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Feynman and His Physics

The Life and Science of an Extraordinary Man

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Jörg Resag
Leverkusen, Nordrhein-Westfalen, Germany

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Preface

If you ask people about the most important physicists of modern times, you will hear some names over and over again. Albert Einstein will certainly be there, as will Isaac Newton and Galileo Galilei. Stephen Hawking will also be known to many, for example, through his bestseller “A Brief History of Time” or the television series “The Big Bang Theory.” But where does Richard Feynman stand, the subject of this book?

At the turn of the millennium, the well-known physics portal “Physics World” of the British Institute of Physics (http://physicsworld.com/) has asked for the ten best physicists of all time. Here is the result[1]:

1. Albert Einstein	Special and General Theory of Relativity
2. Isaac Newton	Laws of Motion and Gravitation
3. James Clerk Maxwell	Equations of Electrodynamics
4. Niels Bohr	Quantum Mechanics, Bohr Model of the Atom
5. Werner Heisenberg	Quantum Mechanics, Uncertainty Principle
6. Galileo Galilei	Law of Inertia, Falling Bodies, Refracting Telescope
7. Richard Feynman	Quantum Electrodynamics, Feynman Diagrams
8. Paul Dirac	Quantum Mechanics, Dirac Equation
9. Erwin Schrödinger	Quantum Mechanics, Schrödinger Equation
10. Ernest Rutherford	Rutherford Model of the Atom, Gold Foil Experiment

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[1] See, e.g., CERN Courier of Jan 26, 2000, http://cerncourier.com/cws/article/cern/28153.

Other names such as Enrico Fermi, Max Planck, or Michael Faraday would have deserved a place here as well. Stephen Hawking does not appear in the list—maybe it is just too early to assess his contribution to physics correctly.

Most people will probably not be surprised that Albert Einstein is at the top. At the beginning of the twentieth century, he influenced physics like hardly anyone else, revolutionizing our views on the nature of space and time and revealing their deep connection to gravity. His Special and General Theory of Relativity forms the basis of modern physics.

Isaac Newton and James Clerk Maxwell are also clearly among the leaders. They formulated the basic laws of motion, gravitation, and electromagnetism and thus laid the foundations for the whole of classical physics.

Other names are closely associated with the development of quantum mechanics, which challenged our physical worldview in the 1920s and continues to do so today. Along with the theory of relativity, quantum mechanics is the second cornerstone of modern physics – and we will encounter both of them on many occasions in this book.

The most recent physicist in this list is ranked seventh (see Fig. 1). It is Richard Feynman! This position is certainly a dream result if you have to compete with geniuses like Einstein, Newton, or Maxwell.

Richard Feynman (Fig. 2) was one of the most remarkable and famous physicists in the mid- and late twentieth century. On the one hand, this was due to his outstanding achievements in physics, to which we will return in detail in this book. Feynman belonged to the first generation of young

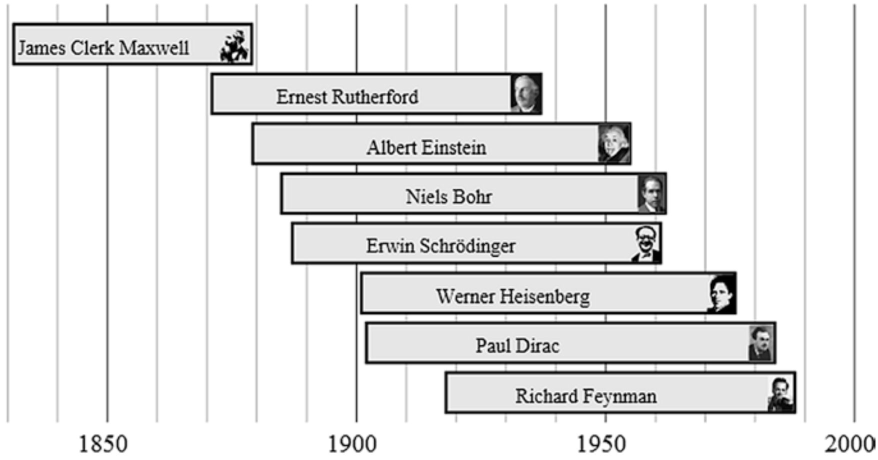

Fig. 1 Lifetimes of the most famous physicists since 1830

Fig. 2 Richard Feynman in 1984 @ Tamiko Thiel, CC-BY-SA 3.0 Unported

physicists who were already familiarized with quantum mechanics during their studies. Prepared in this way, he and some of his colleagues later succeeded in overcoming the enormous difficulties that arose in combining Einstein's Special Theory of Relativity with the principles of quantum mechanics. While his colleagues mostly relied on abstract mathematical formalisms, Feynman followed a more intuitive approach that was typical of him. Based on his own vivid idea of the quantum behavior of particles, he created a completely new formulation of quantum theory which has become the standard tool in relativistic quantum theory today: path integrals and Feynman diagrams. Together with Julian Schwinger and Shinichirō Tomonaga, he received the Nobel Prize for physics in 1965.

But Feynman was not satisfied with that. He was interested in many aspects of physics and was reluctant to commit himself to a single specialty. With his physical intuition, his mathematical abilities, and his deep understanding of quantum theory, he was also able to lead the way in other areas of physics, for example, in the physics of low temperatures (superconductivity and superfluidity). Regarding the so-called weak interaction that triggers, among other things, the radioactive beta decay of atomic nuclei, he and others explained how nature violates the law of reflection symmetry – nature fundamentally distinguishes between right and left! In particle physics, he showed how the data for the scattering of high-energy electrons on protons could be explained by the fact that the electrons were deflected by point-like particles within the protons (partons or quarks).

