Chapter 1

If a Person Falls Freely

DURING THE autumn of 1907, Albert Einstein worked under pressure. He had been invited to deliver the definitive review of his theory of relativity to the *Yearbook of Electronics and Radioactivity.* It was a tall order, to summarize such an important piece of work at such short notice, especially since he could do so only in his spare time. From 8:00 a.m. to 6:00 p.m. Monday through Saturday, Einstein could be found working at the Bern Federal Office for Intellectual Property in the newly built Postal and Telegraph Building, where he would meticulously pore over plans for newfangled electrical contraptions and figure out if there was any merit in them. Einstein's boss had advised him, "When you pick up an application, think that everything the inventor says is wrong," and he took his advice to heart. For much of the day, the notes and calculations for his own theories and discoveries had to be relegated to the second drawer of his desk, which he referred to as his "theoretical physics department."

Einstein's review would recap his triumphant marriage of the old mechanics of Galileo Galilei and Isaac Newton with the new electricity and magnetism of Michael Faraday and James Clerk Maxwell. It would explain much of the weirdness that Einstein had uncovered a few years before, such as how clocks would run more slowly when moving, or how objects would shrink if they were speeding ahead. It would explain his strange and magical formula that showed how mass and energy were interchangeable, and that nothing could move faster than the speed of light. His review of his principle of relativity would describe how almost all of physics should be governed by a new common set of rules.

In 1905, over a period of just a few months, Einstein had written a string of papers that were already transforming physics. In that inspired burst he had pointed out that light behaves like bundles of energy, much like particles of matter. He had also shown that the jittery, chaotic paths of pollen and dust careening through a dish of water could arise from the turmoil of water molecules, vibrating and bouncing off one another. And he had tackled a problem that had been plaguing physicists for almost half a century: how the laws of physics seem to behave differently depending on how you look at them. He had brought them together with his principle of relativity.

All these discoveries were a staggering achievement, and Einstein had made them all while working as a lowly patent expert at the Swiss patent office in Bern, sifting through the scientific and technological developments of the day. In 1907, he was still there, having yet to move into the august academic world that seemed to elude him. In fact, for someone who had just rewritten some of the fundamental rules of physics, Einstein was thoroughly undistinguished. Throughout his unimpressive academic studies at the Polytechnic Institute in Zurich, Einstein skipped classes that didn't interest him and antagonized the very people who could nurture his genius. One of his professors told him, "You are a very clever boy . . . But you have one great fault: you'll never let yourself be told anything." When Einstein's supervisor prevented him from working on a topic of his own choice, Einstein handed in a lackluster final essay, lowering his grade to a point where he was unable to secure a post as an assistant at any of the universities to which he had applied.

From his graduation in 1900 until he finally landed his job in the patent office in 1902, Einstein's career was a sequence of failures. To compound his frustration, the doctoral thesis he submitted to the University of Zurich in 1901 was rejected a year later. In his submission, Einstein had set about to demolish some of the ideas put forward by Ludwig Boltzmann, one of the great theoretical physicists of the end of the nineteenth century. Einstein's iconoclasm had not gone over well. It wasn't until 1905, when he submitted one of his magical papers, "A New Determination of Molecular Dimensions," that he finally obtained his doctorate. The degree, a newly diplomatic Einstein discovered, "considerably facilitates relations with people."

While Einstein struggled, his friend Marcel Grossmann was on the fast track to becoming an august professor. Well organized, studious, and beloved by his teachers, it was Grossmann who had saved Einstein from going off the rails by keeping detailed, immaculate notebooks of the lecture courses. Grossmann became close friends with Einstein and Einstein's future wife, Mileva Marić, while they studied together in Zurich, and all three graduated in the same year. Unlike Einstein's, Grossmann's career had progressed smoothly from then on. He had been appointed as an assistant in Zurich and in 1902 had obtained his doctorate. After a short stint teaching in high schools, Grossmann had become a professor of descriptive geometry at the Eidgenössische Technische Hochschule, known as the ETH, in Zurich. Einstein had failed to even get an appointment as a schoolteacher. It was only through the recommendation of Grossmann's father to an acquaintance, the head of the patent office in Bern, that Einstein had finally secured a job as a patent expert.

Einstein's job in the patent office was a blessing. After years of financial instability and depending on his father for an income, he was finally able to marry Mileva and begin to raise a family in Bern. The relative monotony of the patent office, with its clearly defined tasks and lack of distractions, seemed to be an ideal setting for Einstein to think things through. His assigned work took only a few hours to complete each day, leaving him time to focus on his puzzles. Sitting at his small wooden desk with only a few books and the papers from his "theoretical physics department," he would perform experiments in his head. In these thought experiments (*gedankenexperimenten* as he called them in German) he would imagine situations and constructions in which he could explore physical laws to find out what they might do to the real world. In the absence of a real lab, he would play out carefully crafted games in his head, enacting events that he would scrutinize in detail. With the results of these experiments, Einstein knew just enough mathematics to be able to put his ideas to paper, creating exquisitely crafted jewels that would ultimately change the direction of physics.

