‘One of the most influential and best-loved physicists of his generation …
This biography is both compelling and highly readable’ *Mail on Sunday*

Richard Feynman

A Life in Science

John Gribbin and Mary Gribbin

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Acknowledgements

Many people gave up time to talk to us about their personal and professional memories of Richard Feynman. Others took the trouble to answer specific queries by mail, e-mail or telephone. Without them, this book could not have been an accurate portrayal of the best-loved scientist of our times. We thank especially Joan Feynman, Carl Feynman, Michelle Feynman and Jacqueline Shaw from Feynman's immediate family circle; James Bjorken, Norman Dombey, David Goodstein, James Hartle, Robert Jastrow, Daniel Kevles, Hagen Kleinert, Igor Novikov, Kip Thorne and Nick Watkins from the world of physics; Feynman's former secretary, Helen Tuck; and Ralph Leighton, who knew Feynman as well as anybody did in the last decade of his life. Even where these people have not been quoted directly, their contributions have helped to shape the image of Richard Feynman in our minds, which we hope comes through in this book.

We have also drawn on published accounts of Feynman's life and work, cited in the text and referred to in full in the Bibliography. Where possible, we have checked important stories about Feynman with their sources; but, of course, we have had to rely on the secondary sources in cases where the originators of the stories are no longer alive, or were otherwise unavailable.

Michael Shermer went to enormous trouble to arrange many interviews for us on a visit to Caltech, and Jagdish Mehra, who was the last person to interview Feynman formally about his life and work, gave permission for us to quote from his own book *The Beat of a Different Drum*, which remains the definitive technical account of the life and science of Richard Feynman, at a more academic level than the present book.

Benjamin Gribbin spent many hours transcribing recordings of interviews with scrupulous accuracy and unfailing good humour, and Jonathan Gribbin prepared the diagrams with speed and skill. The archivists at Princeton University and Caltech, respectively Ben Primer and Charlotte Erwin, helped us to find source material, as did Karl Berkelman at Cornell University, Helen Samuels at MIT, and Roger Meade at the Los Alamos National Laboratory.

Prologue: ‘We love you Dick’

Does the world really need *another* book about Richard Feynman? We think so, or we wouldn’t have written it. And this is why. Richard Feynman was the best-loved scientist of modern times, perhaps of all times, and that is something that simply does not come across in any of the other books about the man and his work. There have been books about Feynman the character, a wise-cracking entertainer who imparted not a little worldly wisdom along with his anecdotes; there have been books about Feynman the scientist, putting his work in the perspective of physics in the second half of the twentieth century; there has even been a picture book, combining the illustrations with reminiscences about Feynman by his family and friends. But nobody has captured the essence of Feynman’s science and the essence of Feynman’s persona in one book. This is especially odd because, of all the scientists of modern times, Feynman seems to have been the one who had the best ‘feel’ for science, who understood physics not simply in terms of lines of equations written on a blackboard, but in some deep, inner sense which enabled him to see to the heart of the subject.

This doesn’t mean that Feynman lived his life ‘like a scientist’, in the stereotypical sense of being a cold-blooded logician in everyday life. Far from it. The point is that he did physics ‘like a human being’, carrying into the world of science his inbuilt sense of fun, his irreverence, and his liking of adventure and the unexpected. The way Feynman did his physics depended on the kind of person he was, far more than in the case of any other physicist we know. It is impossible to understand Feynman’s science properly without understanding what kind of a person he was, and nobody put more life into science than he did.

Equally, it is impossible to understand what kind of man Feynman was without understanding at least something of the science that was so important to him. A fun-loving, adventurous character like Feynman was attracted to physics because physics is fun, and offers opportunity for adventure. You may find that hard to believe. But what’s wrong with the public image of physics is not so much the science itself as the way that the science is taught and portrayed. Perhaps Feynman’s greatest achievement was as a teacher, conveying the fun of science, and entertainer, providing an image of science that cut right across the stereotypes. Ralph Leighton describes Feynman as a ‘shaman of physics’. Feynman talked of nature as ‘She’ or ‘Her’, and seemed to have a contact with the way the world works that few people have. When he gave lectures, he brought his audience into contact with nature in ways that they could not achieve on their own, allowing them to see nature differently, in a transforming experience, so much so that often when he explained some subtle point in a way that they could understand the audience would break out into spontaneous applause, even laughter. The physicist Freeman Dyson has commented,[1] ‘I never saw him give a lecture that did not make the audience laugh’, but the laughter stemmed as much from the pleasure of finding things out as from the jokes that Feynman cracked.

After this experience, people would often have a memory of understanding something, but couldn’t always quite reconstruct how it was they had understood – Feynman would raise people to a level of understanding that they had never before achieved, but then they couldn’t quite remember how he had done it. Even fellow scientists sometimes felt this way about a Feynman lecture – Leighton recalls his own father, one of Feynman’s colleagues at Caltech, remarking on this almost transcendental experience. People who attended Feynman’s lectures say that they seemed like magic, almost literally spellbinding, while people who met him report the same sort of feeling, an awareness of being in the presence of something special, even when they can’t quite put their finger on why. They just felt changed by the experience. And people who never met Feynman still write to Leighton to say that they have been inspired by Feynman’s example. It may well be that he will be remembered more in this way, as a ‘wise man’, rather than for the specific aspects of the science that he was involved with.

This would be appropriate, and perhaps what Feynman himself would have wanted. To Feynman, love was more important than science; but it just happened that, as well as loving people, he loved physics.

And people, including physicists, loved him. In an obituary published in *Nature* on 14 April 1988 (volume 332, page 588), Hans Bethe, who had been Feynman’s boss both at Los Alamos and at Cornell, said ‘more than other scientists, he was loved by his colleagues and his students’. The day Feynman died, the students at Caltech hung a banner across the eleven-storey library building on the campus. The message on the banner read: ‘WE LOVE YOU DICK’. Around the world, many people who hadn’t even met Feynman felt a sense of personal loss when he died. Neither of us ever met him; but the physicist half of the partnership (JG) was exactly the right age to be among the first undergraduates to benefit from Feynman's *Lectures on Physics* while at university. The clarity of those lectures helped to shape his career, and reinforced his own feeling that science, even at research level, could still be fun. Reading books and papers by Feynman over the years, and seeing him on TV, reinforced that belief, and made Feynman seem like an old friend.

But to many people who felt the same way, Feynman was, more than any other great scientist of modern times, 'famous for being famous'. The name of Stephen Hawking is inextricably linked with black holes; Albert Einstein's with relativity theory; Charles Darwin's with evolution. But Feynman? To many non-scientists, he was just 'a scientist'. This is ironic, because Feynman's greatest work was actually in the area of quantum theory, a subject of enormous fascination to non-scientists today. We want to explain why this work was so important, and how it lies at the heart of investigations of the quantum mysteries today; but we also want to share with you our understanding of the kind of man who carried out that work.

Even today, writing seven years after Feynman died in 1988, it is far too soon to produce a definitive account of the historical importance of the man and his work. We don't claim that this is more than a personal view of our subject, but it is one we have arrived at through a long (if one-sided) association with his works, and through recent discussions with Feynman's family and friends.

The one thing that is clear above all else in Feynman's character, from his own work and from conversations with people who knew him, is passion. His passion for physics, for drawing, for drumming, for life itself and for his jokes. Of course Feynman's own anecdotes, gathered together by Ralph Leighton and published in two volumes, tend to portray Feynman as a larger than life, legendary scientific superman and scourge of established authority. Were those stories accurate? We asked Feynman's sister, Joan, on a visit to Pasadena in April 1995. 'It's easy to tell which stories are accurate', she replied. 'How?', we asked. 'My brother didn't lie.'

Ralph Leighton, to whom the stories were told, agrees, but stresses that Feynman was a showman, who loved telling stories.[2] The stories were all true, in that they were about real things that had happened to Feynman; but he used to try telling them in different ways, with different emphasis, until he found the way that worked best. They were not, after all, just anecdotes; in many cases, the stories became parables, and have a moral, telling you something about the right way to live and how to get on in the world, as well as offering amusement and entertainment.

There is indeed a legend growing up around Richard Feynman; but there is truth behind the legend.[3] In the classic western *The Man Who Shot Liberty Valence*, a reporter is faced with a choice between printing the truth about the early career of a great man, or the legend, and in a memorable moment decides to 'print the legend'. We don't intend to go that far, although we agree with the spirit of that decision. We offer you something of the legend of Richard Feynman, but also something of the man behind the legend; and we hope we can put across the importance of his scientific work in language that non-scientists can both understand and enjoy. That, after all, is what Feynman himself would have wanted.

John Gribbin[*]
Mary Gribbin
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Notes

1. See Freeman Dyson, *From Eros to Gaia* (Pantheon, New York, 1992).
2. Joan Feynman, interviewed by JG in April 1995, said that according to her mother 'when Richard was very little he couldn't decide whether he wanted to be a comedian or a scientist, so he combined the two options'.
3. Interviewed by JG in April 1995, David Goodstein, who is Professor of Physics and Vice Provost at Caltech, said, 'Feynman is a person of historic proportions; he deserves the kind of attention that he's gotten, in my opinion.'

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1 A fascination with physics

Family legend has it that when his wife Lucille became pregnant for the first time, Melville Feynman commented ‘if it’s a boy, he’ll be a scientist’.[1] The baby was born on 11 May 1918 in Manhattan, and brought up in Far Rockaway, New York; he was named Richard Phillips Feynman,[*] and he grew up to be the greatest scientist of his generation. He not only won the Nobel Prize for Physics for his first major contribution to science, but carried out at least two other pieces of research that were worthy of the prize; he was one of the leaders of the team that worked on the Manhattan Project, to develop the atomic bomb; and he was, above all, a great teacher who encouraged generations of students to think about physics in a new way.

Melville Feynman has to take some of the credit for this, because he deliberately set out to stimulate his son to think, from an early age, in a ‘scientific’ way. When the boy was sitting in his high chair, Melville would play games with him using a collection of coloured bathroom tiles. At first, the game mainly involved setting up a row of tiles on end, in any order, and toppling them, like dominoes; but soon they moved on to setting up patterns, maybe two white tiles followed by a blue one, then two more white and another blue, and so on. The young Feynman – called Ritty or Richy by his parents, family and friends – became very good at the game, which his father had started in a conscious attempt to get young Ritty to think about patterns and the basics of mathematical relations.[2]

Melville encouraged his son’s interest in science in the obvious ways – buying a set of the *Encyclopaedia Britannica*, taking Ritty on trips to the American Museum of Natural History, and so on. But even the conventional sources of information were used by Melville as jumping-off points for extrapolations which made the dry material come alive, and which brought home to Richard the magical, mysterious aspects of science. When the *Britannica* mentioned that a long-extinct dinosaur had been ‘twenty-five feet high’ and had a head ‘six feet across’, Melville would stop reading and explain what that meant – that if the dinosaur stood in the front yard of the house in Far Rockaway, he would be able to look in through the second-floor window, but his head would be too big to fit through the window.

But the special nature of Richard's relationship with his father, and the special nature of the way in which Melville encouraged the younger Feynman's fascination with science, is highlighted by two of Richard Feynman's favourite anecdotes about his father.

