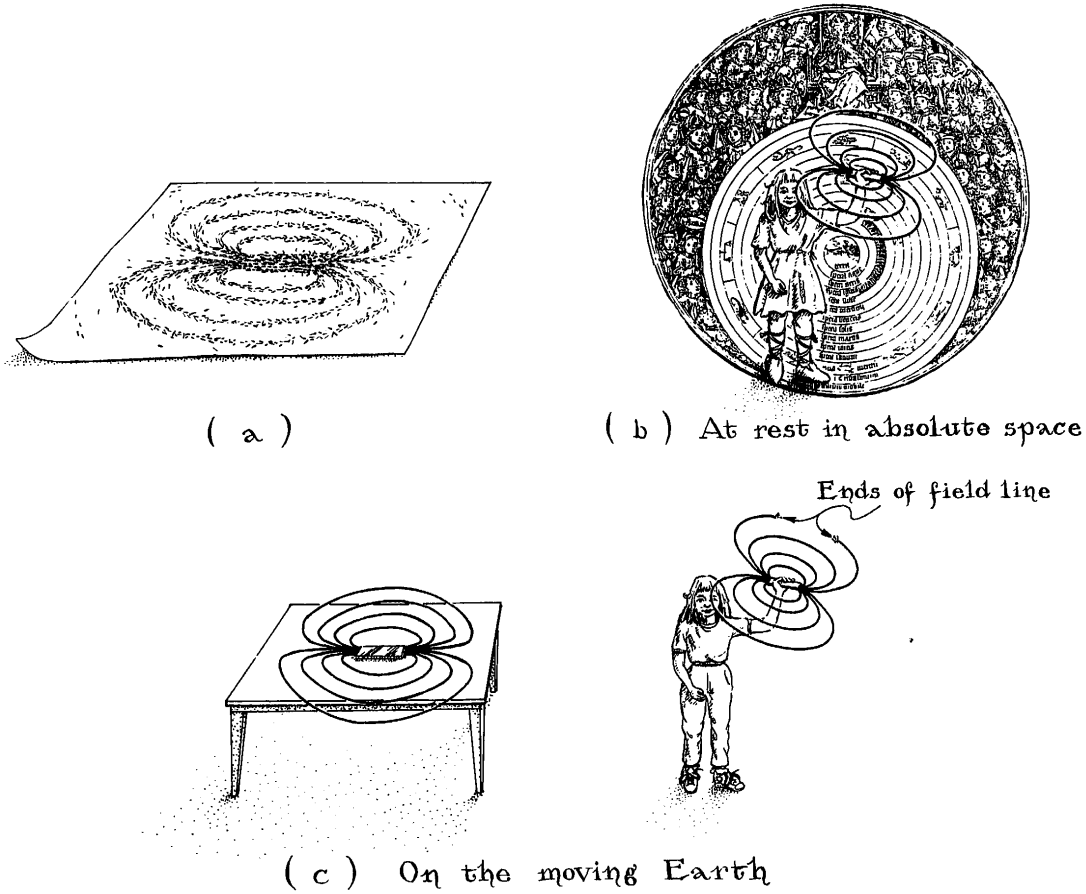
A tiny (five parts in a billion) contraction of length along the direction of the Earth's motion could, indeed, account for the null result of the Michelson–Morley experiment. But this required a repudiation of physicists' understanding of the behavior of matter: No known force could make moving objects contract along their direction of motion, not even by so minute an amount. If physicists understood correctly the nature of space and the nature of the molecular forces inside solid bodies, then uniformly moving solid bodies would always have to retain their same shape and size relative to absolute space, regardless of how fast they moved.

Hendrik Lorentz in Amsterdam also believed the Michelson–Morley experiment, and he took seriously Fitzgerald's suggestion that moving objects contract. Fitzgerald, upon learning of this, wrote to Lorentz expressing delight, since "I have been rather laughed at for my view over here." In a search for deeper understanding, Lorentz—and independently Henri Poincaré in Paris, France, and Joseph Larmor in Cambridge, England—reexamined the laws of electromagnetism, and noticed a peculiarity that dovetailed with Fitzgerald's length-contraction idea:

If one expressed Maxwell's electromagnetic laws in terms of the electric and magnetic fields measured at rest in absolute space, the laws took on an especially simple and beautiful mathematical form. For example, one of the laws said, simply, "As seen by anyone at rest in absolute space, magnetic field lines have no ends" (see Figure 1.1a,b). However, if one expressed Maxwell's laws in terms of the slightly different fields measured by a moving person, then the laws looked far more complicated and ugly. In particular, the "no ends" law became, "As seen by someone in motion, most magnetic field lines are endless, but a few get cut by the motion, thereby acquiring ends. Moreover, when the moving person shakes the magnet, new field lines get cut, then heal, then get cut again, then reheal" (see Figure 1.1c).

The new mathematical discovery by Lorentz, Poincaré, and Larmor was a way to make the moving person's electromagnetic laws look beautiful, and in fact look identical to the laws used by a person at rest in absolute space: "Magnetic field lines never end, under any circumstances whatsoever." One could make the laws take on this beautiful form by pretending, contrary to Newtonian precepts, that all moving objects get contracted along their direction of motion by precisely the amount that Fitzgerald needed to explain the Michelson–Morley experiment!

If the Fitzgerald contraction had been the only "new physics" that one needed to make the electromagnetic laws universally simple and beautiful, Lorentz, Poincaré, and Larmor, with their intuitive faith that the laws of physics *ought to be* beautiful, might have cast aside Newtonian precepts and believed firmly in the contraction. However, the contraction by itself was not enough. To make the laws beautiful, one also had to pretend that time flows more slowly as measured by someone moving through the Universe than by someone at rest; motion "dilates" time.