His employers at the patent office were pleased with Einstein's work and promoted him to Expert II Class, yet they remained oblivious to his growing reputation. Einstein was still working on a daily quota of patents in 1907 when the German physicist Johannes Stark commissioned Einstein to write his review "On the Relativity Principle and the Conclusions Drawn From It." He was given two months to write it, and in those two months Einstein realized that his principle of relativity was incomplete. It would need a thorough overhaul if it was to be *truly* general.

The article in the *Yearbook* was to be a summary of Einstein's original principle of relativity. This principle states that the laws of physics should look the same in any inertial frame of reference. The basic idea behind the principle was not new and had been around for centuries.

The laws of physics and mechanics are rules for how things move, speed up, or slow down when subjected to forces. In the seventeenth century, the English physicist and mathematician Isaac Newton laid out a set of laws for how objects respond to mechanical forces. His laws of motion consistently explain what happens when two billiard balls collide, or when a bullet is fired out of a gun, or when a ball is thrown up in the air.

An inertial frame of reference is one that moves at a constant velocity. If you're reading this in a stationary spot, like a cozy chair in your den or a table in a café, you're in an inertial frame. Another classic example is a smoothly moving fast train with the windows closed. If you're sitting inside it, once the train gets up to speed there's no way to know you're moving. In principle, it should be impossible to tell the difference between two inertial frames even if one is moving at a high speed and the other is at rest. If you do an experiment in one inertial frame measuring the forces acting on an object, you should get the same result as in any other inertial frame. The laws of physics are identical, regardless of the frame.

The nineteenth century brought a completely new set of laws that wove together two fundamental forces: electricity and magnetism. At first glance, electricity and magnetism appear to be two separate phenomena. We see electricity in the lights in our home or lightning in the sky, and magnetism in the magnets stuck to our fridge or the way the North Pole draws a compass. The Scottish physicist James Clerk Maxwell showed that these two forces could be seen as different manifestations of one underlying force, electromagnetism, and that how they are perceived depends on how an observer is moving. A person sitting next to a bar magnet would experience magnetism but no electricity. But a person whizzing by would experience not only the magnetism but also a modicum of electricity. Maxwell unified the two forces into one that remains equivalent regardless of an observer's position or speed.

If you try to combine Newton's laws of motion with Maxwell's laws for electromagnetism, troubles arise. If the world indeed obeys both of these sets of laws, it is possible, in principle, to construct an instrument out of magnets, wires, and pulleys that will not sense any force in one inertial frame but can register a force in another inertial frame, violating the rule that inertial frames should be indistinguishable from one another. Newton's laws and Maxwell's laws thus appear inconsistent with each other. Einstein wanted to fix these "asymmetries" in the laws of physics.

In the years leading up to his 1905 papers, Einstein devised his concise principle of relativity through a series of thought experiments aimed at solving this problem. His mental tinkering culminated in two postulates. The first was simply a restatement of the principle: The laws of physics must look the same in any inertial frame. The second postulate was more radical: In *any* inertial frame, the speed of light always has the same value and is 299,792 kilometers per second. These postulates could be used to adjust Newton's laws of motion and mechanics so that when they were combined with Maxwell's laws of electromagnetism, inertial frames remained completely indistinguishable. Einstein's new principle of relativity also led to some startling results.

The latter postulate required some adjustments to Newton's laws. In the classic Newtonian universe, speed is additive. Light emitted from the front of a speeding train moves faster than light coming from a stationary source. In Einstein's universe, this is no longer the case. Instead, there is a cosmic speed limit set at 299,792 kilometers per second. Even the most powerful rocket would be unable to break that speed barrier. But then odd things happen. So, for example, someone traveling on a train moving at close to the speed of light will age more slowly when observed by someone sitting at a station platform, watching the train go by. And the train itself will look shorter when it is moving than when it is sitting still. Time dilates and space contracts. These strange phenomena are signs that something much deeper is going on: in the world of relativity, time and space are intertwined and interchangeable.

With his principle of relativity, Einstein seemed to have simplified physics, albeit with strange consequences. But in the autumn of 1907, as Einstein set out to write the review, he had to admit that while his theory seemed to work well, it wasn't yet complete. Newton's theory of gravity didn't fit into his picture of relativity.