Throughout his life, Feynman was always interested in computers and the physical foundations of computation, and he later brought quantum mechanics into this field. Today, quantum computers have become an active area of research. He was also one of the first to attempt a quantum description of gravity, i.e., a quantization of Einstein's theory of General Relativity. Even today, this is probably the biggest unresolved problem of physics. A host of physicists are struggling with this, for example, in the context of string theory or loop quantum gravity or as experimenters at large-scale particle accelerators such as the LHC at CERN in Geneva.

But Feynman was not only a great physicist. Much of his fame and popularity can be traced back to his unusual personality. He was an unconventional, cheerful person – more of an eccentric freethinker than the typical, old-fashioned university professor you would often imagine. In addition to his passion for physics, he liked to visit strip clubs and play bongos and later discovered a love for drawing and painting. Unlike some of his colleagues, he had no interest in the emblems of power, whose pompous display he disliked. He also loved getting to the bottom of things and working on a problem until he finally found the solution. He had no problem admitting his own mistakes and hated it when others were not willing to do so, out of vanity or stubbornness. His motto was: "The first principle is that you must not fool yourself – and you are the easiest person to fool."[2]

Feynman was a charismatic speaker and had a talent for dramaturgy, with which he was able to fascinate and inspire his audience. He could captivate you with his humorous and passionate manner, so that in the end you had the feeling of having understood something important – even if you could not always remember exactly what it was.

On the Internet, you can find many videos showing Feynman in action, so that even today you can get an idea of his stirring style of lecture. Bill Gates, the founder of Microsoft, has purchased the BBC videos of seven Feynman lectures and made them freely available to everyone on the Internet at http://research.microsoft.com/apps/tools/tuva/. Feynman gave the lectures in 1964 under the title "The Character of Physical Law" as part of the Messenger Lectures at Cornell University. Take a look at them – the lectures are a real pleasure!

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[2] See Feynman: *Surely You're Joking, Mr. Feynman!*

Many of Feynman's lectures were also written and published in book form. Even today, his "Feynman Lectures on Physics" from 1961 to 1963 are a treasure trove for every physics student and lecturer. Feynman's deep enthusiasm for physics is clearly visible there. He rethinks all aspects of physics in his own refreshing way, revealing some insights that cannot be found in other standard physics textbooks. No wonder the Feynman lectures are still being printed and purchased, even after more than half a century, something that hardly any other physics textbook can claim.

Feynman's personality predestined him for a task which he tackled with much energy in his later years, at a time when he was fighting against cancer, and which made him known to the general public: his work on the commission to understand the Challenger explosion in January 1986, when all seven crew members of the Space Shuttle died, shortly after the launch. Unlike some of his colleagues on the commission, who spent more of their time in meetings, he went directly to NASA's technicians and engineers and soon discovered the cause of the explosion: a rubber gasket (called an O-ring) that had lost its flexibility in the frosty weather of the launch day, allowing hot gas to escape. The pictures are unforgettable: Feynman dipped such a sealing ring into a glass of ice water in front of the cameras and made it clear to everyone where the problem lay.

Several books have already been written about Richard Feynman's life, along with countless anecdotes – some of which he even wrote himself. This book is therefore not intended to be another comprehensive Feynman biography. Of course, Feynman's life will also play a role in this book and serve as a guide. But the focus will be on what Feynman himself loved so much: physics!

We will try to understand why physics was so fascinating to Feynman and what ideas he and his colleagues actually contributed to it. In doing so, we will focus heavily on one of the fundamental pillars of modern physics, which Feynman quite rightly said nobody understands: quantum mechanics. Of course, this does not mean that we do not have a precise theory of how quantum mechanics works – Feynman himself made important contributions to this. It just means that nobody knows why it works just like that, testing our imagination to the extreme. "But how can it be like that?" asks Feynman in his 1964 Messenger Lectures, illustrating our futile attempt to grasp quantum mechanics with the concepts we are familiar with. Of course, the present book cannot solve this problem, but we can at least try to understand how quantum mechanics works and what is so strange about it.

Our aim is to follow Feynman's path through physics and see how he combined quantum mechanics and relativity theory and how he described antiparticles, the weak interaction, or ice-cold superfluid helium using quantum theory, but also what he thought about nanotechnology and future computers. In doing so, we will encounter a multitude of topics that are fundamental to our current understanding of the laws of nature, and we will thus learn a great deal about the modern worldview provided by physics. We will almost completely dispense with mathematical formulas – sometimes, they are shown in separate boxes and can be skipped without affecting the overall understanding. On the other hand, these boxes will offer the interested reader the opportunity to delve a little deeper into the topic at one point or another.

Feynman would have been one hundred years old in 2018 if his illness had not taken him from us thirty years previously. I hope that, in his honor, I will be able to convey some of the fascination he felt when dealing with physics, which he expressed in the following words from his Messenger Lectures in 1964:

> Our imagination is stretched to the utmost, not, as in fiction, to imagine things which are not really there, but just to comprehend those things which are there.

I would like to take this opportunity to thank Lisa Edelhäuser of Springer Spektrum. It was on her initiative that the German edition of this book about the life and science of Richard Feynman was published again in a new form on his one-hundredth birthday. She worked through the manuscript page by page and made decisive contributions to the success of this complex project with her many constructive suggestions. Bettina Saglio accompanied the finished manuscript to print and discovered many beautiful graphics for the book. Many thanks also to Angela Lahee and Stephen Lyle, who made the English edition of this book possible. And finally, I would like to thank my dear wife Karen and my sons Kevin, Tim, and Jan for their support and patience when the book project took up much more of my time than planned.