The first dates back to summers spent in the Catskill Mountains, where families from New York would go to escape the heat of the city. Mothers and children would stay in the mountains for several weeks, but the fathers of the families still had to work in the city, only visiting their families at weekends. On long weekend walks in the woods, Melville introduced Richard to many of the wonders of nature – but with his typical sideways manner of looking at the world. So when one of the other children pointed out a bird to Richard and asked if he knew its name, he had to reply that he didn't. Triumphantly, the other kid named the bird, sneering that 'your father doesn't teach you anything'. 'But', Feynman tells us,[3] 'it was the opposite.' His father had already pointed out that kind of bird:

> 'See that bird?' he says. 'It's a Spencer's warbler.' (I knew he didn't know the real name.) 'Well, in Italian, it's a *Chutto Lapittida*. In Portuguese, it's a *Bom da Peida*. In Chinese it's a *Chung-long-tah*, and in Japanese it's a *Katano Tekeda*. You can know the name of that bird in all the languages of the world, but when you're finished, you'll know absolutely nothing whatever about the bird. You'll only know about humans in different places, and what they call the bird. So let's look at the bird and see what it's *doing* – that's what counts.'

So Richard learned, at a very early age, the difference between knowing the name of something and knowing something. To such a person, it made perfect sense, years later when he was in graduate college, to ask a baffled librarian where he could find 'the map of a cat', and to be equally baffled by her reaction to this simple request. The actual telling of this story, many years later, also gave a fundamental insight into Feynman's childhood and upbringing. While going through that story with Feynman, not long before Feynman died, Ralph Leighton said to him, 'there's all this about your father, but what did your mother teach you?' He replied, 'My mother taught me that the highest forms of understanding that we can achieve are laughter, and human compassion.'[4]

The second key anecdote from Richard's early childhood concerns the occasion when he noticed the odd behaviour of a ball left lying in his little wagon when he pulled the wagon forward. The ball rolled to the back of the wagon, then, when the wagon stopped the ball rolled to the front. He asked his father why this happened, and got this reply:

> That, nobody knows. The general principle is that things which are moving tend to keep on moving, and things which are standing still tend to stand still, unless you push them hard. This tendency is called ‘inertia’, but nobody knows why it’s true.

This represents a deep insight into the nature of physics and the nature of the world, and it was examples like this that encouraged Richard Feynman, in later years, to question everything, to search for underlying truths, and never to believe that just because some process had been labelled meant that it was understood.[†]

But there is another aspect to this way Melville had of teaching his son, which has echoes in the way Feynman later used his own anecdotes to bring out highlights of his own life when he became a storyteller in his turn. The stories don’t have to be literally ‘true’, in every detail, in order to make a valid point. As Feynman himself said, he knew full well that the bird being described by Melville wasn’t really called a ‘Spencer’s warbler’, and that the foreign ‘names’ his father made up for the bird were just nonsense words. But he also knew that that didn’t matter – that, indeed, the whole point of this particular story was that names didn’t matter, so if Melville wanted to call the bird a Spencer’s warbler he was fully entitled to do so. Richard Feynman’s own stories should always be understood in this spirit – that as long as the underlying message is correct, the details and emphasis can be adjusted to improve the impact of the story. Joan Feynman’s brother didn’t lie, but as a great showman he presented his stories in the best possible light. As he said of his father’s stories, ‘I knew that they weren’t quite accurate, and yet they were utterly accurate, if you see what I mean, in the character of the story he was trying to tell me.’[5] We could say the same about his own stories, especially when, for example, he quotes childhood conversations with his father verbatim, as if he had total recall, when in fact he was making up dialogue to match what he remembered of the occasion. The truth in Richard Feynman’s anecdotes is a much deeper truth than the trivia of exactly what words were said on a particular day in the 1920s.

But if Richard learned so much about how to think about science and the world – not just an accumulation of scientific facts – from his father, where did Melville learn to think about the world in this way? Melville’s own father, Richard’s grandfather, was, apparently, also interested in mathematical and scientific ideas, so to that extent, at least, there was a tradition of science in the family. This offers hope for all of us; even if we cannot aspire to being a Richard Feynman, at least we can aspire to being a Melville Feynman – to have an understanding and enthusiasm for nature, and to pass that enthusiasm on to a child, even without the detailed mathematical knowledge that a professional scientist needs. But neither Richard's father nor his grandfather had an opportunity to develop their interest into a career.

Melville had been born in 1890. He was the son of Jakob and Anne Feynman, Lithuanian Jews who lived for a time in Minsk, in Byelorussia, and emigrated to the United States in 1895. The family settled in Patchogue, on Long Island, and Melville was initially taught at home, by his father (a precursor of his own relationship with Richard), but later attended the local high school. He wanted to become a doctor, but there was no way the family could afford to support the education required to fulfil his ambition, so instead he enrolled in a college to study homoeopathic medicine. Even these studies proved impossible to sustain financially, and Melville dropped out of college and into a variety of occupations, at none of which he was particularly successful, although he always managed to keep the family afloat, even through the Depression. He finally settled in the uniform business, providing ample opportunity for Richard to learn at first hand the difference between formal authority represented by a uniform and the frail human being inside the uniform. On one occasion, Feynman recalled, his father showed him a picture in the newspaper of the Pope, with people bowing down in front of him. 'What's the difference', Melville asked Richard, 'between this man and all the others?' He immediately answered his own question. 'The difference is the hat he's wearing. But this man has the same problems as everybody else: he eats dinner; he goes to the bathroom. He's a human being.'[6]

The parents of Lucille Phillips, Richard Feynman's mother, both came to the United States as young children. Her maternal grandfather (Richard's great-grandfather) was a Polish Jew who was involved in anti-Russian activities in the 1860s and 1870s, was imprisoned and sentenced to death, but escaped and eventually made his way to America, where his children later joined him. The eldest daughter among those children, Johanna Helinsky, worked with her father in the watchmaking store he opened on the Lower East Side in New York, and it was there that she met her future husband, Richard Feynman's maternal grandfather.

Henry Phillips was born in Poland, but lost his parents as a child and spent some time in an English orphanage, where he was given his name, before being sent on to America to seek his fortune. Unlike many immigrants in a similar position, Henry Phillips really did succeed in making a modest fortune. He started out selling needles and thread door-to-door from a pack on his back, and went on, with Johanna, to develop a successful millinery business, which thrived until changing fashions at the end of the First World War saw the hat business go into decline. Henry met Johanna when he had a watch that needed repairing, and took it into a watchmaking store where he was surprised to find the job being done by a beautiful young woman. They soon married, went into business together, and during the height of their success in the hat trade they moved to the Upper East Side, on 92nd Street, where Lucille Phillips (the youngest of five children) was born in 1895.[7] The family later moved to a large house with a big garden in Far Rockaway, which was then a semi-rural community in Queens County, at the southern tip of Long Island.

As the daughter of a successful businessman, Lucille was educated at the Ethical Culture Institute (where she was followed, nine years later, by Robert Oppenheimer), and intended to become a kindergarten teacher. But just after she graduated from high school, when she was eighteen years old, she met Melville Feynman; they hit it off at once, and almost immediately he asked her to marry him. Her father wouldn’t give his permission for her to marry so young, so they had to wait until 1917, after she had turned 21. At first, the newly married couple lived in upper Manhattan; Richard Phillips Feynman was born there, in a Manhattan hospital, a year after their marriage.

If Melville Feynman contributed, at least in part, to his son’s becoming a scientist, Lucille had an equally great influence on him through her sense of humour, warmth and compassion. Joan Feynman feels that the role of their mother has been downplayed in most versions of the Feynman legend, leaving her in the shadows of the father who turned young Ritty on to science. Perhaps that is understandable, at least from the point of view of those recounting the legend. After all, many of us have mothers who have a wonderful sense of humour and are full of compassion, but very few people have fathers like Melville Feynman, so his part in the story seems at first sight more interesting and more profound. Without Lucille’s influence, though, Richard Feynman might well have become a more or less conventional, dry as dust academic, rather than the safecracking, bongo-playing figure of legend. It is, after all, the combination of serious science, a sense of fun and the very sane view that ‘the highest forms of understanding we can achieve are laughter and human compassion’[8] that made Feynman so special, and that combination is found in neither of his parents alone, but in both of them put together. And if any further proof of Lucille’s influence on her son were needed, she was a great storyteller. Joan recalls:

> wonderful memories of evenings at the supper table when Richard was home from college and he and Mother would get going. My father and I would laugh so hard that our stomachs hurt and we

> would beg for mercy, but they wouldn’t stop until I had fallen off my chair and was literally rolling on the floor.[9]

Even Lucille’s good humour and compassion were severely tested, however, early in 1924, when Richard was five. She had another son, Henry Phillips Feynman, who was born on 24 January that year, but lived only for a month and a day, dying on 25 February. It wasn’t until Richard was nine that his sister Joan was born; but that doesn’t mean that he led anything like the usual life of an ‘only child’ for the first nine years of his life.

The Feynman family moved a couple of times when he was very small, but settled in Far Rockaway, where they shared Lucille’s father’s house with her sister Pearl and her family. That family included a son Robert, three years older than Richard, and a daughter Frances, three years younger than him. So he was in the middle of an extended family of children that were in fact cousins, but lived like siblings. The reason for the house-sharing was financial. Pearl’s husband, Ralph Lewine, worked in the shirt business, but never achieved as much success as Melville did in his own line of business. The Feynman family was far from poor; they weren’t as well off as Lucille’s parents had been, but Joan Feynman recalls that they were always comfortable financially, right through the Depression years. Living in such close proximity wasn’t always easy, at least for the adults in the two families (and, of course, the very fact that the house had been passed on by Henry Phillips was a constant reminder to both Melville and Ralph that they had not achieved as much as their father-in-law), and shortly after Joan was born, when Richard was ten, the Feynman family moved out to the nearby town of Cedarhurst. But within a couple of years they had returned, and although neither son-in-law ever became as successful in business as Henry Phillips, thanks in part to the house they had inherited from him both families survived the Depression in relative comfort. Joan remembers that she ‘had nice clothes from good stores in New York’, and that there was a woman who came in every day to clean and do laundry. ‘Before the war, we had a new car every year (usually an Oldsmobile).’[10]

Even Melville, usually so iconoclastic and unwilling to be bound by convention, had one blind spot, though. True to his word, he encouraged Richard to take an interest in science. But he never attempted to rouse any similar enthusiasm in Joan. In the 1930s, it was almost inconceivable, even to someone as broadminded as Melville Feynman, that a girl could become a scientist. But Joan became a scientist anyway, ending up in space research at the prestigious Jet Propulsion Laboratory in Pasadena – she became, in fact, exactly the kind of scientist that Melville must have imagined Ritty might become. It all started when she would hear Melville and Richard talking about all these interesting things, and later she would ask her brother about what she had overheard. Soon, he was explaining things to her in the same way that he had learned them from their father, becoming a scientific raconteur (albeit to an audience of one) in his early teens.[11] Joan, too, helped to influence her brother's development, and likes to describe herself as 'Richard Feynman's first student'.[12]

It started when she was still a baby, and Richard had the duty of looking after her. Propped up in her baby carriage, she would watch Richard and a friend tinkering with the collection of wires, batteries and other electrical bits and pieces that they called their 'laboratory'. The family had a dog at the time, which had been taught tricks, and Richard reasoned that since his sister was brighter than the dog, she ought to be able to do better tricks. He decided to teach her arithmetic, in order to impress his friends, and encouraged her to learn by allowing her to pull his hair if she got the sum right. Joan still recalls standing in her crib, at the age of about three, 'yanking on his hair with great delight' having just learned to add two and three.

