PART I

Einstein Discovered: Special Relativity, $E = mc^2$, and Spacetime

Chapter 1

From Unknown to Revolutionary

The most beautiful thing we can experience is the mysterious. It is the source of all true art and all science.[1]

Albert Einstein

The year is 1905. Working alone at a Government Issue desk at the Swiss patent office on the corner of Grain Storage and Geneva Lane in Berne, a brash young man with a driving passion for physics is stuck. He has been wrestling with the problem off-and-on for nearly a decade.

His passion has become an obsession. He works on it in every spare moment at the patent office. He discusses the problem with his friend on walks home from work. His thoughts turn to it while in his small apartment with his wife, rocking his new son in his bassinet.

Then one fine day in May it comes to him. "I've completely solved the problem," he tells his friend. "An analysis of the concept of *time* is my solution," he declares over the clip-clop of horse-drawn buggies and rumble of new-fangled motor cars.[2] With this insight, it all falls into place.

In that eureka moment on the streets of Berne, 26-year-old Albert Einstein altered our concept of reality forever. Einstein had begun the "relativity revolution" — a startling new vision on the nature of time and space.

It's Relative!

Einstein's strange new theory came to be called special relativity because it deals with the special case of motion called *uniform* motion.[3] What is uniform motion? An object which travels at a constant speed and in a constant direction is in uniform motion.

Say you are in your car heading north at a speed of 60 miles an hour. As long as you don't speed up or slow down or steer the car in another direction, your car is in uniform motion. (Since, in physics, velocity is defined as both speed and direction, uniform motion is also referred to as traveling at a constant velocity.)

Special relativity, however, said nothing about *non*-uniform motion, where speed or direction does change. Nor did it take into account the effects of gravity. Despite these limitations, Einstein showed the fundamental science accepted for centuries by physicists and lay people alike was wrong. Time and space are not absolute, they are not the same for everyone — they are *relative*.

What does this mean?[4] Let's take a look. Hold on to your hats — this is very strange:

Time is Relative

According to special relativity, *clocks run slower when they move through space*.[5]

Imagine you are attending one of my fascinating physics lectures. Hey, you in the back, wake up! Assume we are both wearing identical super-accurate watches. Say I walk across the front of the classroom at a steady pace — while you remain seated.

Per Einstein, you see my watch running a tiny bit slower than your watch. Why? Because I am moving with respect to you.

Now at the speed I am walking, this slowing of time is a very small effect — less than a billionth of a billionth of a second for each elapsed second. That's why we don't notice it. Nonetheless, it is a real effect.

The slowing of time becomes dramatic at speeds approaching the speed of light. Say I somehow speed by you at 87% the speed of light or about 580 million miles an hour. Because of my tremendous speed, you now see my watch running at only *half the rate* of your watch. That is, for every second that ticks off on your watch, only a half-second ticks off on mine. This is what you see and measure.

The next question is: what do I see? I see the exact opposite — I see your watch running slower than mine! As strange as this sounds, this is exactly what Einstein's theory of special relativity predicts.

Whose point of view is correct? They both are. Time is relative. If your head is beginning to hurt, it means you are beginning to grasp the counter-intuitive ideas of relativity.

Per Einstein's theory, space is also affected by motion:

Space is Relative

What if I walk across the same room, this time holding up a pen in my hand pointed in my direction of motion. What do you see? You measure the length of my pen as *shortened* — because I am moving with respect to you. Per special relativity, *the length of an object contracts along its direction of motion*.[6]

This effect is also extremely tiny at walking speeds. That is why we don't notice it. But if I were to somehow streak across the room at 87% the speed of light, then you would measure my pen compressed to *half* its length!

What do I see? Again, just the opposite. If you hold up a pen (oriented in the same direction), I measure your pen as shortened by half.

So if I am moving with respect to you, you measure my pen as shortened — and I measure your pen as shortened. Whose point of view is correct? They both are. Space is relative.

Why didn't anyone notice these effects before Einstein? Because, as noted, they only become significant at so-called relativistic speeds — speeds which are an appreciable fraction of the speed of light.