Leverkusen, Germany
June 2018

Jörg Resag

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Adolescent Years and the Principle of Least Action

These were troubled times when Richard Phillips Feynman was born in New York on May 11, 1918. In Europe, the First World War was still raging and had already cost the lives of countless people. The United States had entered the war about a year earlier (in April 1917), and this would ultimately lead to victory over Germany, although it would still take until November 1918 before the war was brought to an end. Fortunately, Feynman's family was not directly affected by the war.

The early twentieth century was also an eventful time in physics. Albert Einstein (Fig. 1.1) had formulated his Theory of Special Relativity in 1905, fundamentally changing our understanding of space and time. Ten years later (in 1915) he succeeded in demonstrating in his Theory of General Relativity that gravity can be modelled by the curvature of space and time. Even light would be influenced by this curvature and deflected from its straight line by gravity, as he predicted. In May 1919, when a total solar eclipse showed that the light of a star was indeed deflected by the sun's gravitational field, Einstein became famous overnight. Feynman had just turned one year old at the time.

Einstein's Theories of Special and General Relativity were not the only milestones at that time. First results indicated a further revolution in physics, whose full potential would be revealed several years after Feynman's birth and which would become the basis for Feynman's own work: quantum mechanics. A groundbreaking discovery was made by the German physicist Max Planck (Fig. 1.2) in 1900: atoms can only emit or absorb light in certain energy packages (quanta). It was in 1918, the year of Feynman's birth, that Planck was awarded the Nobel Prize for physics for his discovery, which was certainly not a matter of course for a German, given the Kaiser's policy of conquest during the war.

J. Resag, *Feynman and His Physics*, Springer Biographies,
https://doi.org/10.1007/978-3-319-96836-0_1

Fig. 1.1 Albert Einstein (1879–1955) in 1921 (from The Scientific Monthly 12:5, p. 483), https://commons.wikimedia.org/wiki/File:Albert_Einstein_photo_1921.jpg

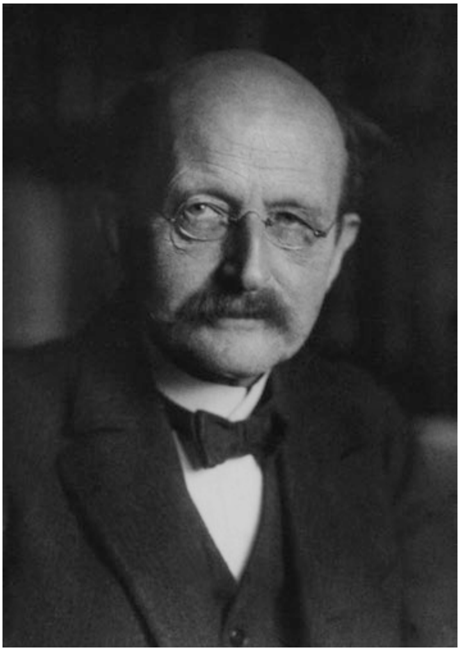

Fig. 1.2 Max Planck (1858–1947). (© akg images/picture alliance)

Planck himself considered the energy quanta to be nothing more than mathematical variables in emission and absorption processes, without any physical reality in themselves. But in 1905 Albert Einstein recognized that these abstract quanta had to be real particles of light, later to be given the name photons. This was the only way to explain, for example, how light in the so-called photoelectric effect could knock out individual electrons from metal surfaces: the photons literally kick them out of the metal.

Light thus consists of particles, but can behave like a wave in many cases. This gives a first taste of the apparent contradictions we have to be prepared for here! Einstein received the Nobel Prize for his photon hypothesis in 1921 – three years after Max Planck. Interestingly, he did not receive the Nobel Prize for his Theories of Special and General Relativity, which made him famous – apparently the Nobel Committee did not consider these revolutionary theories to be sufficiently proven at that time.

So this was the world into which Richard Feynman was born about a century ago and in which he grew up. Feynman had a wonderful childhood and from an early age his father awakened in him a deep enthusiasm for the natural sciences. Not surprisingly, Feynman studied physics at the renowned MIT (Massachusetts Institute of Technology) in Boston. There he encountered two closely related physical principles that are much older than relativity theory and quantum mechanics: Fermat's principle and the principle of least action. They exerted a great fascination on Feynman and would later form the basis for his new view of quantum mechanics.

1.1 Childhood, High School and MIT

Richard Feynman was born on May 11, 1918 in Far Rockaway, a small town in the New York borough of Queens, near the sea on the southern tip of Long Island. Here he spent most of his childhood and youth, which explains his typical New York accent. His physicist colleagues Wolfgang Pauli and Hans Bethe later put it this way: "Feynman spoke like a bum".[1]

Feynman's parents Melville and Lucille were both of Jewish origin. Their families came from Eastern Europe. Melville's parents came from Lithuania and had lived in Minsk (Belarus) before emigrating to the USA in 1895, when Melville was only five years old. Lucille was born that same year in the USA. Her parents had already come to the USA as small children from

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[1] See Sykes (1994): *No ordinary genius: the illustrated Richard Feynman*.

Poland and had achieved some prosperity there, so that they were able to acquire a large house in the then still rural Far Rockaway.