1.1 One of Maxwell's electromagnetic laws, as understood within the framework of nineteenth-century, Newtonian physics: (a) The concept of a magnetic field line: When one places a bar magnet under a sheet of paper and scatters iron filings on top of the sheet, the filings mark out the magnet's field lines. Each field line leaves the magnet's north pole, swings around the magnet and reenters it at the south pole, and then travels through the magnet to the north pole, where it attaches onto itself. The field line is therefore a closed curve, somewhat like a rubber band, without any ends. The statement that "magnetic field lines never have ends" is Maxwell's law in its simplest, most beautiful form. (b) According to Newtonian physics, this version of Maxwell's law is correct no matter what one does with the magnet (for example, even if one shakes it wildly) *so long as one is at rest in absolute space.* No magnetic field line *ever* has any ends, from the viewpoint of someone at rest. (c) When studied by someone riding on the surface of the Earth as it moves through absolute space, Maxwell's law is much more complicated, according to Newtonian physics. If the moving person's magnet sits quietly on a table, then a few of its field lines (about one in a hundred million) will have ends. If the person shakes the magnet wildly, additional field lines (one in a trillion) will get cut temporarily by the shaking, and then will heal, then get cut, then reheal. Although one field line in a hundred million or a trillion with ends was far too few to be discerned in any nineteenth-century physics experiment, the fact that Maxwell's laws predicted such a thing seemed rather complicated and ugly to Lorentz, Poincaré, and Larmor.

Now, the Newtonian laws of physics were unequivocal: Time is *absolute.* It flows uniformly and inexorably at the same universal rate, independently of how one moves. If the Newtonian laws were correct, then motion cannot cause time to dilate any more than it can cause lengths to contract. Unfortunately, the clocks of the 1890s were far too inaccurate to reveal the truth; and, faced with the scientific and technological triumphs of Newtonian physics, triumphs grounded firmly on the foundation of absolute time, nobody was willing to assert with conviction that time really does dilate. Lorentz, Poincaré, and Larmor waffled.

Einstein, as a student in Zurich, was not yet ready to tackle such heady issues as these, but already he was beginning to think about them. To his friend Mileva Marić (with whom romance was now budding) he wrote in August 1899, "I am more and more convinced that the electrodynamics of moving bodies, as presented today, is not correct." Over the next six years, as his powers as a physicist matured, he would ponder this issue and the reality of the contradiction of lengths and dilation of time.

Weber, by contrast, showed no interest in such speculative issues. He kept right on lecturing about Newtonian physics as though all were in perfect order, as though there were no hints of cracks in the foundation of physics.

As he neared the end of his studies at the ETH, Einstein naively assumed that, because he was intelligent and had not really done all that badly in his courses (overall mark of 4.91 out of 6.00), he would be offered the position of "Assistent" in physics at the ETH under Weber, and could use it in the usual manner as a springboard into the academic world. As an Assistent he could start doing research of his own, leading in a few years to a Ph.D. degree.

But such was not to be. Of the four students who passed their final exams in the combined physics–mathematics program in August 1900, three got assistantships at the ETH working under mathematicians; the fourth, Einstein, got nothing. Weber hired as Assistents two engineering students rather than Einstein.

Einstein kept trying. In September, one month after graduation, he applied for a vacant Assistent position in mathematics at the ETH. He was rejected. In winter and spring he applied to Wilhelm Ostwald in Leipzig, Germany, and Heike Kamerlingh Onnes in Leiden, the Netherlands. From them he seems never to have received even the courtesy of a reply—though his note to Onnes is now proudly displayed in a museum in Leiden, and though Ostwald ten years later would be the first to nominate Einstein for a Nobel Prize. Even the letter to Ostwald from Einstein's father seems to have elicited no response.

To the saucy and strong-willed Mileva Marić, with whom his romance had turned intense, Einstein wrote on 27 March 1901, "I'm absolutely convinced that Weber is to blame. . . . it doesn't make any sense to write to any more professors, because they'll surely turn to Weber for information about me at a certain point, and he'll just give me another bad recommendation." To a close friend, Marcel Grossmann, he wrote on 14 April 1901, "I could have found [an Assistent position] long ago had it not been for Weber's underhandedness. All the same, I leave no stone unturned and do not give up my sense of humor . . . God created the donkey and gave him a thick hide."

A thick hide he needed; not only was he searching fruitlessly for a job, but his parents were vehemently opposing his plans to marry Mileva, and his relationship to Mileva was growing turbulent. Of Mileva his mother wrote, "This Miss Marić is causing me the bitterest hours of my life, if it were in my power, I would make every effort to banish her from our horizon, I really dislike her." And of Einstein's mother, Mileva wrote, "That lady seems to have made it her life's goal to embitter as much as possible not only my life but also that of her son. . . . I wouldn't have thought it possible that there could exist such heartless and outright wicked people!"

Einstein wanted desperately to escape his financial dependence on his parents, and to have the peace of mind and freedom to devote most of his energy to physics. Perhaps this could be achieved by some means other than an Assistent position in a university. His degree from the ETH qualified him to teach in a *gymnasium* (high school), so to this he turned: He managed in mid-May 1901 to get a temporary job at a technical high school in Winterthur, Switzerland, substituting for a mathematics teacher who had to serve a term in the army.

To his former history professor at the ETH, Alfred Stern, he wrote, "I am beside myself with joy about [this teaching job], because today I received the news that everything has been definitely arranged. I have not the slightest idea as to who might be the humanitarian who recommended me there, because from what I have been told, I am not in the good books of any of my former teachers." The job in Winterthur, followed in autumn 1901 by another temporary high school teaching job in Schaffhausen, Switzerland, and then in June 1902 by a job as "technical expert third class" in the Swiss Patent Office in Bern, gave him independence and stability.