Relativistic Speed

The speed of light is an incredible 670 million miles an hour (approximately). Per Einstein's formula, we would have to travel at hundreds of millions of miles an hour to notice relativity effects. But we don't experience anywhere near these speeds in everyday life. A commercial jet, for instance, travels at some 600 miles an hour relative to the ground, which is only about a millionth the speed of light.

So at everyday speeds, the effects of special relativity are simply too small to notice.[7] But they are still real. As we shall see, all kinds of evidence — from atomic clocks on airplanes, rockets, and satellites to the measured lifetimes of subatomic particles and countless laboratory experiments — have borne out virtually all of Einstein's incredible predictions.

What are we to conclude from over a century of evidence confirming the predictions of relativity? Albert Einstein's strange universe is our universe!

To understand how Einstein came to develop special relativity, how a virtual unknown upstaged the most prominent physicists of his time; we first need to understand a little about the man himself, his early life experiences, his education both formal and informal, and most important — the formation of his character. Let's take a brief look.

The Early Years

Albert Einstein was born on Friday, March 14, 1879 in Ulm, a small city on the banks of the Danube nestled in the German Bundesland of Baden-Württemberg bordering Bavaria. The Einstein family was amongst the 2% of the Ulm population of Jewish ancestry. However, neither parent was particularly religious.

His mother Pauline was the 21-year-old daughter of a well-to-do wholesale grain trader. His father, 32-year-old Hermann, prided himself on being a freethinker.[8] He was, nonetheless, "exceedingly friendly and wise," his son later recalled.[9]

The easygoing Hermann was an electrical engineer who showed "a marked inclination for mathematics".[10] Pauline, on the other hand, was an accomplished pianist noted for a rather strong personality. It appears that Albert got his technical abilities from his father and his extraordinary tenacity from his mother.

Reportedly, Albert did not speak until he was three years old. Then he exhibited an odd habit of whispering to himself. "Every sentence he uttered … he repeated to himself softly," recalled his younger sister Maja (Fig. 1.1).[11] Because of this, the family maid labeled him "the dopy one."

Einstein's first encounter with science involved a pocket compass his father gave him. How, young Albert wondered, could the compass needle's direction be influenced by an invisible source, by something in empty space? "This experience made a deep and lasting impression on me," Einstein recalled.[12] "Something deeply hidden has to be behind things."

At age ten, his parents enrolled Albert in the prestigious Luitpold Gymnasium in Munich. It practiced a strict, formal, learning by rote method of instruction. Einstein hated it. He was a teacher's nightmare — smart, arrogant, bored, and stubborn, with little respect for authority.[13]

Figure 1.1. Albert with his Sister Maja.

At age 12, led by what was to become a lifelong desire to find the unity in all things, Albert studied Judaism. He became quite religious for a brief time. But then Max Talmud, a poor Jewish medical student befriended by the family, introduced Albert to popular books in science as well as texts in mathematics and philosophy.[14]

"Through reading (about science), I soon reached the conviction that much in the stories of the Bible could not be true," Albert concluded.[15] "Suspicion against every kind of authority grew out of this experience, an attitude which has never left me."[16]

At age 15, Einstein was expelled by the headmaster of the Gymnasium for disruptions in class and disrespect for teachers.[17] A year later, without completing high school, Albert took entrance exams to a teachers college in Switzerland — the Swiss Federal Polytechnical Institute in Zurich.[18] "Zurich Poly" (later the "ETH") was considered one of the top schools for training mathematics and science teachers in Central Europe.

He failed in French, chemistry, and biology — subjects he did not care to learn — but did very well in mathematics and physics. Based on this, the principal of Zurich Poly arranged for Einstein to attend a small progressive non-denominational school in Aarau, Switzerland for additional instruction. Einstein (Fig. 1.2) then retook the Zurich Poly entrance exams and was accepted in the physics/mathematics program in 1896.