For many years this house was also the home of Melville and Lucille with their little son Richard. They shared it with Lucille's sister Pearl and her family for financial reasons. So Feynman grew up with his older cousin Robert and his younger cousin Frances. Lucille gave birth to another son when Richard was five years old, but he died after just one month. It took another four years before Richard's little sister Joan was born on March 31, 1927. Despite the large age difference of nine years, a close bond developed between the two siblings.

Not much is known about Feynman's mother Lucille and her relationship with her son. She must have been a very humorous and warm-hearted woman who, like her son, loved to tell stories. Feynman once said that he learned from his mother that the highest form of knowledge is laughter and compassion. When Feynman was already a famous Nobel Prize laureate and was named *the world's smartest man* by Omni magazine in 1979, she said: "If that's the world's smartest man, God help us". However, she never had much to do with the natural sciences.

Feynman's Father Melville and His Passion for Natural Science

Feynman's father Melville, on the other hand, loved the natural sciences, but had never had the financial means to begin his studies. He wanted to give his son this opportunity, so he did everything he could to inspire him with the secrets of nature and introduce him to scientific thinking. He bought the Encyclopaedia Britannica, put little Richard on his lap, and read to him from it. But he not only read aloud. He also explained what it meant. For example, if it said how big a brontosaur was, he imagined together with Richard what would happen if the dinosaur stood in the front yard of their house. It would be big enough to put its head through the window – only such a huge head would break the window.

Melville also taught his son to keep an independent mind and not be impressed by authorities and their symbols of power. Since Melville was in the uniform business, he knew the difference between the man with the uniform off and the man with the uniform on: it was the same man. In an interview with the BBC in 1981, Feynman tells one of his typical anecdotes in this context[2]:

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[2] See also: *The Pleasure of Finding Things Out*.

> One day his father showed him a picture in the New York Times. It showed people bowing in front of the Pope – and Melville was not particularly keen on the Pope. So he asked his son what was so special about this man that made all the others bow before him. And he explained that the difference lay in the hat he wore. Otherwise, he had all the same worries as anyone else: he had to eat and drink and go to the bathroom. He was only human. So it was only his position and his special clothes that made him stand out, nothing particular about what he did or his honourable character.

There are other anecdotes about the way Melville introduced his son to the world and its secrets. Physics was part of this, at least as far as Melville had knowledge of it. One day, for example, the phenomenon of inertia came up. Richard had noticed that a ball would roll to the back of a wagon when the latter was suddenly pulled forward. But Melville showed him that in fact the ball hardly moved – it was actually the back of the wagon that had approached the ball. The young Richard was fascinated, and indeed, if he looked closely, he could see that his father was right. "Why is that?" he asked him. "That nobody knows!" his father replied. "The general principle is that things that are moving try to keep on moving and things that are standing still tend to stand still unless you push on them hard. This tendency is called inertia but nobody knows why it's true!" This was exactly the way in which Feynman himself later approached the mysteries of nature. The term *inertia* alone says little – it's just a name.

Feynman enjoyed these conversations with his father. Many years later, in *The Pleasure of Finding Things Out*, he said: "So that's the way I was educated by my father, with those kinds of examples and discussions, no pressure, just lovely interesting discussions." What a wonderful way to grow up, especially for such an intelligent and inquisitive boy as Feynman.

Joan – Feynman's Talented Sister

Feynman's nine-year-younger sister Joan also developed into a very bright and intelligent child with similar interests to her elder brother. In an intelligence test at high school, she scored 124 points, while her brother scored 123 points – one point less, as Joan jokingly remarked[3]: "So I was actually smarter than he was!" These IQ scores were certainly good, but not exceptional. In later years, Feynman used this result to reject an offer of

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[3] See, e.g., Sykes, Christopher: *No Ordinary Genius: The Illustrated Richard Feynman*.

membership from the high IQ society MENSA: he said his IQ was just not high enough. In truth, to Feynman's eyes, this was an elitist club, membership being based on having a certain minimum IQ, and it represented exactly the kind of pompous snobbery he loathed.

It was not easy for Joan to develop her talents. Unfortunately, in the early twentieth century, many still held that the female brain was not naturally suitable for anything as demanding as the natural sciences. Joan's mother Lucille also shared this view. Although from today's point of view it appears completely absurd, it was quite common at that time. And Lucille herself was by no means behind the times in this regard – as a young woman, she had marched for women's suffrage, as Joan's son Charles Hirshberg tells in *My Mother, the Scientist*. When eight-year-old Joan announced that she intended to be a scientist, Lucille replied: "Women can't do science because their brains can't understand enough of it." That came as a major blow to Joan. Her dream to become a scientist seemed to be impossible, and even many years later she still had doubts about her abilities.

Other women also suffered from such prejudices. Some were nevertheless successful. For example, the Austrian nuclear physicist Lise Meitner was involved in the discovery of nuclear fission around 1938, and Marie Curie, a native of Poland, had even received two Nobel Prizes (in physics for the discovery of radioactivity in 1903 and in chemistry for the discovery of the radioactive elements radium and polonium in 1911). In 1918, the year Richard was born, the then 36-year-old German mathematician Emmy Noether found a deep connection between symmetries and conservation laws (Noether's theorem, see Infobox 1.1). Among other things, this answered the question of the origin of inertia, at least in a certain sense. But to Joan, these women seemed to be of another world – and impossible to emulate.

Infobox 1.1: Noether's Theorem and the Origin of Inertia

In 1918, the German mathematician Emmy Noether proved the following fundamental connection:

> Every continuous symmetry of a physical system corresponds to a conservation law.