Before Albert Einstein came along, Isaac Newton was like a god in the world of physics. Newton's work was held up as the most stunning success of modern thought. In the late seventeenth century, he had unified the force of gravity acting on the very small and the very large alike in one simple equation. It could explain the cosmos as well as everyday life.

Newton's law of universal attraction, or the "inverse square law," is as simple as they come. It says that the gravitational pull between two objects is directly proportional to the mass of each object and inversely proportional to the square of their distance. So if you double the mass of one of the objects, the gravitational pull also doubles. And if you double the distance between the two objects, the pull *decreases* by a factor of four. Over two centuries, Newton's law kept on giving, explaining any number of physical phenomena. It proved itself most spectacularly not only in explaining the orbits of the known planets but also in predicting the existence of new ones.

Beginning in the late eighteenth century, there was evidence that the planet Uranus's orbit had a mysterious wobble. As astronomers amassed observations of Uranus's orbit, they could slowly map out its path in space with ever more precision. Predicting Uranus's orbit was not a straightforward exercise. It involved taking Newton's law of gravity and working out how the other planets influenced Uranus's motion, nudging it here and there, making its orbit ever so slightly more complicated. Astronomers and mathematicians would publish the orbits in the form of tables that would, for different days and years, predict where Uranus or any other planet should be in the sky. And when they compared their predictions with subsequent observations of Uranus's actual position, there was always a discrepancy they couldn't explain.

The French astronomer and mathematician Urbain Le Verrier was particularly skilled at working out the celestial orbits and producing orbits for various planets in the solar system. When he focused his attention on Uranus, he assumed from the start that Newton's theory *was* perfect, given how well it worked for the other planets. If Newton's theory was correct, he surmised, the only other possibility was that there had to be something out there that hadn't been accounted for. And so Le Verrier took the bold step of predicting the existence of a new, fictitious planet and producing its very own astronomical table. To his delight, a German astronomer in Berlin, Gottfried Galle, pointed his telescope in the direction that Le Verrier's table indicated and found a big, undiscovered planet shimmering in his field of view. As Galle put it in a letter to Le Verrier, "Monsieur, the planet of which you indicated the position really exists."

Le Verrier had taken Newton's theory a step further than anyone before and was rewarded for his audacity. For decades, Neptune was known as "Le Verrier's planet." Marcel Proust used Le Verrier's discovery as an analogy for ferreting out corruption in his *Remembrance of Things Past,* and Charles Dickens referred to it when describing hardboiled detective work in his short piece "The Detective Police." It was a beautiful example of using the fundamental rules of scientific deduction. Le Verrier, basking in the glory of his discovery, then turned his attention to Mercury. It too seemed to have a strange, unexpected orbit.

In Newtonian gravity, an isolated planet orbiting the sun follows a simple, closed orbit with the shape of a squashed circle, known as an ellipse. A planet will go around and around, endlessly following the same path, periodically getting closer to and then more distant from the sun. The point in its orbit at which the planet is closest to the sun — called its perihelion — remains constant over time. Some planets, like the Earth, have almost circular orbits — the ellipse is barely squashed — while others, like Mercury, follow much more elliptical paths.

Even accounting for all the other planets' effects on Mercury's orbit, Le Verrier found that Mercury's actual orbit was at odds with the predictions of Newtonian gravity; the planet's perihelion shifted by approximately 40 arcseconds per century. (An arcsecond is a unit of angular measurement; the entire dome of the sky is made up of about 1.3 million arcseconds, or 360 degrees.) This anomaly, known as the precession of the perihelion of Mercury, could not be explained by Le Verrier's deployment of Newton's rules. Something else was going on.

Once again, Le Verrier assumed that Newton had to be right, and so, in 1859, he conjectured that a new planet, Vulcan, about the same size as Mercury had to exist very close to the sun. It was a bold, outlandish conjecture. As he put it, "How could a planet, extremely bright and always near the Sun, fail to have been recognized during a total eclipse?"

Le Verrier's conjecture set off a race to discover the new planet Vulcan. Over the following decades, there were occasional reported sightings of an object nearer the sun, but none of them stood up to scrutiny. Although the search for Vulcan didn't end with Le Verrier's death, the precession of the perihelion of Mercury remained firmly entrenched in astronomical lore. Something other than an invisible planet would have to explain the 40-arcsecond anomaly.

When Einstein sat down to worry about gravity in 1907, he had to reconcile Newton's theory with his principle of relativity. In the back of his mind, he knew that he also had to explain Mercury's anomalous orbit. It was a tall order.