What was Albert's reaction to now being in college? He complained his classes were old-fashioned — they didn't even teach Maxwell's equations, the relatively new theory uniting electricity and magnetism. So the young rebel "played hooky a lot and studied the masters of theoretical physics with a holy zeal at home," as he later put it.[19]

Figure 1.2. Young Albert Einstein.

The only thing that interferes with my learning is my education.[20]

Albert Einstein

Einstein managed to graduate from Zurich Poly with an overall grade of 4.91 out of 6.0, a low B — fifth of the six math/physics students in his class. His "dark and intense Serbian" girlfriend Mileva Maríc, the only female physics student, received the lowest grade.[21] She was not allowed to graduate.

It was now July of 1900, with the 21-year-old college graduate looking for employment.[22] Einstein's impudent classroom behavior came back to haunt him. His physics professor, Heinrich Weber, had written unfavorable references about him. Albert found himself unable to find work and in poor financial straits.

After nearly two years of searching for a job, Einstein's college friend, mathematician Marcel Grossman, came to Einstein's rescue. Marcel's father knew the director of the Swiss patent office. With his help, Einstein landed a reasonably good-paying job as a patent examiner for the Swiss government. Einstein had just what the patent office needed — a physicist who could understand inventions in the growing field of electromagnetism.

I am doing well. I am an honorable federal ink pisser with a regular salary.[23]

Albert Einstein in a letter to a friend

So here was the man who was to become the greatest scientist of our age working as a Technical Expert 3rd Class (the lowest rank) reviewing patent applications. The year was 1902 and Einstein was now 23 years old. He worked on physics in every spare moment.

"I enjoyed my work at the office very much because it was uncommonly diversified," Einstein recalled.[24] "I was able to do a full day's work in only two or three hours. The remaining part of the day, I would work out my own ideas. When anyone would come by, I would cram my notes into my desk drawer and pretend to work on my office job."

Later that year, Einstein's father Hermann died. This was "the deepest shock I had ever experienced," Einstein recalled.[25] On his deathbed, Hermann reluctantly gave his consent to the marriage of Albert and his college sweetheart, Mileva Maríc . They were wed in early 1903 — no family members attended the ceremony.

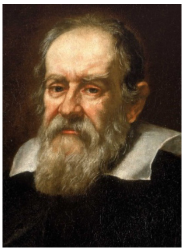
The couple settled into a quiet family life in Berne and had their first son, Hans Albert, the following year. The young father liked to make toys for his boy. Years later his son still remembered a cable car his father made from odds and ends from around the house. "That was one of the nicest toys I had at the time and it worked," Hans recalled.[26] "Out of little string and matchboxes and so on, he could make the most beautiful things."

From 1900 to 1904, Einstein managed to get five physics papers published in the German *Annuls of Physics* (*Annalen der Physik)*, Europe's leading physics journal. He wrote two of the manuscripts while working six days a week at the patent office. None were particularly noteworthy. He wrote to his sister, Maja wondering if he would ever make it.

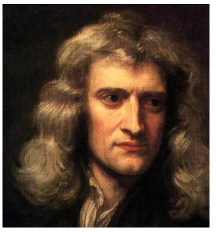
During this period, however, the seeds of great ideas were percolating in young Einstein's mind. His thinking was rooted in the major scientific questions of the time.

Physics in 1900 — The End or the Beginning?

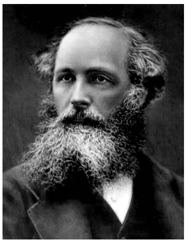
At dawn of the 20th century, physics was for the most part based on the works of three great scientists — Galileo, Newton, and Maxwell. (See Fig. 1.3.) In his treatise of 1638, the brilliant Tuscan scientist Galileo Galilei had established the science of *mechanics* — how forces affect the motion of objects. Among a number of notable achievements, Galileo provided the first formulas for how an object falls to Earth.



Galileo Galilei
(1564–1642)



Isaac Newton
(1643–1727)



James Clerk Maxwell
(1831–1879)

Figure 1.3. The Giants of Classical Physics at the Dawn of the 20th Century.