As Joan got bigger, so did her tasks. At five, she was a paid lab assistant, earning two cents a week for carrying out odd jobs and sometimes playing the part of the magician's assistant, sticking her finger in a small spark gap and enduring a modest electric shock, again to amaze Richard's friends. No anecdote sums up their relationship better; the hero-worshipping younger sister knew that her big brother would never hurt her, and trusted him to keep the shock at the level of mild discomfort, even though the sparks that leapt across the gap when no finger was in place looked terrifying to anyone not in the know. In exchange, as well as the financial rewards, Richard introduced her to the wonders of the world, showing her the stars and demonstrating centrifugal force by whirling a glass of water in an upside down arc without spilling a drop (except on one memorable occasion when the glass slipped out of his hand and flew across the room).

One of the things Richard showed her has stayed vividly in Joan's mind. She recalls that the household was run in a very orderly fashion, with strict rules about things like bedtime. As the youngest child in the household, she went to bed first. But one night, when she was about four years old, her brother, then about thirteen, got permission to wake her up. He told her he had something wonderful to show her, and took her out into the middle of a nearby golf course, before telling her to look up at the sky, where she saw the aurora borealis.

But the real turning point in Joan's becoming a scientist came when she was fourteen, and Richard was a graduate student at

Princeton. Joan had long been fascinated by astronomy, but had actually been told by her mother that the female brain wasn't up to doing science.[13] Then, on her fourteenth birthday, Richard gave her a college level textbook on astronomy, and when she protested that it was too difficult for her, he told her to persevere. 'You start at the beginning and you read as far as you can, until you get lost. Then you start at the beginning again, and you keep working through until you can understand the whole book.'[14] Persevering in this way, she made steady progress. Eventually, she came to page 407, where there was a graph showing part of the spectrum of a star. The caption credited the astronomer who had obtained the information – Cecilia Payne-Gaposhkin – a woman! 'The secret was out: it was possible! From that day on, I was able to take my own interest in science seriously.'[15]

There was 'this excitement in the house, this great love of physics, so naturally I thought it sounded great', she remembers.[16] 'The feeling of excitement was in the house all the time, in my brother and my father. So I just grew up with it. Science became the thing to do.' But she was never any more in awe of Richard than other kid sisters were in awe of their big brothers. 'Your brother, he's your brother. You don't make any assumptions he's particularly brilliant.' It is only hindsight that made her realize that the family was actually unusual in its interest in science. 'Well, we were interested in relativity when I was a kid, so that then we had to be different than many other families.'

Two decades after Ritty had shown her the aurora, after she had finished her own PhD in solid state physics, Joan became interested in the aurora again. She was enjoying the work, and wanted to tell Richard about it. But the last thing she wanted was for her smart elder brother to solve the problem before she could have the pleasure of working it all out. So she went up to him and offered a deal, dividing up the Universe. If he would promise not to work on the aurora, she would leave everything else to him. Richard agreed.

In the 1980s, however, he visited Alaska, where he was shown around an observatory dedicated to the study of the aurora. Having learned about the work being done there, and expressing interest in the intriguing problems still to be solved, he was asked, well, why don't you work on some of these puzzles yourself? 'I would like to', Feynman replied, 'but I can't. I'd have to get my sister's permission.'

A little later, at a meeting of aurora experts, one of the Alaskan researchers came up to Joan, asking whether her brother had been joking. No, she said, the story was correct. On his return to California, Richard had asked her permission to work on the aurora, and she had turned him down. True to his word, given three decades earlier, he left the aurora to her.[17]

About the time Richard showed his little sister the aurora for the first time, he started in high school, in the autumn of 1931. By then, he was already established as an unusually clever child, both within school and outside. It was during the years in Cedarhurst that he really began to develop a conscious interest in science, and he was allowed to have a laboratory in the basement of the house, where he could experiment with chemicals. School in Cedarhurst, as far as science was concerned, was a complete waste of time. It was taught only in the eighth grade (the last grade in elementary school), and the only thing Feynman ever learned from it was that there are 39.37 inches in 1 metre. But in arithmetic, it was different. He was already ‘known as some kind of a whiz-kid at arithmetic in elementary school’, and at the age of ten or eleven he was called out of his class and into another to explain his method of doing subtraction, which the teacher thought was particularly neat, to the younger children.[18]

In his last year at elementary school, though, Richard did make some of his first scientific contacts. He had a dentist who took the trouble to answer his questions about how teeth worked, and who he built up in his mind as ‘a scientist’. He also tried to struggle through the few popular books in the public library about new developments in science (more of these developments in Chapter 2), and although the dentist was not really much of a scientist he realized that Richard had more than a passing interest in scientific matters. The dentist had another patient, William LeSur, who was an English teacher in Far Rockaway High School, but who helped out with the science teaching there; he told him about the boy’s interest. The outcome was that LeSur invited Richard to visit the high school once a week, after classes had finished, and hang out in the lab while they cleaned up. Through this contact, Richard met the real chemistry teacher at the high school, and the head of science, Dr Edwin Barnes, who talked to him about science while he helped clean up the apparatus.

But if Richard learned little science from the teachers at Cedarhurst, it was during his time there that he learned about atoms from a new friend, Leonard Mautner, who explained what would happen if you kept on breaking up a substance into smaller and smaller pieces. To someone who has had any kind of scientific education, that may sound fairly trivial. But it was a landmark event in Feynman’s life. Just over 30 years later, in his famous *Lectures*, he would say:

> If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the most

> information in the fewest words? I believe it is the *atomic hypothesis* (or the atomic *fact*, or whatever you wish to call it) that *all things are made of atoms – little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another.* In that one sentence, you will see, there is an *enormous* amount of information about the world, if just a little imagination and thinking are applied.[19]

Imagination and thinking were what the pre-teenage Richard Feynman (like the adult Richard Feynman) was superb at. In one of his favourite anecdotes (or parables, if you prefer), he told how while he was in Cedarhurst he learned how to repair radios. Radio sets were simple in those days, and he had started out, in Far Rockaway, by building his own crystal set, then moved on to fixing some problems for the family. Word spread, and friends and acquaintances used to call him in, rather than go to the expense of calling a regular radio repair man. The highlight of the story comes when a total stranger asks the kid to fix his radio, which makes an awful noise when it is switched on, but then settles down when it has warmed up. The kid paces up and down, trying to work out what is going on, while the owner of the radio gets more and more agitated, muttering about how stupid he has been to ask a little kid to do a man's job, and asking what Feynman is up to, to which the kid replies, 'I'm thinking'.

Eventually, having thought things through carefully, the kid realizes that the problem might be solved by reversing the order of two of the tubes (valves) in the radio. He swaps the tubes, switches it on, and it works perfectly. The owner of the set is enchanted, completely converted to the cause of the budding genius, and gets him more work, telling all his friends, 'He fixes radios by *thinking*!'[20]

Now, the point of the story is not that the older Feynman was on some ego trip, boasting about his childhood achievements. It is a story (which happens to be true) about the importance of imaginative thought, and how to solve problems in general. At another level, here is someone who was opposed to what Feynman was trying to do (or, at least, to the way he was trying to do it) who turned around completely to become almost embarrassingly enthusiastic once the technique had been shown to work. So when you know you are right, you should keep your courage in the face of opposition, carrying on the way you know is right. And it also tells us something a little more subtle about Feynman's character – he did not give up. Faced with a puzzle of any kind, from a neighbour's broken radio to the fundamental nature of quantum physics, he did not rest until he had solved it (unless, of course, he had promised his sister not to try).

In high school, the pattern continued. Older students would come to him, for example, with tricky geometrical problems they had been assigned in the advanced mathematics class, and he would solve the puzzles – not because he was trying to ingratiate himself with the older boys, but because he couldn't resist the challenge. As it happens, the reputation he developed for being some kind of whiz at maths did help him socially. He was hopeless at ball games and what were generally regarded as 'manly' pursuits, shy with girls, and worried about being thought a 'sissy'. In *What Do You Care What Other People Think?* he describes being 'petrified' when passing a group of kids playing a ball game in case the ball rolled in his direction and he would be expected to pick it up and throw it back. The ball would always fly out of his hand in totally the wrong direction and everybody would laugh. The fact was, though, that he was simply too useful to the older boys for them to alienate him by making too much fun of these deficiencies.

Richard always tackled those geometry problems (and all other problems) his own way, using techniques that he had developed largely by himself, from first principles. Partly out of a desire to do it himself, partly through Melville's instruction that you shouldn't believe anything just because somebody else, no matter how eminent, told it to you, that was the way Feynman would work throughout his scientific life. With his friend Mautner, but largely on his own, he worked out most of the rules of Euclidean geometry for himself. 'I wanted to find the formula', he told Jagdish Mehra in 1988. 'I didn't care whether it had been worked out by the Greeks or even by the Babylonians; that didn't interest me at all. It was *my* problem, and I had fun out of it.'

He was also, as he put it, lucky enough to learn algebra his own way before coming into contact with it at school. His older cousin Robert could never get to grips with algebra, and had a tutor who came to coach him. Feynman was allowed to sit in on these sessions, and quickly learned that in algebra the problem was to find the value of the unknown variable, x, in an equation. While Robert struggled to do this by rote, using rules memorized at school, Feynman appreciated that it didn't matter *how* you got the answer, as long as it was the right one. Before he left elementary school, Richard had learned how to solve simultaneous equations – sets of two equations with two unknown quantities, such as

$$2x + y = 10$$

and

$$2y - x = 5$$

to find the values of both x and y (in this case, $x = 3$ and $y = 4$). Then, he made up for himself a problem with four equations and four unknowns.

Hardly surprisingly, by the time Richard came to algebra in high school he was bored to tears by what was on offer. He suffered in silence for a while, then told the teacher that he already knew what she was trying to teach the class. The head of the mathematics department gave him a problem to solve as a test; it was too difficult for him, but he made a good enough stab at it for them to see he really did know something about algebra. So he was put in a special class for the subject, really for students who had failed algebra once and were repeating it, with a teacher, Lillian Moore, flexible enough to cope with Richard's precocity. It was here that he met a new kind of puzzle. Miss Moore asked the class to solve the equation $2^x = 32$. Nobody could make head or tail of it. They didn't have a set of rules for solving that kind of problem. But Richard didn't need a set of rules; he saw straight away that the solution is $x = 5$, because 5 twos multiplied together is 32. This kind of thing was self-evident to Richard, and the fact that nobody else in the class felt the same way was one of the first indications he had that he really was different from the other students.

That difference came to the fore when Richard became the star of the school maths team, competing with other New York high schools in the 'Interscholastic Algebra League'. The algebra team would travel to different schools to compete with their maths whizzes. There were five members of each team, and they would be given problems that required what would nowadays be called lateral thinking to solve, with a strictly limited time in which to solve them – typically 45 seconds. Each member of the team worked independently, and could write anything he wanted on the paper in front of him. All that mattered was that before the time was up each competitor had to draw a circle around the one number on the paper that was his answer to the problem. The problems were deliberately chosen so that although they could, of course, be solved 'by the rulebook', it would be just about impossible to do so in the time available; but they were easy once you saw the short cut (or invented your own short cut). Feynman always won these competitions, writing down his number and ostentatiously drawing a circle around it, often on an otherwise blank piece of paper, usually before the other competitors had really got to grips with it at all. The practice served him well in later life, when he retained the ability to solve algebraic problems quickly and neatly, without ploughing through the textbook methods.