Despite continued turbulence in his personal life (long separations from Mileva; an illegitimate child with Mileva in 1902, whom they seem to have put up for adoption, perhaps to protect Einstein's career possibilities in staid Switzerland; his marriage to Mileva a year later in spite of his parents' violent opposition), Einstein maintained an optimistic spirit and remained clear-headed enough to think, and think deeply about physics: From 1901 through 1904 he seasoned his powers as a physicist by theoretical research on the nature of the forces between molecules in liquids, such as water, and in metals, and research on the nature of heat. His new insights, which were substantial, were published in a sequence of five articles in the most prestigious physics journal of the early 1900s: the *Annalen der Physik.*

The patent office job in Bern was well suited to seasoning Einstein's powers. On the job he was challenged to figure out whether the inventions submitted would work—often a delightful task, and one that sharpened his mind. And the job left free half his waking hours and all weekend. Most of these he spent studying and thinking about physics, often in the midst of family chaos.

His ability to concentrate despite distractions was described by a student, who visited him at home several years after his marriage to Mileva: "He was sitting in his study in front of a heap of papers covered with mathematical formulas. Writing with his right hand and holding his younger son in his left, he kept replying to questions from his elder son Albert who was playing with his bricks. With the words, 'Wait a minute, I've nearly finished,' he gave me the children to look after for a few moments and went on working."

In Bern, Einstein was isolated from other physicists (though he did have a few close non-physicist friends with whom he could discuss science and philosophy). For most physicists, such isolation would be disastrous. Most require continual contact with colleagues working on similar problems to keep their research from straying off in unproductive directions. But Einstein's intellect was different; he worked more fruitfully in isolation than in a stimulating milieu of other physicists.

Sometimes it helped him to talk with others—not because they offered him deep new insights or information, but rather because by explaining paradoxes and problems to others, he could clarify them in his own mind. Particularly helpful was Michele Angelo Besso, an Italian engineer who had been a classmate of Einstein's at ETH and now was working beside Einstein in the patent office. Of Besso, Einstein said, "I could not have found a better sounding board in the whole of Europe."

Left: **Einstein seated at his desk in the patent office in Bern, Switzerland, ca. 1905.** ***Right:*** **Einstein with his wife, Mileva, and their son Hans Albert, ca. 1904.** [Left: courtesy the Albert Einstein Archives of the Hebrew University of Jerusalem; right: courtesy Schweizerisches Literaturachiv/Archiv der Einstein-Gesellschaft, Bern.]

Einstein's Relative Space and Time, and Absolute Speed of Light

Michele Angelo Besso was especially helpful in May 1905, when Einstein, after focusing for several years on other physics issues, returned to Maxwell's electrodynamic laws and their tantalizing hints of length contraction and time dilation. Einstein's search for some way to make sense of these hints was impeded by a mental block. To clear the block, he sought help from Besso. As he recalled later, "That was a very beautiful day when I visited [Besso] and began to talk with him as follows: 'I have recently had a question which was difficult for me to understand. So I came here today to bring with me a battle on the question.' Trying a lot of discussions with him, I could suddenly comprehend the matter. The next day I visited him again and said to him without greeting: 'Thank you. I've completely solved the problem.' "

Einstein's solution: *There is no such thing as absolute space. There is no such thing as absolute time. Newton's foundation for all of physics was flawed. And as for the aether: It does not exist.*

By rejecting absolute space, Einstein made absolutely meaningless the notion of "being at rest in absolute space." There is no way, he asserted, to ever measure the Earth's motion through absolute space, and that is why the Michelson–Morley experiment turned out the way it did. One can measure the Earth's velocity only *relative to other physical objects* such as the Sun or the Moon, just as one can measure a train's velocity only relative to physical objects such as the ground and the air. For neither Earth nor train nor anything else is there any standard of absolute motion; motion is purely "relative."

By rejecting absolute space, Einstein also rejected the notion that everyone, regardless of his or her motion, must agree on the length, height, and width of some table or train or any other object. On the contrary, Einstein insisted, *length, height, and width are "relative" concepts.* They depend on the relative motion of the object being measured and the person doing the measuring.

By rejecting absolute time, Einstein rejected the notion that everyone, regardless of his or her motion, must experience the flow of time in the same manner. *Time is relative,* Einstein asserted. Each person traveling in his or her own way must experience a different time flow than others, traveling differently.

It is hard not to feel queasy when presented with these assertions. If correct, not only do they cut the foundations out from under the entire edifice of Newtonian physical law, they also deprive us of our common-sense, everyday notions of space and time.

But Einstein was not just a destroyer. He was also a creator. He offered us a new foundation to replace the old, a foundation just as firm and, it has turned out, in far more perfect accord with the Universe.

Einstein's new foundation consisted of two new fundamental principles:

- *The principle of the absoluteness of the speed of light:* Whatever might be their nature, space and time must be so constituted as to make the speed of light absolutely the same in all directions, and absolutely independent of the motion of the person who measures it.

This principle is a resounding affirmation that the Michelson–Morley experiment was correct, and that regardless of how accurate light-measuring devices may become in the future, they must always continue to give the same result: a universal speed of light.

- *The principle of relativity:* Whatever might be their nature, the laws of physics must treat all states of motion on an equal footing.

This principle is a resounding rejection of absolute space: If the laws of physics did not treat all states of motion (for example, that of the Sun and that of the Earth) on an equal footing, then using the laws of physics, physicists would be able to pick out some "preferred" state of motion (for example, the Sun's) and define it as the state of "absolute rest." Absolute space would then have crept back into physics. We shall return to this later in the chapter.