The term "symmetry" means that we can do something to a physical system without changing its physics. For example, we could move our Solar System to another place in the universe and everything would remain the same, because it doesn't matter where exactly the Solar System is located. The laws of physics are, as far as we know, the same everywhere in the universe. According to Noether's theorem, there must be a corresponding physical quantity that does not change over time and is therefore referred to as a conserved quantity. For the "translation symmetry in space", this conserved quantity is simply the total momentum of the Solar System, i.e., the total momentum of the Sun, planets, and all the other bodies in the Solar System taken together.

Emmy Noether thus taught us that the conservation of momentum is a consequence of the translation symmetry of our world. And conservation of momentum means that there is no change of momentum and therefore no change of velocity without there being some external cause. So our Solar System as a whole would just glide through space at a steady speed and in a fixed direction if there were no external forces acting on it. This is exactly the principle of inertia that Feynman's father explained to him using the example of the ball in the wagon. And Emmy Noether thus discovered a deeper reason for this principle through her theorem.

There are other symmetries and conserved quantities. For example, one could stop the Solar System in thought and let it continue to run later – physics would be the same, because it doesn't depend on the exact moment in time. According to Noether's theorem, it follows that the total energy of the Solar System does not change. Furthermore, the Solar System would not change fundamentally if it were rotated or tilted a few degrees – and so it follows that the so-called angular momentum of the Solar System as a whole remains constant.

For the proof of Noether's theorem one needs the principle of least action, which we will soon encounter. In his popular lecture *Symmetry in Physical Law* in the series *The Character of Physical Law*, Feynman outlines the idea of proof.

So Joan didn't get the same attention from her father as her brother Richard, at least when it came to science. But Richard filled this gap by explaining to his little sister all the wonderful things his father had taught him. Joan would later describe herself as Richard's first student.

One night Richard woke his sister to show her a magnificent light in the sky: it was the aurora borealis! This was a key experience for Joan. It was at this moment that the desire to become an astronomer and deal with celestial phenomena began to take shape in her mind. So Richard gave her an astronomy textbook for her fourteenth birthday, and she worked through it page by page. On page 407, she finally came across a figure that particularly caught her attention. It carried the caption: "Relative strengths of the Mg^+ absorption line at 4481 angstroms … from *Stellar Atmospheres* by Cecilia Payne". There it was: Cecilia Payne! This proved that it was possible: even a woman could become an astronomer!

But it was not easy for Joan to establish herself against all the prejudices then prevalent in science, and she had to fight much harder than her brother to gain a place in this world. But in the end she succeeded, and the solar wind and its interaction with the Earth's magnetic field became one of her main themes. And so it was that the aurora, which Richard had shown her as a child, eventually had its effect. She made a lifelong agreement with her brother: she would leave all other topics to him if only he would leave her the Northern Lights. She wanted to keep this topic all to herself without her clever brother interfering, and he stuck to that agreement.

As Richard grew older, his father's stories were often not enough for him. At about eleven years of age, he set up his own little laboratory at home, and often used it to prepare delicious French fries, as he recounts in *Surely You're Joking, Mr. Feynman*. He loved radios and experimented with their electrical circuits. Eventually, he even earned some money repairing these devices. And his little sister Joan was allowed to join in – Richard paid her 2 cents a week for her help. Apparently, Joan was not only his first student, but also his first assistant.

High School Days

At the age of 13, Feynman went to Far Rockaway High School, which he attended from 1931 to 1935. Like many other gifted children, he was often under-challenged and bored. He learned most not from school lessons, but from books or conversations. Some of the teachers who recognized his talent helped him to do so, for example by lending him advanced math books. Feynman loved these books and his mathematical knowledge was soon far superior to that of his peers. He became the star of the school's **competitive** mathematics group and even won the New York University Math Championship in his last year at high school. In doing so, Feynman benefited from an ability that was also essential for his later success: he did not have to work strictly according to a scheme like many of his fellow students in order to solve a problem. On the contrary, he was not keen on such predefined solutions and always tried to understand and deduce everything from scratch. With his mathematical intuition, he was often able to guess in situations where others were calculating according to some predetermined scheme. Feynman was reluctant to follow fixed rules, even in mathematics.

All in all, his interest was rather one-sided: he loved mathematics and the natural sciences, but had little to do with the humanities, English, religion, or even philosophy. From his point of view, these subjects had little substance. In his youth, Feynman did everything he could to keep contact with these disciplines to a minimum.

In his last year at high school, Feynman was lucky enough to have a young physics teacher who had just arrived at the school: Abram Bader.

He had previously worked on his doctoral thesis with the well-known physicist Isidor Isaac Rabi, but because of the global economic crisis he had run out of money. It was bad luck for Bader, but good luck for Feynman!

Bader realized that Feynman was bored with physics classes. So after one physics lesson he took him aside to introduce him to a particularly interesting physical concept, which unfortunately had no place in normal school lessons: the principle of least action. In Feynman's Lectures on Physics, Feynman deals with this topic in Vol. II, Chap. 19, where he recalls: "Then he told me something which I found absolutely fascinating, and have, since then, always found fascinating. Every time the subject comes up, I work on it."

We will take a closer look at the details of this principle later on, but the basic idea is amazingly simple. Here it is. Imagine a stone moving from one place to another in a gravitational field, which would of course take a certain amount of time. We can calculate its motion step by step using Newton's law if we know its initial speed. However, we can also consider imaginary trajectories between the two places, which take just as long, but do not obey Newton's law of motion. These imaginary motions would therefore not be "chosen" by the stone. Nevertheless, we can still ask ourselves what it would mean if it were to be guided along such a path as if by magic.