So Richard learned a little maths in high school, although he always claimed that he didn't learn any science at all there, because he was always ahead of what was being taught in class. The kind of biology, physics and chemistry taught in Far Rockaway High School in the 1930s was already familiar to him from the *Encyclopaedia Britannica*, his own tinkering (for example with electricity), and informal conversations with his teachers and others. Even the maths he learned while at high school was largely self-taught – the big new thing for him in those years was calculus, which he learned from two books, *Calculus Made Easy*, by S. P. Thompson (St Martin's Press, New York, 1910) and *Calculus for the Practical Man* by J. E. Thompson (Van Nostrand, New York, 1931), one of a series of 'practical man' guides to mathematics that Richard devoured around the time he left elementary school and went to high school.

But two mathematical experiences that Richard had while in high school did stick with him for the rest of his life. One gave him an insight into what it was like for ordinary students; the other shaped his entire subsequent career.

The glimpse of mathematical mortality came when Richard was introduced to solid geometry, the study of shapes in three dimensions, in high school. He was completely thrown, and couldn't understand what the teacher was getting at at all, although he could use the rules the teacher gave in order to carry through calculations properly. For once, he was in the same position as students who used the rules of algebra to solve equations without understanding what was going on. Then, the penny dropped. After a couple of weeks, he realized that the mess of lines being drawn on the blackboard was indeed meant to represent three-dimensional objects, not some crazy pattern in two dimensions. Everything came into focus, and he never had any trouble with the subject again. As far as science was concerned, 'it was my only experience of how it must feel to the ordinary human being', he later said.[21]

In 1933, the Feynman family visited the World's Fair in Chicago; a year later, Richard began his final year in high school, and made the mathematical encounter that was to shape his career.

He owed the encounter to the Depression. That year, a new physics teacher, Abram Bader, joined the school. He had been working for a PhD at Columbia University, under the Austrian-born physicist I. I. Rabi, whose work on the magnetic properties of fundamental particles would bring him the Nobel Prize in 1944. But Bader ran out of money, and had to drop out of research to become a teacher. He quickly appreciated Feynman's unusual abilities, lending him a book on advanced calculus, and often talking to him, out of class, about scientific matters. Once he explained something called the Principle of Least Action. They discussed the topic only once, but the whole scene stuck in Feynman's mind for the rest of his life. He was so excited by the idea that he remembered everything about the occasion – exactly where the blackboard was, where he was standing, where Mr Bader was standing, and the room they were in. 'He just explained, he didn't prove anything. There was nothing complicated; he just explained that such a principle exists. I reacted to it then and there, that this was a miraculous and marvelous thing to be able to express the laws in such an unusual fashion.'[22]

The 'miraculous and marvelous thing' can be understood in terms of the flight of a ball tossed from the ground through an upper-storey window. In this context, the term 'action' has a precise meaning. At any point in its flight, you can calculate the difference between the kinetic energy of the ball (the energy of the ball's motion, related to its speed) and its potential energy (the gravitational energy the ball possesses because of its height above the ground). The action is the sum of all these differences, all along the path of the ball through the air (action can be calculated in a similar way for charged particles moving in electric or magnetic fields, including electrons moving in atoms). There are many different curves the ball could follow to get through the window, ranging from low, flat trajectories to highly curved flight paths in which it goes far above the window before dropping through it. Each curve is a parabola, one of the family of trajectories possible for a ball moving under the influence of the Earth's gravity. All this Feynman knew already. But Bader reminded him that if you know how long the flight of the ball takes, from the moment it leaves the thrower's hand to the moment it reaches the window, that rules out all but one of the trajectories, specifying a unique path for the ball. And then he told him about the Principle of Least Action.

One of the most important principles in physics is the conservation of energy – the total amount of energy associated with the ball (in this example) stays the same. Some of this energy is in the form of gravitational potential energy, which depends on its height above the surface of the Earth (strictly speaking, on its distance from the centre of the Earth). When the ball rises, it gains gravitational potential energy; when it falls, it loses some of this energy. The only other relevant form of energy possessed by the ball is its energy of motion, or kinetic energy. Higher speeds correspond to greater kinetic energy. At the moment the ball leaves the thrower's hand, it has a lot of kinetic energy because it is moving fast. As it rises, some of this kinetic energy is lost, traded for gravitational potential energy, and it slows down. At the top of its trajectory, it has minimum kinetic energy and maximum potential energy, then as it falls down the other side of the curve it gains kinetic energy and loses potential energy. But the *total*, the sum of (kinetic + potential) energy is always the same.

All this Feynman knew. But what he didn't know was that given the time taken for the journey, the trajectory followed by the ball is always the one for which the *difference*, kinetic energy *minus* potential energy, added up all along the trajectory, is the least. This is the Principle of Least Action, a property involving the whole path.

Looking at the curved line on a blackboard representing the flight of the ball, you might think, for example, that you could make it take the same time for the journey by throwing it slightly more slowly, in a flatter arc, more nearly a straight line; or by throwing it faster along a longer trajectory, looping higher above the ground. But nature doesn't work that way. There is only one possible path between two points for a given amount of time taken for the flight. Nature 'chooses' the path with the least action – and this applies not just to the flight of a ball, but to any kind of trajectory, at any scale. Mr Bader didn't work out the numbers involved, or ask Feynman to work them out. He just told him about the principle, a deep truth which impressed the high school student in his final year before going on to college.

It's worth a slight detour to give another example of the principle at work, this time in the guise of the Principle of Least Time, because it is so important both to science and to Feynman's career. This version of the story involves light. It happens that light travels slightly faster through air than it does through glass.[‡] Either in air or glass, light travels in straight lines – an example of the Principle of Least Time, because, since a straight line is the shortest distance between two points, that is the quickest way to get from A to B. But what if the journey from A to B starts out in air, and ends up inside a glass block? If the light still travelled in a single straight line, it would spend a relatively small amount of time moving swiftly through air, then a relatively long time moving slowly through glass. It turns out (see Figure 1) that there is a unique path which enables the light to take the least time on its journey, which involves travelling in a certain straight line up to the edge of the glass, then turning and travelling in a different straight line to its destination. The light seems to 'know' where it is going, apply the Principle of Least Action, and 'choose' the optimum path for its journey.

The connection between mathematics and physics highlighted by the Principle of Least Action reinforced a growing fascination that Richard had had with this area of science right through high school. While working with radio receivers, building his own circuits and working out how to tune them, he had come across equations describing the behaviour of these practical objects that involved the Greek pi, the ratio of the circumference of a circle to its diameter. Although there were circular (or cylindrical) coils in these circuits, it is also possible to work with square coils, and pi came into the equations whatever the shape of the coils. There was some deep link between physics and mathematics, which Feynman did not understand, but which intrigued him. Although still known as a whiz at maths, his fascination was really with physics.

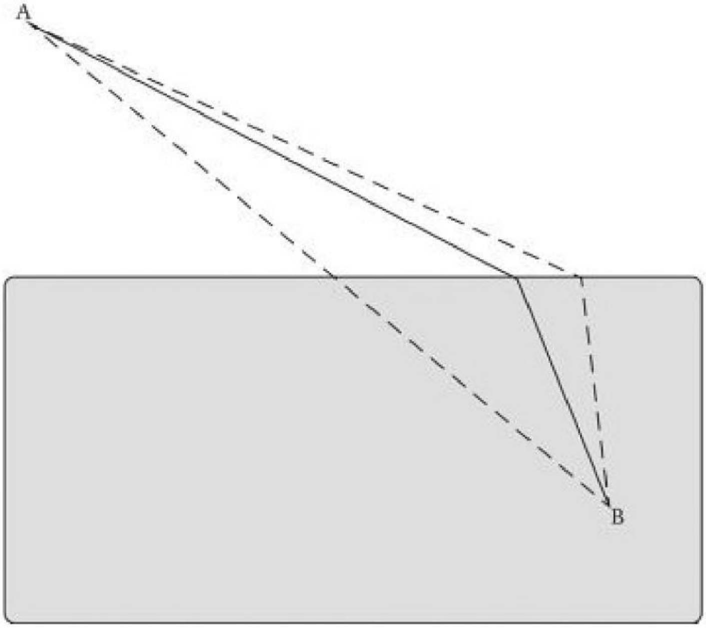

Figure 1. Light travels faster through air than through glass. So the quickest journey from A to B that is partly through air and partly through glass is not the (dotted) straight line from A to B, but there is a unique 'path of least time' made up of two straight lines. This is a special case of the Principle of Least Action at work. The dotted lines to the right show an example of a path that takes longer than the path of least time (solid lines).

We have emphasized the role of science in young Richard's life because it was, indeed, the main thing in his life. He went through the educational system in what seemed, superficially, a conventional way, but actually learned his science for himself, outside the system (including teaching himself about relativity theory from books while still in high school). He found school boring, but sailed through examinations with ease, appearing, in that respect, to have been a model student.

How clever did he have to be, to do all that? Joan Feynman once sneaked a look at the results of the standard IQ tests that both she and her brother had taken in high school.[23] Her score was 124, his was 123, so she could always claim to be smarter than he was. It is notoriously true that IQ tests are only any good at measuring the ability of people to do IQ tests, but much later in life Feynman took great delight in being able to quote his IQ score when invited to join the organization Mensa, which is exactly the kind of 'club' for the self-important that he despised. Unfortunately, he replied, he could not join Mensa because his IQ was not high enough for them.

But that didn't stop his being a genius, because some kinds of genius cannot be measured in IQ tests. The mathematician Mark Kac, who was born in Poland but spent most of his career in the United States, once explained that there are two kinds of genius. One is the kind of person that you or we would be just as good as, if only we were a lot more clever. There is no mystery about how their minds work, and once what they have done is explained to us we think we could have done it, if only we had been bright enough. But the other kind of genius is really a kind of magician. Even after what they have done is explained to us, we cannot understand how they did it. 'Richard Feynman', said Kac in 1985, 'is a magician of the highest caliber.'[24]

But in spite of being clearly different from his peers in this way, even as a child, and in spite of his fears of being thought a sissy, Richard wasn't what would now be called a 'nerd'. He had a handful of close friends, some interested in science, others on the humanities side; and his feet were kept firmly on the ground in those Depression days by the need to work at odd jobs to earn spending money.

His father earned about $5,000 a year in the early 1930s, which Richard knew because Melville would sometimes send him to the bank with a cheque for a week's salary, about $100. It was Melville's way of teaching Ritty the value of money, and it worked. Richard knew how much money the family had, and knew that they lived in reasonable comfort. He remembered thinking 'that everything was all right, we lived fine, and my ambition was to earn that much money … I knew I wanted about $5,000 a year, that's all I needed.'[25] He worked part time for a printer while in high school, and in the summer after graduation at a hotel run by his aunt, giving rise to some of the stories recounted in *Surely You're Joking, Mr. Feynman!* In many ways, this was a typical lifestyle for a bright Jewish kid in New York in the 1930s – it bears striking resemblances, for example, to the story Isaac Asimov tells in his autobiographical *I Asimov* (Doubleday).