From the absoluteness of the speed of light, Einstein deduced, by an elegant logical argument described in Box 1.1 below, that if you and I move relative to each other, *what I call space must be a mixture of your space and your time, and what you call space must be a mixture of my space and my time.*

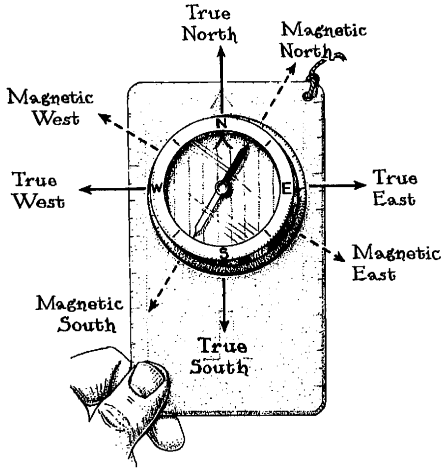
This "mixing of space and time" is analogous to the mixing of directions on Earth. Nature offers us two ways to reckon directions, one tied to the Earth's spin, the other tied to its magnetic field. In Pasadena, California, magnetic north (the direction a compass needle points) is offset eastward from true north (the direction toward the Earth's spin axis, that is, toward the "North Pole") by about 20 degrees; see Figure 1.2. This means that in order to travel in the magnetic north direction, one must travel partly (about 80 percent) in the true north direction and partly (about 20 percent) toward true east. In this sense, *magnetic north is a mixture of true north and true east;* similarly, true north is a mixture of magnetic north and magnetic west.

To understand the analogous mixing of space and time *(your space is a mixture of my space and my time, and my space is a mixture of your space and your time),* imagine yourself the owner of a powerful sports car. You like to drive your car down Colorado Boulevard in Pasadena, California, at extremely high speed in the depths of the night, when I, a policeman, am napping. To the top of your car you attach a series of firecrackers, one over the front of the hood, one over the rear of the trunk, and many in between; see Figure 1.3a. You set the firecrackers to detonate simultaneously as seen by you, just as you are passing my police station.

Figure 1.3b depicts this from your own viewpoint. Drawn vertically is the flow of time, as measured by you ("your time"). Drawn horizontally is distance along your car, from back to front, as measured by you ("your space"). Since the firecrackers are all at rest in your space (that is, as seen by you), with the passage of your time they all remain at the same horizontal locations in the diagram. The dashed lines, one for each firecracker, depict this. They extend vertically upward in the diagram, indicating no rightward or leftward motion in space whatsoever as time passes—and they then terminate abruptly at the moment the firecrackers detonate. The detonation events are depicted by asterisks.

This figure is called a *spacetime diagram* because it plots space horizontally and time vertically; the dashed lines are called *world lines* because they show where in the world the firecrackers travel as time passes. We shall make extensive use of spacetime diagrams and world lines later in this book.

If one moves horizontally in the diagram (Figure 1.3b), one is moving through space at a fixed moment of your time. Correspondingly, it is convenient to think of each horizontal line in the diagram as depicting space, as seen by you ("your space"), at a specific moment of your time. For example, the dotted horizontal line is your space at the moment of firecracker detonation. As one moves vertically upward in the diagram, one is moving through time at a fixed location in your space. Correspondingly, it is convenient to think of each vertical line in the spacetime diagram (for example, each firecracker world line) as depicting the flow of your time at a specific location in your space.

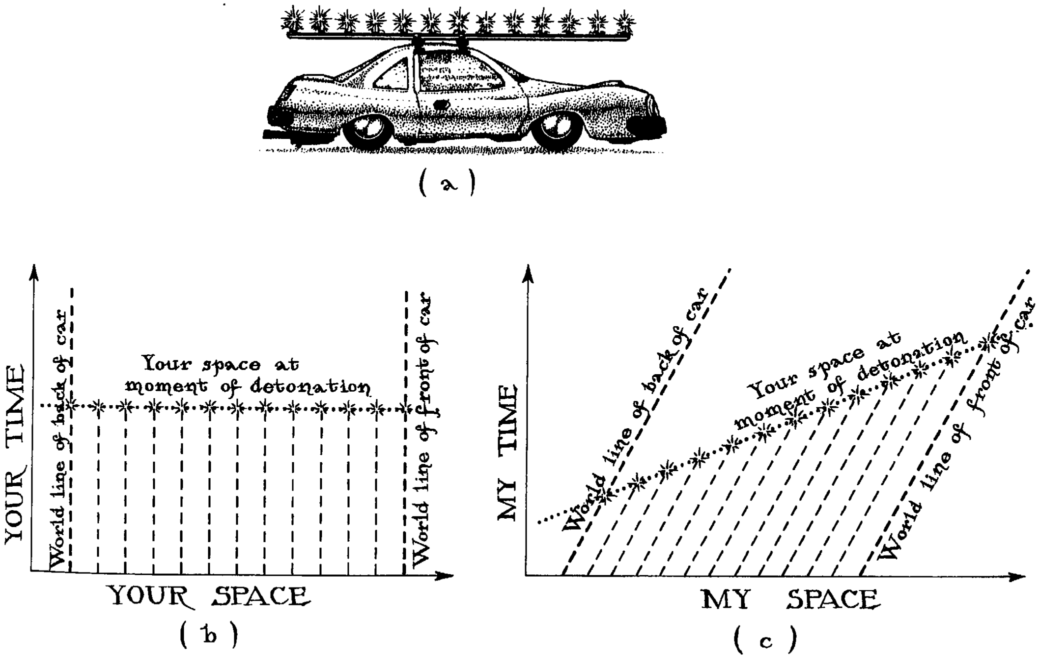


1.2 Magnetic north is a mixture of true north and true east, and true north is a mixture of magnetic north and magnetic west.

I, in the police station, were I not napping, would draw a rather different spacetime diagram to depict your car, your firecrackers, and the detonation (Figure 1.3c). I would plot the flow of time, as measured by me, vertically, and distance along Colorado Boulevard horizontally. As time passes, each firecracker moves down Colorado Boulevard with your car at high speed, and correspondingly, the firecracker's world line tilts rightward in the diagram: At the time of its detonation, the firecracker is farther to the right down Colorado Boulevard than at earlier times.

Now, the surprising conclusion of Einstein's logical argument (Box 1.1) is that the absoluteness of the speed of light requires the firecrackers *not* to detonate simultaneously as seen by me, even though

1.3 (a) Your sports car speeding down Colorado Boulevard with firecrackers attached to its roof. (b) Spacetime diagram depicting the firecrackers' motion and detonation from your viewpoint (riding in the car). (c) Spacetime diagram depicting the same firecracker motion and detonation from my viewpoint (at rest in the police station).



they detonate simultaneously as seen by you. From my viewpoint the rearmost firecracker on your car detonates first, and the frontmost one detonates last. Correspondingly, the dotted line that we called "your space at moment of detonation" (Figure 1.3b) is tilted in my spacetime diagram (Figure 1.3c).