We can calculate the kinetic energy at every moment on the path and subtract the potential energy, no matter whether it is a real or imaginary motion. We can then sum these energy differences up (more precisely, we integrate them) over the entire time along the whole path. For each of the motions (imaginary as well as real) we get a number, which is called the *action* of the motion. (This is a somewhat confusing term, but it is just a name for the number we calculate for each motion.) And here it comes: the action we get for the imaginary motions is always bigger than the action for the physical motion, which corresponds to Newton's law. Nature always chooses the motion with the smallest action!

Apparently, we can find the right motion without Newton's law, by searching for the one with the smallest action. This is amazing, because at first glance the two descriptions do not seem to have much in common. It even turns out that all the fundamental laws of nature known today can be described by a suitable action, and this suggests that the principle of least action must have a very fundamental character in nature. But how does nature actually find the path with the smallest action? Does the flying object somehow smell the action of the imaginary paths and then choose the one with the smallest action? Well, as we shall see, this idea is not so far from the truth!

Arline, the Love of His Life

In addition to this experience, which would have a decisive influence on his later scientific work, there was another encounter in Feynman's high school years that would strongly influence his life outside of physics: he got to know Arline Greenbaum (often misspelled "Arlene"). She became the great love of his life, but unfortunately their relationship would come to a tragic end, for Arline died of tuberculosis on June 16, 1945, at the age of only 25 years (Fig. 1.3).

Arline was a pretty girl with long hair who lived not far from the Feynman's. She was very popular with the boys in Far Rockaway and many would have liked to go out with her. In the end, however, it was Richard, who managed to win her heart, even though he was a bit shy as a young man. At first glance, they didn't seem to fit together so well: Arline was cultivated, liked playing the piano, danced, drew, and took an interest in literature and art – all the things that Richard tended to avoid. And yet they were

Fig. 1.3 Richard and Arline (© Emilio Segre visual Archives/American Institute of Physics/Science Photo Library)

soul mates, complementing each other in a wonderful way. They both loved life and faced the world with an unconventional mixture of adventure and open-mindedness. Arline's favorite remark was: "What do you care what other people think?" – a phrase that later became the title of Feynman's last autobiographical book. With this remark she provided Richard with encouragement when he was uncertain and came into conflict with established ideas. He would need this support when he later began to go his own way, and Arline's dictum continued to do its work in Feynman's mind long after she had died.

Going to MIT: Feynman Learns Quantum Mechanics – And We Can Learn with Him

In the summer of 1935, Feynman's high school years came to an end. In almost all subjects he had passed with distinction, even in English, which was not his favorite subject. His parents were determined to give him a college education – an opportunity that Feynman's father Melville had never been fortunate enough to have. However, Columbia University in New York rejected Feynman's application despite his excellent grades, because it had already used up its quota of Jewish students. It is hard to believe that there was such a thing back then, but anti-Semitism was still widespread at that time. Feynman had more luck at MIT (Massachusetts Institute of Technology) in Cambridge, near Boston, and even received a small scholarship of $100 a year.

So in the fall of 1935, at the age of 17, Feynman drove to Boston, about 350 km northeast of New York. Or rather, he was picked up by some fellow students who hoped he would join their student association. A fellow student as talented as Feynman was in great demand, and Feynman was flattered: "It was a big deal; you are grown up!"

Initially, Feynman had enrolled in mathematics at MIT, but he soon realized that this was too theoretical for him. So he changed his mind and tried electrical engineering, but that was too practical. Eventually, he found the golden mean: physics. Here he felt at last that he was in good hands.

During the 17 years since his birth, physics had developed enormously. Within the framework of quantum mechanics, it was finally understood how electrons move in the shells of atoms. Quantum mechanics had thus become the fundamental theory of the subatomic world, and Feynman and his fellow students had the opportunity to get to know this new theory in some detail during their studies. So let's begin by taking a closer look at what quantum mechanics is all about.

The first important finding was that the electrons in the atom do not move on fixed orbits around the atomic nucleus, as proposed by the Danish physicist Niels Bohr in 1913. Rather, they had to be described by waves, as the French physicist Louis de Broglie pointed out in his famous doctoral thesis in 1924. Just as light waves are composed of special particles (photons), electrons are also related to certain electron waves, according to the same formulas:

$$E = h \cdot f$$
$$p = h/\lambda.$$

Particles with high energy E thus belong to waves with high frequency f, where a large particle momentum p leads to a short wavelength λ. The conversion factor between particle and wave properties is given by the Planck constant h – a fundamental physical constant whose value must be determined by experiment. And these relations actually apply quite generally to any object in the quantum world, no matter whether it is a photon, an electron, or a proton.

The most common symbol for the electron wave (which is also often called the *wave function*) is the Greek letter ψ. In many cases it is sufficient to imagine this electron wave as being similar to a water wave. Positive values of ψ stand for a wave peak and negative values for a wave trough.

If one wants to be mathematically correct, the values of the electron wave are not actually simple positive or negative numbers, but complex numbers. These can be imagined as arrows or clock hands in a two-dimensional plane (see Fig. 1.4).