Some 50 years later, illustrious English genius Isaac Newton extended Galileo's work with ground-breaking theories in mechanics, optics, and universal gravity. Along the way he invented calculus.[27] His *Principia,* published in 1687, is considered the most influential book in the history of physics.

Nearly two centuries later, Scottish physicist James Clerk Maxwell established the third pillar of classical physics. He published his great opus uniting electricity and magnetism in 1864: his theory of *electromagnetism*.

The turn of the century (1900) was a heady time for scientists. First and foremost, there was the outstanding success of Isaac Newton's laws. The predictions of Newton's theories had proved remarkably accurate for over 200 years — from the motion of gases and everyday objects, the paths of the Sun, planets, moons, and comets, to the slightly oblate shape of the Earth and the timing of its tides.

And where Newton's laws did not work, Maxwell's theory took over. Maxwell's equations provided a solid foundation for understanding electricity and magnetism. Its predictive powers proved monumental — revealing light as an electromagnetic wave. By the end of the 19th century, the relationship between heat and energy was also well established, with significant advances in optics, chemistry, and molecular theory as well.

It appeared to some that the foundations of physics had been firmly established for all time. In 1900, physicist William Thomson aka Lord Kelvin reportedly declared: "There is nothing new to be discovered in physics now.[28] All that remains is more and more precise measurement." And when Max Planck, co-founder of quantum mechanics, first considered becoming a physicist, his advisor told him to "switch fields because physics was basically finished."[29]

There were, nonetheless, certain "anomalies" which no theory at the time could explain. In 1887, Heinrich Hertz discovered when you shine ultraviolet light on a metal surface, it loses electrical charge. No one could explain this strange "photoelectric effect". Nine years later, Henri Becquerel discovered that uranium salts emitted a continuous stream of radiation. How this so-called radioactivity worked was a mystery.

Heated objects gave off light only in specific colors, like the red glow of a hot poker.[30] No one knew why. The famous Michelson-Morley experiments failed to find the *ether*, the medium believed to be necessary for the transmission of light. And the orbit of Mercury was a tiny bit off from Newton's predictions.

And most important to our discussion here: No one could explain a stubborn disagreement between Newton's Laws and Maxwell's theory — a fundamental conflict concerning the effects of uniform motion.

Like the initial vibrations of an earthquake, the rumblings of change in the structure of classical physics had begun. Attempts in the early 20th century to uncover what was behind these anomalies would lead to a new set of nature's laws. At once strange and wonderful, these new theories would challenge our most fundamental assumptions about reality itself. They were:

- quantum mechanics.
- special relativity, and
- general relativity.

Quantum mechanics was developed by a number of physicists in the early 20th century, including Einstein. Quantum mechanics is beyond the scope of this book — it requires a book of its own. We discuss some aspects of the theory in the text and notes. Additional information can be found in the suggested reading.

Unlike quantum theory, the two theories of relativity were developed primarily by a single individual, Albert Einstein.

While cutting class and sipping coffee at cafes in Zurich — later in free moments at the patent office in Berne and at home with his wife Mileva and baby Hans Albert — Einstein pondered the physics issues of his day. He revealed the results of his contemplations in what we now call his "Miracle Year."

1905 — The Year of Einstein

In 1905, 26-six-year-old Albert Einstein published three papers in volume 17 of *Annalen der Physik* (Fig. 1.4) which would resolve conflicts in physics that had escaped all other scientists — and provide humanity with a radical new view of reality.[31] Einstein wrote to a friend that he had produced these papers in his spare time. They were:

The Photoelectric Effect — In this seminal paper, Einstein introduced the quantum theory of light to explain the puzzling results of the photoelectric effect. Based on Max Planck's formulation, Einstein made the radical assertion that light behaves like a *particle* as well as a wave. Einstein termed his proposition "very revolutionary" and it was.[32] Planck and Einstein's work gave birth to quantum mechanics — the most accurate and strangest theory in the history of physics.