As a teenager, Feynman later said, he was interested in only two things, maths and girls (that's one more thing than most teenage boys are interested in). He learned to dance, which was very useful for one of his interests, and he also quickly learned about the difference between social niceties and the truth.

Richard was always uncomfortable with the phoney way many other people used language. He regarded English, as taught in high school, as ‘a kind of baloney’, had a lifetime disdain of philosophy, and dismissed religion, which seemed to him to be based purely on wishful thinking. He talked straight, meant what he said, and was genuinely confused if that seemed to upset other people. So when, at the end of his first date, the girl he had taken out said, ‘Thank you for a very lovely evening’, he thought she meant it. When the next girl he took out ended the evening with exactly the same words, he began to wonder. So the third time he took a girl out on a date, when the time came to say goodnight he got in first, saying the stock phrase before she could, and leaving her tongue-tied, unable to think what to say in response, because she had been just about to say the same thing.[26] This was one of Feynman’s first encounters with this kind of empty formality, but he seldom bothered with such niceties himself.

It wasn’t too long before he got to know a girl who would end up caring even less about social niceties than he did, and making him blissfully happy, as his first wife, in the process. When Richard first met Arline Greenbaum, when he was about thirteen, she was one of his wider circle of acquaintances, not a close friend. As they grew up together, he got to dance with her on occasion, but she soon had a regular boyfriend and to a large extent he admired her from a distance (Joan Feynman recalls Richard first mentioning this ‘wonderful girl’ to her when he was about fifteen and Joan was six). Arline was the most popular girl in the group, and everybody liked her. As Feynman recounted in *What Do You Care What Other People Think?*, she once made his day simply by coming over to him at a party and sitting on the arm of his chair to talk to him. ‘Oh boy!’, he thought, ‘somebody I like has paid attention to me!’ (his comments at home the next day may have been the occasion Joan remembers). He even joined an art group, something he had no ability at whatsoever at that time, simply because Arline was a member.

Eventually, Arline’s steady relationship with her boyfriend ended, and during his final year in high school Richard got to know her better, although she was still dating other boys at that time. But Harold Gast, one of Richard’s contemporaries who also dated Arline, says that by then it was obvious to everyone in the group ‘that they were really very fond of each other and nobody was going to interfere’.[27] Still rather shy and insecure socially, however, Richard imagined that Gast was a serious competitor, and was relieved when Arline chose to sit with Melville and

Lucille at his graduation ceremony, a public acknowledgement of her interest in him.

The graduation was, of course, a triumph for Feynman, who took top honours in just about everything, ironically including English. The reason for that particular triumph, also recounted in *What Do You Care*, was that, knowing his limitations, in the examination he had written an uncontentious essay about technology and aviation, designed to appeal to his teachers by ‘slinging the bull’ – saying simple things in an impressive way, using long words and technical terms. His friends with greater literary talent (including Gast) had been confident enough to spread their wings and take up more controversial themes, with which the examiners could take issue (another example, to Feynman, of the ‘baloney’ involved in English). So they ‘only’ scored 88 per cent, while Richard scored 91 per cent (in one of his worst subjects).

In those days (Feynman graduated in the summer of 1935) many bright kids had to forgo a college education for financial reasons, but Melville and Lucille were determined to give Richard the best education they could. Even with his academic track record and his parents’ backing, though, getting into college wasn’t all plain sailing. He applied to Columbia University and the Massachusetts Institute of Technology (MIT). Columbia required an examination, and charged wouldbe students $15 for the privilege of taking it (at a time when the Feynman family income, remember, was about $100 per week); Richard took the exam, and presumably passed, but was denied a place at Columbia because they had already filled up their quota of Jewish students for that year. Feynman wasn’t bothered by the quota system, incredible though it seems to modern eyes; that was just the way things worked in the 1930s. But he would probably have appreciated it if the university had rejected him out of hand, without taking his $15 first.

That left MIT. Apart from the academic requirements, they insisted upon a recommendation from an MIT graduate for all prospective freshmen. This did rankle, but it was a hoop that had to be jumped through, and Melville did the jumping, persuading an acquaintance whom he knew had gone to MIT to provide the recommendation. But the acquaintance really knew nothing about Richard, who later described the system,[28] as ‘evil, wrong, and dishonest’, a falseness that was the only thing he disliked about applying to MIT. The unpleasant taste was eased somewhat when the college offered Richard a small scholarship – he had applied for a full scholarship, which he failed to get, but received the small award of about $100 per year, which would be a help.

In the summer of 1935, before he left for MIT, Feynman worked in his aunt's hotel (putting money aside ready for college) and spent a lot of time getting to know Arline better. It was at MIT that he would formally make the transition from being a mathematician to being a physicist, and he was lucky enough to arrive on the scene at a time when the physics textbooks had been completely rewritten by the development, in the 1920s, of quantum theory. The younger Feynman had read about some of this new work already, for pleasure; soon, it would become his vocation. In order to appreciate where Feynman was coming from when he began to make his own original contributions to science, it is time to take stock of the state physics was in just before Feynman came on the scene, in the aftermath of the quantum revolution and the slightly older revolution initiated by Albert Einstein with his two theories of relativity. Twentieth-century science was a very different world from the one in which physicists had operated for the previous 200 years, from the time of Isaac Newton (at the end of the 17th century), to the time of Max Planck (at the end of the 19th century).

Notes

1. Richard Feynman, interview with Jagdish Mehra, quoted in Mehra's book *The Beat of a Different Drum* (hereafter referred to as Mehra; details in Bibliography).
2. Feynman often recounted this anecdote. See, for example, *What Do You Care What Other People Think?*, by Richard Feynman & Ralph Leighton (hereafter referred to as *What Do You Care*; details in Bibliography). The widely recounted dinosaur, bird and wagon anecdotes can be found in the same source.
3. *What Do You Care.*
4. Leighton, interview with JG, April 1995.
5. Quoted in *No Ordinary Genius*, edited by Christopher Sykes (see Bibliography).
6. *What Do You Care.*
7. The story of Johanna and Henry Phillips is told by Joan Feynman in *No Ordinary Genius.*
8. *What Do You Care.*
9. See Joan Feynman's contribution to the Feynman memoir *Most of the Good Stuff*, edited by Laurie Brown & John Rigden (see Bibliography).
10. Joan Feynman's comments taken from correspondence with JG, January/February 1996.
11. Mehra.
12. *Most of the Good Stuff.*
13. There is no evidence that Lucille believed this. But she must have been aware of the extremely limited career opportunities

for women in science at the time, and was probably trying to steer Joan away from the likelihood of a major disappointment.

14. Interview with JG, April 1995; see also *No Ordinary Genius*.
15. *Most of the Good Stuff.*
16. Interview with JG, April 1995.
17. *No Ordinary Genius*; see also note 10.
18. Mehra.
19. See also *Six Easy Pieces* (see Bibliography).
20. See, for example, *Surely You're Joking, Mr. Feynman!*, by Richard Feynman & Ralph Leighton (see Bibliography; hereafter referred to as *Surely You're Joking*).
21. Mehra.
22. Mehra.
23. *No Ordinary Genius.*
24. Quoted by Hans Bethe, whom Kac described as an ordinary genius, in *No Ordinary Genius.*
25. Mehra.
26. *What Do You Care.*
27. Mehra.
28. Mehra.

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[*] The name is pronounced, rather appropriately, 'Fine Man.'

[†] Intriguingly, one of Feynman's own insights into the nature of the world now provides us (although it was not appreciated in his lifetime) with one way of explaining what inertia 'really is'; see Chapter 14.

[‡] The famous 'ultimate speed limit' from relativity theory is the speed of light *in a vacuum*, which is greater still.

2 Physics before Feynman

The two revolutions that transformed physics in the 20th century, relativity theory and quantum mechanics, both developed from new understandings of the nature of light, and both had their roots in the 19th century. When Albert Einstein developed his Special Theory of Relativity early in the 20th century[1] (it was published in 1905), the foundation stone on which he built was a discovery that had been made four decades earlier, in the 1860s, by the Scottish physicist James Clerk Maxwell.

Maxwell, who was born in 1831 and died in 1879 (the year Einstein was born), was one of the great physicists of his day, who made many contributions to science. But he is best remembered for his work on electricity and magnetism, which led him to the discovery that light can be described as an electromagnetic wave travelling through space at a certain speed. He developed a set of four equations, now known as Maxwell's equations, which can provide the answer to any question you want to ask about the 'classical' (that is, pre-quantum theory) behaviour of electricity and magnetism. Maxwell's equations will tell you the force that operates between two electrical charges of a certain strength a certain distance apart; they will tell you how strong an electric current is generated in a nearby wire by a magnet moving past at a certain speed; and so on. Every problem involving electricity and magnetism, above the quantum level, can be solved by using Maxwell's equations, which represented the greatest unifying discovery in science since Isaac Newton discovered the Universal Law of Gravitation.

One solution of Maxwell's equations, a natural component of the unified whole, describes electromagnetic waves moving through space. The speed with which the waves move, usually denoted by the letter c, is a constant which emerges naturally from the equations, as a fundamental property of nature. It is *not* put in by hand. It was when Maxwell found that the value of c which automatically comes out of his theory is exactly the same as the speed of light measured in a vacuum (which was already quite well determined by the 1860s) that he realized that his equations also described the behaviour of light. In 1864, he wrote:

> The velocity is so nearly that of light that it seems we have strong reason to conclude that light itself … is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws.[2]

That word ‘field’ is one to watch out for. It is related to the idea of lines of force, which helps us to visualize, for example, what happens when two magnets are brought together. In this case, the lines of force are thought of as something like stretched elastic bands, which start out from the magnetic ‘north pole’ on a bar magnet and end up on the magnetic ‘south pole’. When a north pole and a south pole are brought together, the lines of force reach out across the gap and pull the two poles together; but when two north poles are pushed together, the lines of force are forced out of the gap, creating a resistance and holding the two north poles apart (see Figure 2). The region around the magnet where it exerts this influence is the region of its ‘magnetic field’. In a similar way, physicists think of massive objects, like the Sun and the Earth, as being surrounded by a ‘gravitational field’, filled with lines of force that tug on any object in that field. Of course, lighter objects, such as our desk, or your pen, also have their own gravitational fields, but these are so weak that they can only be detected using very sensitive equipment.