From Figure 1.3c it is clear that, to move through your space at your moment of detonation (along the dotted detonation line), I must move through both my space and my time. In this sense, your space is a mixture of my space and my time. This is just the same sense as the statement that magnetic north is a mixture of true north and true east (compare Figure 1.3c with Figure 1.2).

You might be tempted to assert that this "mixing of space and time" is nothing but a complicated, jingoistic way of saying that "simultaneity depends on one's state of motion." True. However, physicists, building on Einstein's foundations, have found this way of thinking to be powerful. It has helped them to decipher Einstein's legacy (his new laws of physics), and to discover in that legacy a set of seemingly outrageous phenomena: black holes, wormholes, singularities, time warps, and time machines.

From the absoluteness of the speed of light and the principle of relativity, Einstein deduced other remarkable features of space and time. In the language of the above story:

- Einstein deduced that, as you speed eastward down Colorado Boulevard, I must see your space and everything at rest in it (your car, your firecrackers, and you) contracted along the east–west direction, but not north–south or up–down. This was the contraction inferred by Fitzgerald, but now put on a firm foundation: The contraction is caused by the peculiar nature of space and time, and not by any physical forces that act on moving matter.
- Similarly, Einstein deduced that, as you speed eastward, you must see my space and everything at rest in it (my police station, my desk, and me) contracted along the east–west direction, but not north–south or up–down. That you see me contracted and I see you contracted may seem puzzling, but in fact it could not be otherwise: It leaves your state of motion and mine on an equal footing, in accord with the principle of relativity.
- Einstein also deduced that, as you speed past, I see your flow of time slowed, that is, dilated. The clock on your car's dashboard appears to tick more slowly than my clock on the police station

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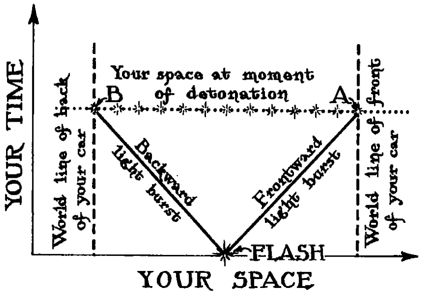
Box 1.1

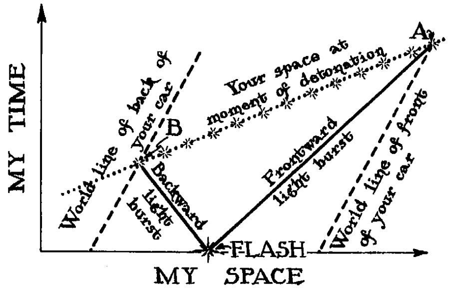
Einstein's Proof of the Mixing of Space and Time

Einstein's principle of the absoluteness of the speed of light enforces the mixing of space and time; in other words, it enforces the relativity of simultaneity: Events that are simultaneous as seen by you (that lie in your space at a specific moment of your time), as your sports car speeds down Colorado Boulevard, are not simultaneous as seen by me, at rest in the police station. I shall prove this using descriptive words that go along with the spacetime diagrams shown below. This proof is essentially the same as the one devised by Einstein in 1905.

Place a flash bulb at the middle of your car. Trigger the bulb. It sends a burst of light forward toward the front of your car, and a burst backward toward the back of your car. Since the two bursts are emitted simultaneously, and since they travel the same distance as measured by you in your car, and since they travel at the same speed (the speed of light is absolute), they must arrive at the front and back of your car simultaneously from your viewpoint; see the left diagram, below. The two events of burst arrival (call them *A* at your car's front and *B* at its back) are thus simultaneous from your viewpoint, and they happen to coincide with the firecracker detonations of Figure 1.4, as seen by you.

Next, examine the light bursts and their arrival events *A* and *B* from my viewpoint as your car speeds past me; see the right diagram, below. From my viewpoint, the back of your car is moving forward, toward the backward-directed burst of light, and they thus meet each other (event *B*) sooner as seen by me than as seen by you. Similarly, the front of your car is moving forward, away from the frontward-directed burst, and they thus meet each other (event *A*) later as seen by me than as seen by you. (These conclusions rely crucially on the fact that the speeds of the two light bursts are the same as seen by me; that is, they rely on the absoluteness of the speed of light.) Therefore, I regard event *B* as occurring before event *A*; and similarly, I see the firecrackers near the back of your car detonate before those near the front.





Note that the locations of the detonations (your space at a specific moment of your time) are the same in the above spacetime diagrams as in Figure 1.4. This justifies the asserted mixing of space and time discussed in the text.

wall. You speak more slowly, your hair grows more slowly, you age more slowly than I.

- Similarly, in accord with the principle of relativity, as you speed past me, you see my flow of time slowed. You see the clock on my station wall tick more slowly than the one on your dashboard. To you I seem to speak more slowly, my hair grows more slowly, and I age more slowly than you.

How can it possibly be that I see your time flow slowed, while you see mine slowed? How is that logically possible? And how can I see your space contracted, while you see my space contracted? The answer lies in the relativity of simultaneity. You and I disagree about whether events at different locations in our respective spaces are simultaneous, and this disagreement turns out to mesh with our disagreements over the flow of time and the contraction of space in just such a way as to keep everything logically consistent. To demonstrate this consistency, however, would take more pages than I wish to spend, so I refer you, for a proof, to Chapter 3 of Taylor and Wheeler (1992).