But what is such a strange electron wave supposed to mean physically? We already know that wavelength and wave frequency determine the energy and

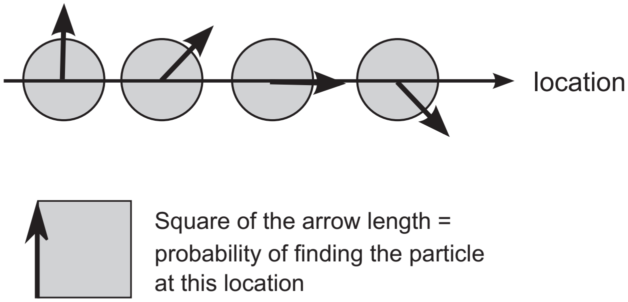

Fig. 1.4 Snapshot of a quantum wave. The values of the wave function at individual locations can be pictured as given by rotating arrows or clock hands

momentum of the particle. But where is the particle? A wave is a spatially extended object, while a particle should always be in a certain place!

The solution to this problem is both ingenious and strange: it is precisely this demand that is dropped, that a particle always stays in a certain place and that it moves on a certain path. Instead, one goes to a description by probabilities, where the square $|\psi|^2$ of the wave function – i.e., the squared height of the quantum wave or, more precisely, its squared arrow length – indicates the probability of finding the particle at the corresponding location. In other words, as long as the location of the particle does not leave any detectable traces in our world, it is basically indefinite. In a way, the particle itself does not know where it is. Only when a sufficiently sensitive interaction with the environment (or a measuring device) takes place does it make sense to speak of a particle location. It is exactly then that the probability interpretation of the wave function takes effect.

We may of course ask why we need a quantum wave at all. Why do we not work with probabilities right away? The reason for this is that the wave crests and troughs of a quantum wave can erase each other when they meet, while two probabilities always add up to a greater overall probability. This phenomenon, known as interference, will be of great importance to our discussion later on.

Why is it that in quantum mechanics the concept of probability suddenly comes into play? We don't actually know. This is one of the greatest mysteries: why do we have to deal with probabilities in a theory that we still consider fundamental today? Randomness seems to play a fundamental role in nature. If you do not want to believe this, you are in good company, because Albert Einstein also had his doubts, expressing them in his famous remark: "God does not throw dice". But for all we know today, God does indeed seem to throw dice. In his 1979 lecture on quantum electrodynamics (QED) at the University of Auckland (New Zealand), Feynman expressed this idea in the following way[4]:

> If you want to know how nature works, we looked at it, carefully. Looking at it, that's the way it looks. You don't like it? Go somewhere else, to another universe where the rules are simpler, philosophically more pleasing, more psychologically easy. I can't help it, okay?

This is typical of Feynman. It is not our desires that are important, but only reality – no matter what we think of it. And yet the fundamental

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[4] A very entertaining video can be found, for example, at https://www.youtube.com/watch?v=iMDTcMD6pOw

role of randomness in quantum mechanics remains strange and is still not well understood today. Feynman also admits this when he says elsewhere: “Nobody understands quantum mechanics!”

In 1926, the Austrian physicist Erwin Schrödinger formulated the basic quantum mechanical wave equation, a differential equation that can be used to calculate the evolution of wave functions. And it turned out that the results obtained with the Schrödinger equation were in perfect agreement with experiment, so physicists knew they had found the right approach to the atomic world.

The theory of quantum mechanics founded by Louis de Broglie, Niels Bohr, Erwin Schrödinger, Werner Heisenberg, and many others was to develop quickly (see Fig. 1.5). In the end, a fundamental theory was built up, describing nature on the microscopic level. The structure and properties of atoms, molecules, solids, and much more could be calculated, at least in principle. The Special Theory of Relativity was also included shortly afterwards, when the British physicist Paul Dirac established his famous Dirac equation in 1928. It was also Paul Dirac who published the first comprehensive textbook on quantum mechanics in 1930: *The Principles of Quantum Mechanics*. And using this, Feynman and his fellow students became the first generation of physicists to be introduced to the new quantum mechanics as part of their studies.

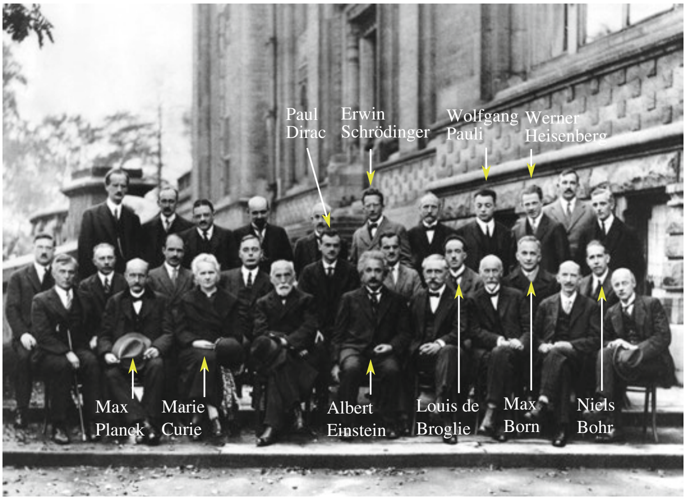

Fig. 1.5 Participants at the Solvay Conference on Quantum Mechanics 1927. Photograph by Benjamin Couprie, Institute International de Physique Solvay, Brussels, Belgium

Feynman, the Free-Thinker

As in high school, Feynman learned a lot from books and from working with other talented students at MIT. He was interested not only in physics, but also the other natural sciences, such as chemistry and metallurgy, and passed all his science exams with very good results. One problem, however, was the humanities subjects and languages, of which he had to take three. Fortunately, astronomy was one of them – that was fine with him. English was compulsory, and as the third subject he chose philosophy, which he didn't like at all. The lectures at MIT only deepened his natural aversion and strengthened his conviction that philosophy was just meaningless verbiage. Later, as an established physics professor, he would gladly use every opportunity to knock the philosophers.