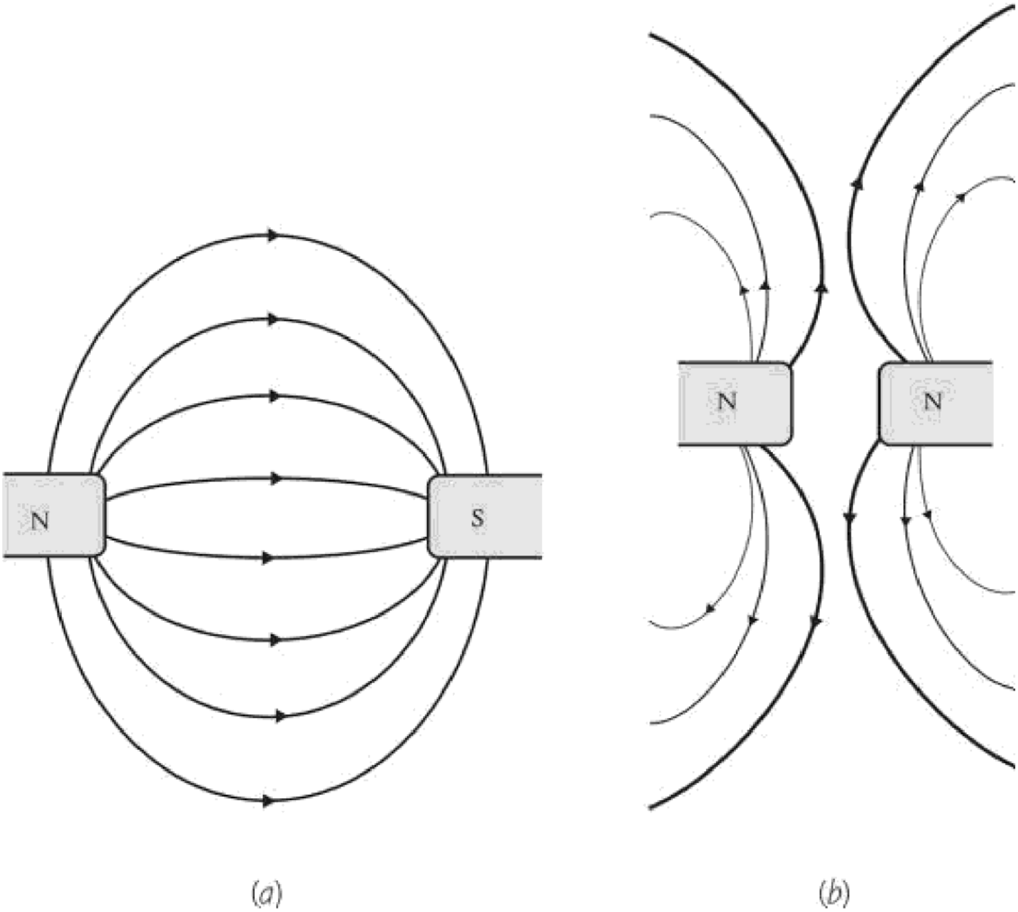

Figure 2. The concept of a field is related to the idea of ‘lines of force’. *(a)* A north magnetic pole and a south magnetic pole attract each other as if they were being pulled together by stretched elastic bands. *(b)* Two north magnetic poles repel each other as if they were separated by a block of stiff, compressed rubber. The magnetic field is stronger where the lines of force are closer together.

Field theory is an extremely successful way of describing the interactions between things like magnets, electrical charges and gravitating bodies. But don’t run away with the idea that it is the *only* way to describe these interactions. Without wishing to get too far ahead of our story, it’s worth warning you that one of the things that most intrigued Richard Feynman in later life was the way in which several different descriptions of the way things work can turn out to be equally effective in the right hands. Maxwell himself actually worked towards his field theory through an intermediate image which involved the forces of electricity and magnetism being conveyed by whirlpool-like vortices spinning in a fluid which filled all the space between material objects. The way the vortices interacted was like the cogs and wheels of some great piece of clockwork, and this early version of the theory looks totally bizarre to modern eyes – but it worked. The lesson to be drawn is that in some deep sense the truth about how the world works resides in the equations – in this case, Maxwell's equations – and not in the physical images that we conjure up to help our limited imaginations to visualize what is going on.

That was a point that was well appreciated by the young Einstein. One of the strangest things about the constant *c* that appeared in Maxwell's equation was that it was just that – a *constant*. It represented the speed of light (and all other electromagnetic radiation, including radio waves), but it took no account of how fast the object producing the light was moving, or how fast the person measuring the speed of the light was moving. This didn't match common sense, or the laws of motion based upon Newton's work in the 17th century and held sacrosanct ever since.

In the everyday world, if you ride in an open car that is travelling at 50 kilometres an hour (km/h) along a straight road, and you throw a ball straight out ahead of you at a speed of 5 km/h, then (if you could ignore wind resistance) you would expect the ball to be moving at 55 km/h relative to the road. But what Maxwell's equations seemed to say was that if you rode in the same car and shone its headlights out in front of you, the speed of the light from the car would not only be *c* relative to the car (as you would expect) but also *c* (not *c* + 50 km/h) relative to the road! Even if you were in a spaceship travelling at half the speed of light, and you met a spaceship travelling the opposite way at half the speed of light, the light from the headlights on the other spaceship would be travelling at the same speed of light, *c*, relative to your measuring instruments *and* relative to the measuring instruments in the other spaceship.

It was clear by the end of the 19th century that there must be something wrong either with Maxwell's equations or with common sense (and Newton's equations). It was Einstein's genius to take Maxwell's equations at face value, and work out all the implications in his Special Theory of Relativity. Einstein's theory explains how it can be that the speed of light (in a vacuum; it travels slightly more slowly in more dense media) is always measured to be the same no matter how the measuring instruments are moving relative to the light source. The implications include the fact that the faster an object moves, the more massive it gets; the fact that nothing can be accelerated from 'ordinary' speeds to travel faster than light (so that even if you are in a spaceship travelling at two-thirds of *c* relative to Earth, and you encounter a spaceship travelling in the opposite direction at two-thirds of *c* relative to Earth, the velocity of the other spaceship relative to yours is still less than c); and the famous relationship between mass and energy, $E = mc^2$.

All of these predictions, it cannot be overemphasized, have been tested many times to great precision. The Special Theory of Relativity passes every test, and has been proven to be a good description of the way the world works.[3] But you only need to use the Special Theory to understand what is going on if you are dealing with things moving at very high speeds, a sizeable fraction of the speed of light. The difference between the predictions of the Special Theory and common sense are of no significance at all for speeds that are small compared with the speed of light, which is itself a huge 300,000 kilometres per second. Unfortunately for the physicists, though, there are things which move at these so-called ‘relativistic’ speeds that have to be taken account of in their attempts to describe the way the everyday world works. In particular, electrons whizzing around inside atoms have to be described taking proper account of the Special Theory of Relativity.[*]

By the time Feynman went to MIT, the structure of the atom, and the way it operated in accordance with both quantum mechanics and special relativity, were pretty well understood, except for some annoying details. The electron had been identified in the 1890s by the British physicist J. J. Thomson, the role of the proton was appreciated by the beginning of the 1920s, and the neutron was identified in 1932. This combination of particles was all that was needed to explain the structure of atoms. Each atom contains a nucleus that is a ball of positively charged protons and electrically neutral neutrons, held together (in spite of the tendency of the positive charge on the protons to make them repel one another) by a very short range force of attraction, called the strong nuclear force. Outside the nucleus, each atom ‘owns’ a cloud of electrons, with one negatively charged electron for each proton in the nucleus, held in place by the mutual attraction between the negative charge on the electrons and the overall positive charge on the nucleus. In addition, during the early 1930s physicists began to suspect the existence of another type of particle, dubbed the neutrino, which had never been detected directly but was required to balance the energy budget whenever a neutron transformed itself into a proton by spitting out an electron (a process known as beta decay). Beta decay involves a fourth kind of force (after gravity, electromagnetism and the strong force), dubbed the weak force, or weak interaction.

Together with light, that’s all you need to explain the workings of the everyday world. But to anyone brought up on classical ideas (the kind of physics you get taught in school), there’s an obvious puzzle about this picture of the atom. Why don’t all the negatively charged electrons in the outer part of the atom get pulled into the nucleus by the attraction of all the positively charged protons? The world would be a far different place if they did, because the nucleus is typically about 100,000 times smaller than the electron cloud that surrounds it. The nucleus contains almost all of the mass of an atom (protons and neutrons have roughly the same mass, each about 2,000 times the mass of an electron), but the electrons are responsible for the atom’s relatively large size, and for the ‘face’ it shows to the world (that is, to other atoms). The reason they don’t fall into the nucleus is explained by the second revolution in 20th-century physics, the quantum revolution. Like the relativity revolution, this was also triggered by studies of the behaviour of light.

At the end of the 19th century, the world seemed to be made up of two components. There were particles, like the newly discovered electrons, and there were waves, like the electromagnetic waves described by Maxwell’s equations. You can make waves in a bowl of water by jiggling your fingers about in the water, and you can make electromagnetic waves by jiggling an electrically charged particle to and fro. So it was pretty clear, even then, that light was produced by electrons jiggling about in some way inside atoms. Unfortunately, though, the best 19th-century theories predicted that this jiggling would produce a completely different spectrum of light from what we actually see.

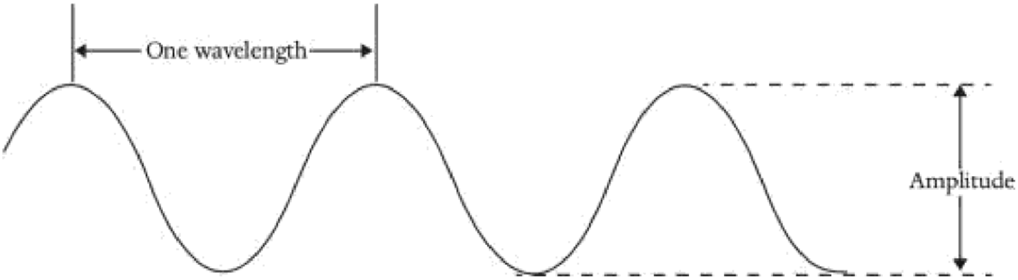

Figure 3. A wave. Two waves are in phase if they move in step so that the peaks reinforce one another. They are out of phase if the peaks of one wave exactly coincide with the troughs of the other wave, so that they cancel each other out. In-between states, with partial cancellation, are also possible.

What the theorists had to do was to explain the way light would be emitted from an idealized source called a ‘black body’. This seemingly bizarre choice of name (if it is black, how can it radiate any light at all?) results from the fact that when such an object is cold, it absorbs all the light that falls on it, without reflecting any away. It treats all colours (each colour corresponds to a particular wavelength of light) the same. But if it is gradually heated up, it will first begin to radiate invisible infrared radiation, then it will start to glow red, then orange, yellow and blue at successively higher temperatures, until eventually it is white hot. You can tell the temperature of a black body precisely by measuring the wavelength of the light it is emitting. This light forms a continuous spectrum (the ‘black body curve’), with most energy radiated in a peak at the characteristic wavelength for that temperature (corresponding to red light, or blue light, or whatever) but some energy coming out in the form of electromagnetic waves with shorter wavelengths than this peak intensity, and some with longer wavelengths. The shape of the black body curve is like the outline of a smooth hill, and the peak itself shifts from longer wavelengths to shorter ones as the black body gets hotter.

But according to 19th-century physics, none of this should happen. If you try to treat the behaviour of electromagnetic waves in exactly the same way that you would treat vibrations of a guitar string, it turns out that it ought to be easier for an electromagnetic oscillator to radiate energy at shorter wavelengths, regardless of its temperature – so easy, in fact, that all of the energy put into a black body as heat should come pouring out as very short wavelength radiation, beyond the blue part of the spectrum, in the ultraviolet. This was known as the ‘ultraviolet catastrophe’, because the prediction certainly did not match up with the real world, where such things as red hot pokers (which behave in some ways very much like black bodies) were well known to the Victorians.