How is it that we as humans have never noticed this weird behavior of space and time in our everyday lives? The answer lies in our slowness. We always move relative to each other with speeds far smaller than that of light (299,792 kilometers per second). If your car zooms down Colorado Boulevard at 150 kilometers per hour, I should see your time flow dilated and your space contracted by roughly one part in a hundred trillion (1×10^{-14})—far too little for us to notice. By contrast, if your car were to move past me at 87 percent the speed of light, then (using instruments that respond very quickly) I should see your time flow twice as slowly as mine, while you see my time flow twice as slowly as yours; similarly, I should see everything in your car half as long, east–west, as normal, and you should see everything in my police station half as long, east–west, as normal. Indeed, a wide variety of experiments in the late twentieth century have verified that space and time do behave in just this way.

How did Einstein arrive at such a radical description of space and time?

Not by examining the results of experiments. Clocks of his era were too inaccurate to exhibit, at the low speeds available, any time dilation or disagreements about simultaneity, and measuring rods were too inaccurate to exhibit length contraction. The only relevant experiments were those few, such as Michelson and Morley's, which suggested that the speed of light on the Earth's surface might be the same in all directions. These were very skimpy data indeed on which to base such a radical revision of one's notions of space and time! Moreover, Einstein paid little attention to these experiments.

Instead, Einstein relied on his own innate intuition as to how things *ought to* behave. After much reflection, it became *intuitively obvious* to him that the speed of light must be a universal constant, independent of direction and independent of one's motion. Only then, he reasoned, could Maxwell's electromagnetic laws be made uniformly simple and beautiful (for example, "magnetic field lines never ever have any ends"), and he was firmly convinced that the Universe in some deep sense insists on having simple and beautiful laws. He therefore introduced, as a new principle on which to base all of physics, his principle of the absoluteness of the speed of light.

This principle by itself, without anything else, already guaranteed that the edifice of physical laws built on Einstein's foundation would differ profoundly from that of Newton. *A Newtonian physicist, by presuming space and time to be absolute, is forced to conclude that the speed of light is relative—it depends on one's state of motion (as the bird and train analogy earlier in this chapter shows). Einstein, by presuming the speed of light to be absolute, was forced to conclude that space and time are relative—they depend on one's state of motion. Having deduced that space and time are relative, Einstein was then led onward by his quest for simplicity and beauty to his principle of relativity: No one state of motion is to be preferred over any other; all states of motion must be equal, in the eyes of physical law.*

Not only was experiment unimportant in Einstein's construction of a new foundation for physics, the ideas of other physicists were also unimportant. He paid little attention to others' work. He seems not even to have read any of the important technical articles on space, time, and the aether that Hendrik Lorentz, Henri Poincaré, Joseph Larmor, and others wrote between 1896 and 1905.

In their articles, Lorentz, Poincaré, and Larmor were groping toward the same revision of our notions of space and time as Einstein, but they were groping through a fog of misconceptions foisted on them by Newtonian physics. Einstein, by contrast, was able to cast off the Newtonian misconceptions. His conviction that the Universe loves simplicity and beauty, and his willingness to be guided by this conviction, even if it meant destroying the foundations of Newtonian physics, led him, with a clarity of thought that others could not match, to his new description of space and time.

The principle of relativity will play an important role later in this book. For this reason I shall devote a few pages to a deeper explanation of it.

A deeper explanation requires the concept of a *reference frame.* A reference frame is a laboratory that contains all the measuring apparatus one might need for whatever measurements one wishes to make. The laboratory and all its apparatus must move through the Universe together; they must all undergo the same motion. In fact, the motion of the reference frame is really the central issue. When a physicist speaks of "different reference frames," the emphasis is on different states of motion and not on different measuring apparatuses in the two laboratories.

A reference frame's laboratory and its apparatus need not be real. They perfectly well can be imaginary constructs, existing only in the mind of the physicist who wants to ask some question such as, "If I were in a spacecraft floating through the asteroid belt, and I were to measure the size of some specific asteroid, what would the answer be?" Such physicists imagine themselves as having a reference frame (laboratory) attached to their spacecraft and as using that frame's apparatus to make the measurement.

Einstein expressed his principle of relativity not in terms of arbitrary reference frames, but in terms of rather special ones: frames (laboratories) that move freely under their own inertia, neither pushed nor pulled by any forces, and that therefore continue always onward in the same state of uniform motion as they began. Such frames Einstein called *inertial* because their motion is governed solely by their own inertia.

A reference frame attached to a firing rocket (a laboratory inside the rocket) is *not* inertial, because its motion is affected by the rocket's thrust as well as by its inertia. The thrust prevents the frame's motion from being uniform. A reference frame attached to the space shuttle as it reenters the Earth's atmosphere also is not inertial, because friction between the shuttle's skin and the Earth's air molecules slows the shuttle, making its motion nonuniform.

Most important, near any massive body such as the Earth, *all* reference frames are pulled by gravity. There is no way whatsoever to shield a reference frame (or any other object) from gravity's pull. Therefore, by restricting himself to inertial frames, Einstein prevented himself from considering, in 1905, physical situations in which gravity is important[3]; in effect, he idealized our Universe as one in which there is no gravity at all. Extreme idealizations like this are central to progress in physics; one throws away, conceptually, aspects of the Universe that are difficult to deal with, and only after gaining intellectual control over the remaining, easier aspects does one return to the harder ones. Einstein gained intellectual control over an idealized universe without gravity in 1905. He then turned to the harder task of understanding the nature of space and time in our real, gravity-endowed Universe, a task that eventually would force him to conclude that gravity warps space and time (Chapter 2).

With the concept of an inertial reference frame understood, we are now ready for a deeper, more precise formulation of Einstein's principle of relativity: *Formulate any law of physics in terms of measurements made in one inertial reference frame. Then, when restated in terms of measurements in any other inertial frame, that law of physics must take on precisely the same mathematical and logical form as in the original frame.* In other words, the laws of physics must not provide any means to distinguish one inertial reference frame (one state of uniform motion) from any other.