Gravity as explained by Newton violates both of the postulates in Einstein's beautiful and concise principle of relativity. For a start, in Newton's theory, the effect of gravity is instantaneous. If two objects are suddenly situated near each other, the force of gravity between them would be in effect immediately — it would require no time to travel from one object to the other. But how could this be if, according to Einstein's new principle of relativity, nothing, no signal, no effect, can move faster than the speed of light? Just as crucial and as vexing was the fact that, while Einstein's principle of relativity harmonized mechanics and electromagnetism, it left out Newton's law of gravity. Newtonian gravity looked different in different inertial frames.

Einstein's first step on his long trek to fix gravity and generalize his theory of relativity came one day as he sat at his chair at the patent office in Bern, lost in his world of thought. Years later he recalled the idea that came to him and led him toward his theory for gravity: "If a person falls freely he will not feel his own weight."

Imagine yourself as Alice in the rabbit hole, falling freely with nothing to stop you. As you fall under the pull of gravity, the speed at which you fall increases at a constant rate. The acceleration will exactly match the gravitational pull, and as a result your fall will feel effortless — you won't feel any force to pull or push against — although it will be undoubtedly terrifying as you hurtle through space. Now imagine a bunch of stuff falling with you: a book, a cup of tea, a similarly panicked white rabbit. All the other objects will accelerate at the same rate to compensate for the pull of gravity, and as a result they will hover around you as you all fall together. If you try to set up an experiment with these objects to measure how they move relative to you so as to determine the gravitational force, you will fail. You will feel weightless and the objects will look weightless. All of this seems to indicate that there is an intimate relationship between accelerated motion and the pull of gravity — in this case one is exactly compensating for the other.

Maybe falling freely is a step too far. There is too much going on around you: the air is rushing by, and the fear that you'll eventually hit the bottom makes clear thinking a challenge. Let's try something slightly simpler, and a little more sedate. Imagine that you have just entered an elevator on the ground floor of a tall building. The elevator starts to go up, and in those first few seconds, as it accelerates, you feel just a little bit heavier. Conversely, suppose you are now at the top of the building and the elevator starts to go down. During those initial moments when the elevator picks up speed, you feel lighter. Of course, once the elevator reaches its maximum speed, you don't feel any heavier or lighter. But during those moments in which the elevator accelerates or decelerates, your sense of your own weight, and hence of gravity, is skewed. In other words, what you sense of gravity is completely dependent on whether you are speeding up or slowing down.

On that day in 1907 when Einstein conjured up his falling man, he realized that there must be some deep connection between gravity and acceleration that would be the key to bringing gravity into his theory of relativity. If he could change his principle of relativity so that the laws of physics remained the same not only in frames moving at constant speed but also in frames that were speeding up or slowing down, he just might be able to bring gravity into the mix with electromagnetism and mechanics. He wasn't sure how, but this brilliant insight was the initial step toward making relativity more general.

Under pressure from his German editor, Einstein wrote up his review, "On the Relativity Principle and the Conclusions Drawn From It." He included a section on what would happen if he generalized his principle to include gravity. He summarily noted a few consequences: The presence of gravity would alter the speed of light and cause clocks to run more slowly. The effects of his generalized principle of relativity might even explain the minute drift in Mercury's orbit. These effects, tossed in at the end of the paper, could eventually be used to test his idea, but they would need to be worked out in more detail and with more care at a later time. They would have to wait. For a few years, Einstein wouldn't work on his theory at all.

By the end of 1907, Einstein's brilliant obscurity was coming to an end. Slowly but surely, his 1905 papers had begun to make an impact.

He started receiving a trickle of letters from distinguished physicists asking for his offprints and discussing his ideas. Einstein was excited by the developments, telling a friend, "My papers are meeting with much acknowledgement and are giving rise to further investigation." One of his admirers quipped, "I must confess to you that I was amazed to read that you have to sit in an office for eight hours of the day. But history is full of bad jokes!" It wasn't that he had a bad life. His job in Bern had allowed him to begin a family with Mileva. In 1904 they had a son they named Hans Albert. Einstein's regular hours at the patent office allowed him to spend time at home building toys for his young son, but he was ready to enter the world of academia.

In 1908, Einstein was finally made a private lecturer at the University of Bern, a position that allowed him to give lectures to paying students. He found teaching incredibly burdensome and earned a terrible reputation as a lecturer. Still, in 1909 he was lured over to the University of Zurich as an associate professor. Einstein remained in Zurich for just over a year. In 1911, he was offered a professorship at the German University in Prague. This time he would have no teaching obligations. Without the bustle of his academic teaching duties, he returned to a state of mind much like that enabled by the ordered and isolated environment of the patent office. He could think about generalizing relativity once again.