The puzzle was resolved – up to a point – by the German physicist Max Planck, in the last decade of the 19th century. Planck, who lived from 1858 to 1947, spent years puzzling over the nature of black body radiation, and eventually (in 1900), as a result of a mixture of hard work, insight and luck, came up with a mathematical description of what was going on. Crucially, he was only able to find the right equation because he knew the answer he was looking for – the black body curve. If he had simply been trying to predict the nature of light radiated from a hot black body, he would never have produced the key new idea that did actually appear in his calculations.

Planck’s new idea, or trick, was to assume that the electric oscillators inside atoms cannot emit any amount of radiation they like, but only lumps of a certain size, called quanta. In the same way, they would only be able to absorb individual quanta, not in-between amounts of energy. And in order to make Planck’s formula match the black body curve, the amount of energy in each quantum had to be determined by a new rule, relating the energy of the quantum involved to the frequency (*f*) of the radiation. Frequency is just one over the wavelength, and Planck found that for electromagnetic radiation such as light

$$E = hf$$

where h is a new constant, now known as Planck’s constant.

For very short wavelengths, f is very big, so the energy in each quantum is very big. For very long wavelengths, f is very small and the energy in each quantum is small. This explains the shape of the black body curve, and avoids the ultraviolet catastrophe. The total amount of energy being radiated at each part of the black body spectrum is made up of the contributions of all the quanta being radiated with the frequency (and wavelength) corresponding to that part of the spectrum. At long wavelengths, it is easy for atoms to radiate very many quanta, but each quantum has only a little energy, so only a little energy is radiated overall. At short wavelengths, each quantum radiated carries a lot of energy, but very few atoms are able to generate such high-energy quanta, so, again, only a little energy is radiated overall. But in the middle of the spectrum, where medium-sized quanta are radiated, there are many atoms which each contain enough energy to make these quanta, so the numbers add up to produce a lot of energy – the hill in the black body curve. And, naturally, the wavelength at which the peak energy is radiated shifts to shorter wavelengths as the black body gets hotter and more atoms are able to produce higher-energy (shorter wavelength) quanta.

Although physicists were pleased to have a black body formula that worked, at first this was regarded as no more than a mathematical trick, and there was no suggestion (least of all from Planck himself) that light could only exist in little lumps, the quanta. It took the genius of Albert Einstein to suggest, initially in 1905, that the quanta might be real entities, and that light could just as well be described as a stream of tiny particles as by a wave equation. Although Einstein’s interpretation of the quantum idea neatly solved an outstanding puzzle in physics (the way in which light shining on a metal surface releases electrons in the photoelectric effect), initially it met with a hostile reaction. One American researcher, Robert Millikan, was so annoyed by it that he spent ten years trying to prove Einstein was wrong, but succeeded only in convincing himself (and everybody else) that Einstein was right.

After Millikan’s definitive experimental results were published (in 1916) it was only a matter of time before first Planck (in 1919) and then Einstein (in 1922, although it was actually the prize from 1921 held over for a year) received the Nobel Prize for these contributions. But the ‘particles of light’ were only given their modern name, photons, in 1926, by the American physicist Gilbert Lewis. By then, the Indian physicist Satyendra Bose had shown that the equation describing the black body curve (Planck's equation) could actually be derived entirely by treating light as a 'gas' made up of these fundamental particles, without using the idea of electromagnetic waves at all.

So, by the mid-1920s, there were two equally well-founded, accurate and useful ways of explaining the behaviour of light – either in terms of waves, or in terms of particles. But this was only half the story. We still haven't explained why electrons don't fall into the nucleus of an atom.

The first step, producing a picture of the structure of the atom that is still the one often taught in schools, was taken by the Dane Niels Bohr, in the second decade of the 20th century. Bohr had been born in 1885 and lived until 1962. He completed his PhD studies in 1911 and a year later began a period of work in Manchester, where he stayed until 1916, working in the group headed by the New Zealand-born physicist Ernest Rutherford.

Bohr's model of the atom was like a miniature Solar System. The nucleus was in the middle and the electrons circled around the nucleus in orbits rather like the orbits of the planets around the Sun. According to classical theory, electrons moving in orbits like this would steadily radiate electromagnetic radiation away, losing energy and very quickly spiralling into the nucleus. But Bohr guessed that they could not do this because, extending Planck's idea, they were only 'allowed' to radiate energy in distinct lumps, the quanta. So an electron could not spiral steadily inwards; instead it would have to jump from one stable orbit to another as it lost energy and moved inward – rather as if the planet Mars were suddenly to jump into the orbit now occupied by the Earth. But, Bohr said, the electrons could not all pile up in the innermost orbit (like all the planets in the Solar System suddenly jumping into the orbit of Mercury) because there was a limit on the number of electrons allowed in each orbit. If an inner orbit was full up, then any additional electrons belonging to that atom had to sit further out from the nucleus.

The picture Bohr painted was based on a bizarre combination of classical ideas (orbits), the new quantum ideas, guesswork and new rules invoked to explain why all the electrons were not in the same orbit. But it had one great thing going for it – it explained the way in which bright and dark lines are produced in spectra.

Most hot objects do not radiate light purely in the smooth, hillshaped spectrum of a black body. If light from the Sun, say, is spread out using a prism to make a rainbow pattern, the spectrum is seen to be marked by sharp lines, some dark and some bright, at particular wavelengths (corresponding to particular colours). These individual lines are associated with particular kinds of atoms – for example, when sodium atoms are heated or energized electrically they produce two bright, yellow-orange lines in the spectrum, familiar today from the colour of certain street lamps. Bohr explained such lines as the result of electrons jumping from one orbit (one energy level) to another within the atoms. You can think of this as like jumping from one step to another on a staircase. A bright line is where identical electrons in many identical atoms (like the sodium atoms in street lights) have all jumped inward by the appropriate step, each releasing the same amount of electromagnetic energy in the form of many quanta of light each with the same frequency given by Planck's formula $E = hf$. A dark line is where background energy has been absorbed by electrons making the appropriate jump up in energy, outward from one stable orbit into a more distant stable orbit ('up a step' on the staircase).

But why should only some orbits be stable, and others not? It was this puzzle that led the French physicist Louis de Broglie to make the next breakthrough in quantum theory, in the 1920s.

De Broglie, who was born in 1892, only began serious scientific work after his military service during the First World War and completed his PhD in 1924, at the relatively ripe old age of 32 (he lived to an even riper old age, until 1982). De Broglie suggested that the way in which electrons could only occupy certain orbits around a nucleus was reminiscent of the way waves behaved, rather than particles. If you pluck an open violin string, for example, you can make waves on it in which there are exactly 1, or 2, or 3, or any whole number of wavelengths, corresponding to different notes (harmonics) 'fitting in' to the length of the string, by lightly touching the string at various points that are simple fractions (½, ⅓, ¼ and so on) of the length. But you can't make a note corresponding to a wave with, say, 4.7 wavelengths filling the open string. In order to play that note you have to change the length of the string by pressing it hard with your finger against the neck of the violin. If electrons were really waves, said De Broglie, then each orbit in an atom might correspond to patterns in which a whole number of electron waves fitted around the orbit, making a so-called standing wave. The transition from one step on the energy level staircase to another would then correspond more to the transition from one harmonic to another than to a particle jumping from one orbit to another.

De Broglie's suggestion was so revolutionary that his thesis supervisor, Paul Langevin, didn't trust himself to decide on its merits, and sent a copy to Einstein, who responded that he thought the work was reliable. De Broglie got his PhD, and the scientific world had to come to terms with the fact that just as light, which they were used to thinking of as a wave, could also be described in terms of particles, so the electron, which they were used to thinking of as a particle, could also be described in terms of waves. In 1927, both an American team of physicists and George Thomson in England carried out experiments demonstrating the wave behaviour of electrons, scattering them from crystals. The wavelengths (frequencies) of electrons with a certain energy, measured in this way, exactly match Planck's formula $E = hf$. George Thomson, who thereby proved that electrons are waves, was the son of J. J. Thomson, who, a generation before, had first proved the existence of electrons as particles.

The notion of 'wave–particle duality' became one of the key ingredients in the quantum theory that was developed in the mid-1920s, and which Richard Feynman studied as an undergraduate. In fact, the quantum theory was developed twice at that time, almost simultaneously, once using what was essentially a particle approach and once using what was essentially a wave approach. The leading light in the development of the particle version was Werner Heisenberg, the first major participant in the quantum game to have been born in the 20th century (on 5 December 1901, at Wurzburg, in Germany). A variation on this theme (in many ways, more complete) was also developed independently by another young physicist, Paul Dirac, who was just a few months younger than Heisenberg, having been born at Bristol, in England, on 8 August 1902.

Erwin Schrödinger, an Austrian physicist, was the odd one out among the pioneers of the new quantum theory, having been born in 1887, and had obtained his doctorate back in 1910. He built from De Broglie's ideas about electron waves, and came up with a version of quantum theory that was intended to do away with all the mysterious jumping of electrons from one level in an atom to another, deliberately harking back to the classical ideas of wave theory.

It was Dirac who proved that all of these ideas were, in fact, equivalent to one another, and that even Schrödinger's version did include this 'quantum jumping', among other things, in its equations. Schrödinger was disgusted, and famously commented of the theory he had helped to develop, 'I don't like it, and I wish I'd never had anything to do with it.' Ironically, because most physicists learn about wave equations very early in their education, and feel comfortable with them, ever since quantum mechanics was established in the 1920s it is Schrödinger's version that has been most widely used for tackling practical problems, like interpreting spectra.

We don't want to go over the whole story of the development of quantum theory in the 1920s here,[4] and instead we'll jump straight to the final picture, which can best be understood (as far as anything in quantum physics can be understood) in terms of an example which Feynman himself would, much later, call the 'central mystery' of quantum mechanics. It is the famous 'experiment with two holes'.

In this example you can imagine sending either a beam of light or a stream of electrons through two tiny holes in a screen – the experiment has actually been done with both, and everything we are going to discuss here has been proved by experiment. When waves travel through two holes in this way, the ripples fan out from each hole on the other side of the screen and combine to form what is called an interference pattern, exactly like the interference pattern you would see on the surface of a still pond if you dropped two pebbles into it at the same time. In the case of light, this basic experiment was one of the techniques used to prove, early in the 19th century, that light is a wave – a second screen placed beyond the one with the two holes will show a pattern of light and dark stripes, 'interference fringes', produced in this way (see Figure 4*a*).

But if individual particles (such as electrons) are fired, one at a time, through the experiment with two holes, you would expect, from everyday experience, that they would pile up in two heaps, one behind each of the holes. A suitable detector screen on the other side (essentially the same as a TV screen) ought, if electrons are particles, to show two blobs, corresponding to the trajectories of electrons going through either of the two holes. But it doesn't. Here's what happens. Each individual particle starts out on one side, passes through the experiment, and strikes the detector screen. Surely, you would think, each particle can only go through one hole or the other. And, to be sure, each particle makes just one spark of light on the detector screen, indicating that it arrives as a particle. But after thousands of particles have been fired through the experiment one after the other, a pattern of sparks of light builds up on the detector screen. Not the two blobs behind the two holes that you might expect from your everyday experience of how particles behave, but the familiar interference pattern for waves! (See Figure 4*b*.) We stress that this experiment really has been done, and both electrons and photons behave in this way. It is as if each particle flies through both holes at once, interferes with itself, decides where it belongs in the interference pattern, and goes there to make its own individual contribution to the emerging pattern. Quantum entities seem to travel as waves, but to arrive (and depart) as particles.