Two examples of physical laws will make this more clear:

- "Any free object (one on which no forces act) that initially is at rest in an inertial reference frame will always remain at rest; and any free object that initially is moving through an inertial reference frame will continue forever forward, along a straight line with constant speed." If (as is the case) we have strong reason to believe that this relativistic version of Newton's first law of motion is true in at least one inertial reference frame, then the principle of relativity insists that it must be true in all inertial reference frames regardless of where they are in the Universe and regardless of how fast they are moving.
- Maxwell's laws of electromagnetism must take on the same mathematical form in all reference frames. They failed to do so, when physics was built on Newtonian foundations (magnetic field lines could have ends in some frames but not in others), and this failure was deeply disturbing to Lorentz, Poincaré, Larmor, and Einstein.

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[3] This means that it was a bit unfair of me to use a high-speed sports car, which feels the Earth's gravity, in my example above. However, it turns out that because the Earth's gravitational pull is perpendicular to the direction of the car's motion (downward versus horizontal), it has no effect on any of the issues discussed in the sports-car story.

> In Einstein's view it was utterly unacceptable that the laws were simple and beautiful in one frame, that of the aether, but complex and ugly in all frames that moved relative to the aether. By reconstructing the foundations of physics, Einstein enabled Maxwell's laws to take on one and the same simple, beautiful form (for example, "magnetic field lines never ever have any ends") in each and every inertial reference frame—in accord with his principle of relativity.

The principle of relativity is actually a *metaprinciple* in the sense that it is not itself a law of physics, but instead is a pattern or rule which (Einstein asserted) must be obeyed by *all* laws of physics, no matter what those laws might be, no matter whether they are laws governing electricity and magnetism, or atoms and molecules, or steam engines and sports cars. The power of this metaprinciple is breathtaking. Every new law that is proposed must be tested against it. If the new law passes the test (if the law is the same in every inertial reference frame), then the law has some hope of describing the behavior of our Universe. If it fails the test, then it has no hope, Einstein asserted; it must be rejected.

All of our experience in the nearly 100 years since 1905 suggests that Einstein was right. All new laws that have been successful in describing the real Universe have turned out to obey Einstein's principle of relativity. This metaprinciple has become enshrined as a governor of physical law.

In May 1905, once his discussion with Michele Angelo Besso had broken his mental block and enabled him to abandon absolute time and space, Einstein needed only a few weeks of thinking and calculating to formulate his new foundation for physics, and to deduce its consequences for the nature of space, time, electromagnetism, and the behaviors of high-speed objects. Two of the consequences were spectacular: mass can be converted into energy (which would become the foundation for the atomic bomb; see Chapter 6), and the inertia of every object must increase so rapidly, as its speed approaches the speed of light, that no matter how hard one pushes on the object, one can never make it reach or surpass the speed of light ("nothing can go faster than light").[4]

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[4] But see Chapter 14 for a caveat.

In late June, Einstein wrote a technical article describing his ideas and their consequences, and mailed it off to the *Annalen der Physik*. His article carried the somewhat mundane title "On the Electrodynamics of Moving Bodies." But it was far from mundane. A quick perusal showed Einstein, the Swiss Patent Office's "technical expert third class," proposing a whole new foundation for physics, proposing a metaprinciple that all future physical laws must obey, radically revising our concepts of space and time, and deriving spectacular consequences. Einstein's new foundation and its consequences would soon come to be known as *special relativity* ("special" because it correctly describes the Universe only in those special situations where gravity is unimportant).

Einstein's article was received at the offices of the *Annalen der Physik* in Leipzig on 30 June 1905. It was perused for accuracy and importance by a referee, was passed as acceptable, and was published.

In the weeks after publication, Einstein waited expectantly for a response from the great physicists of the day. His viewpoint and conclusions were so radical and had so little experimental basis that he expected sharp criticism and controversy. Instead, he was met with stony silence. Finally, many weeks later, there arrived a letter from Berlin: Max Planck wanted clarification of some technical issues in the paper. Einstein was overjoyed! To have the attention of Planck, one of the most renowned of all living physicists, was deeply satisfying. And when Planck went on, the following year, to use Einstein's principle of relativity as a central tool in his own research, Einstein was further heartened. Planck's approval, the gradual approval of other leading physicists, and most important his own supreme self-confidence held Einstein firm throughout the following twenty years as the controversy he had expected did, indeed, swirl around his relativity theory. The controversy was still so strong in 1922 that, when the secretary of the Swedish Academy of Sciences informed Einstein by telegram that he had won the Nobel Prize, the telegram stated explicitly that relativity was *not* among the works on which the award was based.

The controversy finally died in the 1930s, as technology became sufficiently advanced to produce accurate experimental verifications of special relativity's predictions. By now, in the 1990s, there is absolutely no room for doubt: Every day more than 10^{17} electrons in particle accelerators at Stanford University, Cornell University, and elsewhere are driven up to speeds as great as 0.9999999995 of the speed of light—and their behaviors at these ultra-high speeds are in complete accord with Einstein's special relativistic laws of physics. For example, the electrons' inertia increases as they near the speed of light, preventing them from ever reaching it; and when the electrons collide with targets, they produce high-speed particles called mu mesons that live for only 2.22 microseconds as measured by their own time, but because of time dilation live for 100 microseconds or more as measured by the physicists' time, at rest in the laboratory.

The Nature of Physical Law

Does the success of Einstein's special relativity mean that we must totally abandon the Newtonian laws of physics? Obviously not. The Newtonian laws are still used widely in everyday life, in most fields of science, and in most technology. We don't pay attention to time dilation when planning an airplane trip, and engineers don't worry about length contraction when designing an airplane. The dilation and contraction are far too small to be of concern.

Of course, if we wished to, we *could* use Einstein's laws rather than Newton's in everyday life. The two give almost precisely the same predictions for all physical effects, since everyday life entails relative speeds that are very small compared to the speed of light.

Einstein's and Newton's predictions begin to diverge strongly only at relative speeds approaching the speed of light. Then and only then must one abandon Newton's predictions and adhere strictly to Einstein's.