Feynman's intellectual independence was also illustrated by his refusal to solve mechanical exercises using the Lagrangian method (see Infobox 1.2). He insisted on applying the original Newtonian law of motion and splitting all the forces into different proportions to suit the problem at hand. The Lagrangian method already incorporates this maneuver, so the solution can be approached schematically. But that was obviously not interesting enough for Feynman. Perhaps he was not aware at that time that the Lagrangian method was closely related to the principle of least action that had fascinated him so much at high school – otherwise he might have shown greater interest in this elegant method. But instead, he preferred to train his physical intuition rather than calculating in this schematic way. He would ponder over a task in a highly concentrated manner and try to illuminate it from various angles until he had the solution. Indeed, he would often guess the solution and only check its correctness afterwards. These are exactly the qualities that a great physicist should have, and that the young Albert Einstein, for example, also possessed.

Infobox 1.2: Lagrangian Method

In 1687, Isaac Newton established his famous law of motion, which says that *force equals mass times acceleration* or $F = m \cdot a$ in the obvious notation, and thus laid the foundations of mechanics. He and Gottfried Wilhelm Leibniz also independently invented the infinitesimal calculus, i.e., the differentiation and integration of functions, and thereby created a powerful mathematical tool that led to rapid developments in mathematics.

To be able to apply Newton's law of motion, Cartesian coordinates x, y, and z are usually used in three-dimensional space. However, these orthogonal coordinates are often not well adapted to the physical problem, resulting in quite complicated equations. For example, for the orbit of a planet around the Sun, it is much easier to use its distance from the Sun and an angle variable indicating its position on the orbit. Instead of working with *x, y,* and *z,* it's better to work with distances and angles, which are examples of generalized coordinates. However, some effort has to be put into express Newton's law of motion for a planet in terms of distances and angles – and that was exactly the way Feynman loved to work.

About 100 years after Newton, the French mathematician Joseph-Louis Lagrange succeeded in finding a general method for establishing equations of motion in arbitrary coordinates – the so-called Lagrangian method. For example, when a planet moves around the Sun, this method provides the equations of motion directly in the desired form, i.e., expressed in terms of the planet's distance from the Sun and its angle variable.

In principle, the method works as follows:

1. We introduce time-dependent coordinates and associated velocities that are adapted to the problem (e.g., distance and angle variables together with their rates of change).
2. We now express the kinetic energy T and the potential energy V in terms of these coordinates and velocities and form the difference $L = T - V$, which is called the *Lagrangian*.
3. The equations of motion for each of the coordinates are now obtained in this way:

- For each individual coordinate, we form the derivative of the Lagrangian L with respect to the coordinate velocity and then with respect to time t.
- We then set the result equal to the derivative of L with respect to the corresponding coordinate.

If you feel your mathematics is up to it, you can test this procedure yourself using the simple example of the spring pendulum. But first of all, let's proceed in the conventional way. In such a pendulum, a mass m hangs on a spring with spring constant D and is set into vertical oscillation (see Fig. 1.6). The spring pulls the mass back in the direction of the resting position with the force $F = -D \cdot x$, where x is the distance from the resting position (so that $x = 0$ in that position). If we use this force in Newton's law of motion, we obtain the equation of motion

$$m \cdot a = -D \cdot x$$

and now consider the same situation using the Lagrangian method. With the kinetic energy $T = m \cdot v^2/2$, where v is the velocity, and the potential energy $V = D \cdot x^2/2$, we get the Lagrangian

$$L = \frac{m}{2} \cdot v^2 - \frac{D}{2} \cdot x^2.$$

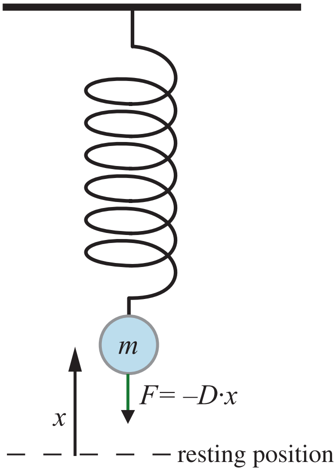

Fig. 1.6 The spring pendulum

Differentiating the Lagrangian *L* with respect to *v*, we obtain $m \cdot v$, and then differentiating with respect to time gives $m \cdot a$, because the acceleration *a* is the derivative of the velocity *v* with respect to time. This is the left side of the equation of motion. Differentiating *L* with respect to the coordinate *x* results in the term $-D \cdot x$ and we have the right side of this equation.

With the spring pendulum the advantages of the Lagrangian method are not yet really evident, since no special coordinates are needed. This is different for the motion of the planets around the Sun – here the Lagrangian method is much easier than the direct calculation of forces using a distance and an angle coordinate.

The procedure can also be generalized to fields, and ultimately even to all physical laws known today. If you know the Lagrangian, then you know the physics – at least in principle.

Theory of Relativity and Quantum Waves

Of course, Feynman was not the only highly talented physics student at MIT. He especially liked his fellow student Theodore Welton, also known as Ted. Both were intelligent and ambitious, and together they tried to go more deeply into the secrets of physics. Feynman loved to deduce everything as far as possible in his own way, and Ted Welton was an ideal companion in this venture.