Brownian Motion — Scientists had known for at least a hundred years that microscopic dust particles floating on a water surface continuously jiggle, but no one could explain why. Einstein showed this jiggling is due to the *thermal vibration* of individual water molecules — effectively confirming the existence of atoms and molecules for the first time.

Special Relativity — In this manuscript, Einstein proposed the radical notion that space and time are relative. Biographer Roland Clark called this "one of the most remarkable scientific papers ever written. . . . (it) overturned man's accepted ideas of time and space in a way which was, as *The Times* of London put it, 'an affront to common sense'."[33]

Einstein termed his relativity paper "only a rough draft at this point . . . (which) employs a modification of the theory of space and time."[34] As was typical of Einstein, he vastly understated the significance of his work.

Einstein had no laboratory. He himself did none of the experiments which he referred to in his papers. His only tools were his pencil and paper. He was a true theoretical physicist. His solutions to the photoelectric effect, Brownian motion, and relativity were generated by pure thought.

Einstein's character as well as his extraordinary technical ability played a critical role in these scientific feats. His independence, stubbornness, and rejection of prevailing thinking led to much trouble at school — but were key to his revolutionary breakthroughs.

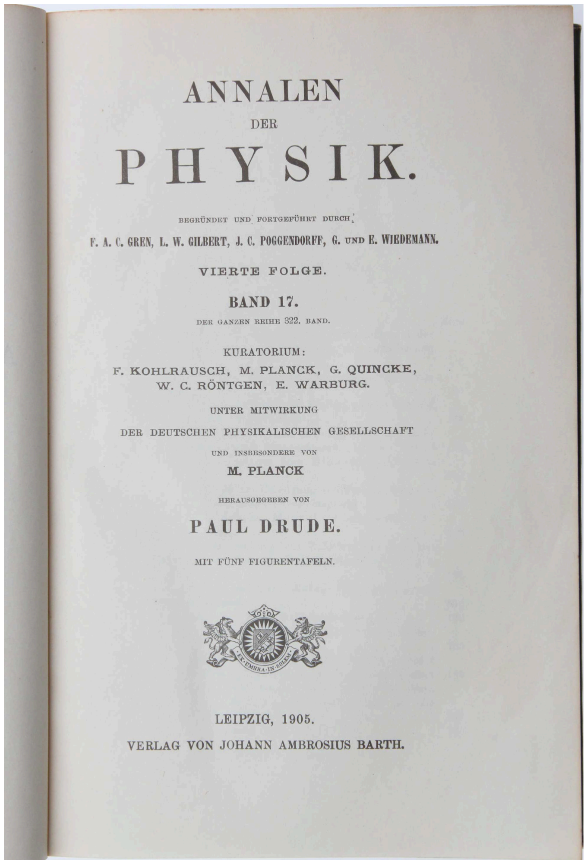

ANNALEN
DER
PHYSIK.
BEGRÜNDET UND FORTGEFÜHRT DURCH
F. A. C. GREN, L. W. GILBERT, J. C. POGGENDORFF, G. UND E. WIEDEMANN.
VIERTE FOLGE.
BAND 17.
DER GANZEN REIHE 322. BAND.
KURATORIUM:
F. KOHLRAUSCH, M. PLANCK, G. QUINCKE,
W. C. RÖNTGEN, E. WARBURG.
UNTER MITWIRKUNG
DER DEUTSCHEN PHYSIKALISCHEN GESELLSCHAFT
UND INSBESONDERE VON
M. PLANCK
HERAUSGEGEBEN VON
PAUL DRUDE.
MIT FÜNF FIGURENTAFELN.
LEIPZIG, 1905.
VERLAG VON JOHANN AMBROSIUS BARTH.

Figure 1.4. Image of first page of *Annalen der Physik* 17, which contains Einstein's famous photoelectric effect, Brownian motion, and special relativity manuscripts.

How did Einstein do it? How did a patent clerk that no one ever heard of discover the relativity of space and time? His path to special relativity began with attempts to understand the physics of Galileo, Newton, and Maxwell — their triumphs and most important, their conflicts.

This is the subject of Chap. 2.