This is an example of a very general pattern, one that we shall meet again in future chapters. It is a pattern that has been repeated over and over in the history of twentieth-century physics: One set of laws (in our case the *Newtonian laws*) is widely accepted at first, because it accords beautifully with experiment. But then experiments become more accurate and this first set of laws turns out to work well only in a limited domain, its *domain of validity* (for Newton's laws, the domain of speeds small compared to the speed of light). Physicists then struggle, experimentally and theoretically, to understand what is going on at the boundary of that domain of validity, and they finally formulate a new set of laws which is highly successful inside, near, and beyond the boundary (in Newton's case, *Einstein's special relativity*, valid at speeds approaching light as well as at low speeds). Then the process repeats. We shall meet the repetition in coming chapters: The failure of special relativity when gravity becomes important, and its replacement by a new set of laws called *general relativity* (Chapter 2); the failure of general relativity near the singularity inside a black hole, and its replacement by a new set of laws called *quantum gravity* (Chapter 13).

There has been an amazing feature of each transition from an old set of laws to a new one: In each case, physicists (if they were sufficiently clever) did not need any experimental guidance to tell them where the old set would begin to break down, that is, to tell them the boundary of its domain of validity. We have seen this already for Newtonian physics: Maxwell's laws of electrodynamics did not mesh nicely with the absolute space of Newtonian physics. At rest in absolute space (in the frame of the aether), Maxwell's laws were simple and beautiful—for example, magnetic field lines have no ends. In moving frames, they became complicated and ugly—magnetic field lines sometimes have ends. However, the complications had negligible influence on the outcome of experiments when the frames moved, relative to absolute space, at speeds small compared to light; then almost all field lines are endless. Only at speeds approaching light were the ugly complications predicted to have a big enough influence to be measured easily: lots of ends. Thus, it was reasonable to suspect, even without the Michelson–Morley experiment, that the domain of validity of Newtonian physics might be speeds small compared to light, and that the Newtonian laws might break down at speeds approaching light.

In Chapter 2 we shall see, similarly, how special relativity predicts its own failure in the presence of gravity; and in Chapter 13, how general relativity predicts its own failure near a singularity.

When contemplating the above sequence of sets of laws (Newtonian physics, special relativity, general relativity, quantum gravity)—and a similar sequence of laws governing the structure of matter and elementary particles—most physicists are driven to believe that these sequences are converging toward a set of ultimate laws that truly governs the Universe, laws that *force* the Universe to behave the way it does, that *force* rain to condense on windows, *force* the Sun to burn nuclear fuel, *force* black holes to produce gravitational waves when they collide, and so on.

One might object that each set of laws in the sequence "looks" very different from the preceding set. (For example, the absolute time of Newtonian physics looks very different from the many different time flows of special relativity.) In the "looks" of the laws, there is no sign whatsoever of convergence. Why, then, should we expect convergence? The answer is that one must distinguish sharply between the predictions made by a set of laws and the mental images that the laws convey (what the laws "look like"). I expect convergence only in terms of predictions, but that is all that ultimately counts. The mental images (one absolute time in Newtonian physics versus many time flows in relativistic physics) are not important to the ultimate nature of *reality*. In fact, it is possible to change completely what a set of laws "looks like" without changing its predictions. In Chapter 11, I shall discuss this remarkable fact and give examples, and shall explain its implications for the nature of reality.

Why do I expect convergence in terms of predictions? Because all the evidence we have points to it. Each set of laws has a larger domain of validity than the sets that preceded it: Newton's laws work throughout the domain of everyday life, but not in physicists' particle accelerators and not in exotic parts of the distant Universe, such as pulsars, quasars, and black holes; Einstein's general relativity laws work everywhere in our laboratories, and everywhere in the distant Universe, except deep inside black holes and in the big bang where the Universe was born; the laws of quantum gravity (which we do not yet understand at all well) may turn out to work absolutely everywhere.

Throughout this book, I shall adopt, without apology, the view that there *does* exist an ultimate set of physical laws (which we do not as yet know but which might be quantum gravity), and that those laws truly *do* govern the Universe around us, everywhere. They *force* the Universe to behave the way it does. When I am being extremely accurate, I shall say that the laws we now work with (for example, general relativity) are "an approximation to" or "an approximate description of" the true laws. However, I shall usually drop the qualifiers and not distinguish between the true laws and our approximations to them. At these times I shall assert, for example, that "the general relativistic laws [rather than the true laws] *force* a black hole to hold light so tightly in its grip that the light cannot escape from the hole's horizon." This is how my colleagues and I as physicists think, when struggling to understand the Universe. It is a fruitful way to think; it has helped produce deep new insights into imploding stars, black holes, gravitational waves, and other phenomena.

This viewpoint is incompatible with the common view that physicists work with *theories* which try to describe the Universe, but which are only human inventions and have no real power over the Universe. The word *theory*, in fact, is so ladened with connotations of tentativeness and human quirkiness that I shall avoid using it wherever possible. In its place I shall use the phrase *physical law* with its firm connotation of truly ruling the Universe, that is, truly forcing the Universe to behave as it does.

2

The Warping of Space and Time

in which Hermann Minkowski unifies space and time, and Einstein warps them

Minkowski's Absolute Spacetime

> The views of space and time which I wish to lay before you have sprung from the soil of experimental physics, and therein lies their strength. They are radical. Henceforth, space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.

With these words Hermann Minkowski revealed to the world, in September 1908, a new discovery about the nature of space and time.

Einstein had shown that space and time are "relative." The length of an object and the flow of time are different when viewed from different reference frames. My time differs from yours if I move relative to you, and my space differs from yours. My time is a mixture of your time and your space; my space is a mixture of your space and your time.

Minkowski, building on Einstein's work, had now discovered that the Universe is made of a four-dimensional "spacetime" fabric that is absolute, not relative. This four-dimensional fabric is the same as seen