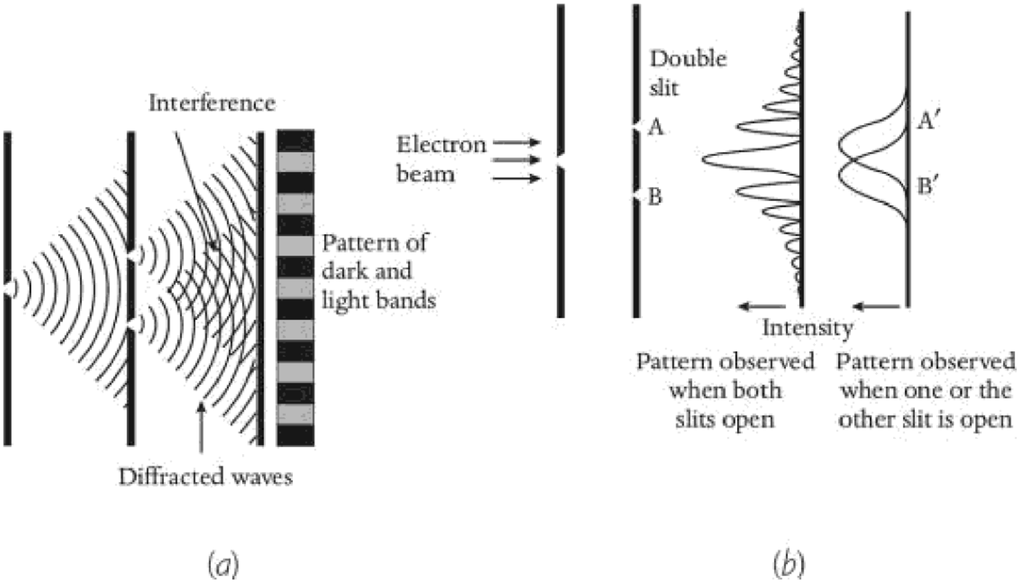

Figure 4. *(a)* When light spreads out from a pinhole in a screen to pass through two pinholes in a second screen, the pattern made up by the light from the second two holes shows alternating dark and light bands, exactly as if the light is behaving as waves which interfere with one another. *(b)* When electrons (or, indeed, photons) are fired through a similar set-up with one hole open, they pile up, like particles, in one heap behind the open hole. But if both holes are open, the 'particles' somehow interfere with each other to produce a pattern exactly equivalent to the pattern produced when waves interfere. This is the central mystery of quantum mechanics, the experiment with two holes. How do the electrons know in advance whether one or both holes are open, and adjust their behaviour accordingly?

As well as wave–particle duality, this example highlights another aspect of the quantum world – the role of probability. Nothing is certain in the quantum world. For example, before an individual electron is fired through the experiment with two holes it is impossible for the experimenter to say exactly where on the screen on the other side it will arrive. You can only calculate, in accordance with the rules of quantum probability, the chance of it ending up in a particular part of the interference pattern. It is likely to turn up in one of the bright parts of the pattern and unlikely to appear in one of the dark stripes in the pattern, but that is all you can say. Quantum processes obey the same rules of chance as the dice at a craps table in Las Vegas, which prompted Einstein to express his own disgust with the theory with his comment, 'I cannot believe that God plays dice.'

So how should we think of an electron 'in' an atom, where it is 'travelling' in its 'orbit', rather than 'arriving' at a detector? The standard picture, used by physicists for the past 70 years, says that the electron cannot be located at any one point in space near ('visible') to physicists as a normal electron. But it would have left behind a 'hole' in the negative-energy sea. Electrons have negative electrical charge, so, as Dirac pointed out at the end of the 1920s, the hole in a sea of negative charge would behave exactly like a particle with positive charge (absence, of negative being the same as presence of positive). If the hole were near a detectable visible electron, for example, negative-energy electrons in the sea would be repelled from the visible electron and would try to escape by hopping in turn into the hole; as one neighbouring invisible electron hopped in, the hole would fill up, leaving a hole where that invisible electron had been, and so on. The effect would be that the hole would move towards the visible electron, behaving just like a positively charged particle. To see what happens when the hole meets the visible electron, read on.

At this point, Dirac had a failure of nerve. Taking his equation at face value, the only physical meaning you could reasonably give to the hole would be as a particle exactly like the electron except for its positive charge. But in 1928, remember, physicists only knew two kinds of particle, the electron (with negative charge) and the proton (much more massive, but with a positive charge the same size as the electron's negative charge). Even the neutron had not yet been discovered. So Dirac suggested in his paper that the holes in the negative-energy electron sea could be identified with protons. This really didn't make sense, and partly as a result nobody really quite knew what to make of the notion of the negative-energy electron sea and its holes at first. But then, in 1932 the American Carl Anderson discovered traces of particles which behaved exactly like electrons but with positive charge, in cosmic ray experiments (cosmic rays are particles that arrive at the Earth from space). He concluded that the 'new' kind of particle was a positively charged counterpart to the electron, and gave it the name positron (an example of what is known as antimatter); it had exactly the right properties to match the behaviour of Dirac's holes. The same year, James Chadwick, in Britain, identified the neutron.

Almost overnight, the number of kinds of individual particles known to physicists had doubled, from two to four, and their view of the physical world was transformed. You can get an idea of the dramatic impact of these discoveries on the physics community by the speed with which the Nobel committee responded to them. In 1933, Dirac received the Nobel Prize in Physics (he deserved it anyway, but the successful 'prediction' of positrons clinched it); in 1934, there was no award (an astonishing decision to modern eyes!); in 1935 it was Chadwick's turn; and in 1936 Anderson received the prize.

Since then, a wealth of other subatomic particles have been discovered, and each variety has its own antimatter counterpart. All of this can be explained by variations on the hole theory, and that theory does still provide one of the best mental pictures of how energy is liberated when a particle (such as an electron) meets its antiparticle counterpart (in this case a positron) and annihilates, leaving nothing behind but a puff of energy. The electron has fallen into the positron hole, releasing energy as it does so, and both hole and electron simply disappear from the everyday world, cancelling each other out. Or, if energy is available (perhaps from an energetic photon) a negative-energy invisible electron can be kicked out of its hole and promoted into visibility, creating, along with the hole it left behind, an electron-positron pair.

But although the physical picture is simple and rather appealing (if you can live with the idea of a sea of negative-energy invisible electrons), the mathematics of the hole theory turned out to be rather cumbersome as a means of describing particle interactions. By the time Dirac received his Nobel Prize, the person who would demonstrate a much simpler way of describing interactions involving electrons and protons was just starting his final year in high school in Far Rockaway. Even though details of all the new discoveries had not yet filtered down into the standard textbooks and courses taught at universities (not even at MIT), Richard Feynman was exactly of the generation to be brought up on the new physics as an undergraduate, and to be prepared to carry things a stage (or two) further when it became time for him to make his own contributions to science. It helped, of course, to be a genius. A genius like Feynman would have made a mark on science whenever he had been born; but the accident of the timing of his birth decided the kind of mark he would make. As a member of the first generation to be brought up on quantum mechanics, he carried the triumphant, but still incomplete, theory through to its greatest fruition.

Even though the standard undergraduate textbooks might not yet tell the full story of quantum mechanics, Dirac himself had written a definitive account in his book *The Principles of Quantum Mechanics*, first published by Oxford University Press in 1930, which was the first comprehensive textbook on the subject. It came out in a new edition the year that Feynman set out for MIT, and the book (which later went through further revisions) is still the best introduction for serious scientists. The 1935 edition would have a profound influence on the young physicist at MIT – but at the time he started his undergraduate courses there, he didn’t even know that he was a physicist.

Notes

1. The full story of the development of Einstein's ideas is told in *Einstein: A Life in Science*, by Michael White & John Gribbin (Simon & Schuster, London, 1993; Dutton, New York, 1994).
2. James Clerk Maxwell, *A Dynamical Theory of the Electromagnetic Field*, 1864; see, for example, Ralph Baierlein, *Newton to Einstein* (Cambridge University Press, 1992), p. 122.
3. See note 1.
4. If you do want the details, see John Gribbin, *In Search of Schrödinger's Cat* (Bantam, New York & London, 1984).
5. But see *Schrödinger's Kittens*.
6. Largely by the American Linus Pauling, who summed up the work in his book *The Nature of the Chemical Bond* (Cornell University Press) in 1939, and received the Nobel Prize for his work in 1954.

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[*] Einstein's second great theory, the General Theory of Relativity, is a field theory of gravity, and is quite different (in spite of the similarity of names) from the Special Theory of Relativity. It comes into our story later, but it had little bearing on the mainstream of physics research in the 1930s and 1940s.

3 College boy

New students at MIT had to find a fraternity which they could join, to provide them with a home and a social group within which they would fit into the college community. This system was basically a good one, in which senior students would look after freshmen in their own fraternity, teaching them the college ropes and looking out for their interests; occasionally, rivalry between fraternities and ragging of younger students by older ones got out of hand, but this doesn't seem to have been a problem at MIT in Feynman's time there.

For many students, the process of joining a fraternity would involve offering themselves to different fraternities, and trying to persuade them that you were a desirable prospective member of the group. For the best students, like Feynman, it worked the other way around. The fraternities sought you out, and tried to persuade you to join them. In fact, in Feynman's case the choice (or competition) was limited. There were only two Jewish fraternities at MIT, and there was no way, in those days, that Richard could join a non-Jewish fraternity. This 'Jewishness' had nothing to do with religion, which Feynman had long since abandoned; it simply had to do with your family background. Both these fraternities were on the lookout for bright students, and held gatherings called 'smokers' to get to know boys from New York who were going to MIT.

Feynman, who still thought of himself as a mathematician at this time, went to both these smokers. At one, for the fraternity Phi Beta Delta, he discussed science and maths with two older students, who told him that since he knew so much maths already he could take examinations at MIT as soon as he arrived there, which would allow him to skip the first-year course and go straight on to the second-year work in the subject. Both Phi Beta Delta and the rival fraternity, Sigma Alpha Mu, were eager to enrol Feynman, who was obviously going to be the kind of student that would add lustre to their groups (but don't run away with the idea that fraternities were only interested in academic ability; they were just as eager to attract students with other talents, such as sportsmen). Partly on the strength of the good advice he had already received from them, Feynman agreed to join Phi Beta Delta.

When the time came to leave Far Rockaway for MIT, however, some of the students from Sigma Alpha Mu called round. They would be driving up to college, and offered Feynman a ride, which he happily accepted. Like all mothers in such circumstances, Lucille watched with mixed feelings when the day came and, as arranged, her son drove off with a bunch of strangers on the journey to Boston, on what became a snowy day with tricky driving conditions. But Feynman was elated that he was being treated like an adult: ‘it was a big deal; you are grown up!’[1]

But the deal wasn’t quite that simple. What Sigma Alpha Mu had done, in effect, was to kidnap Feynman, hoping to enrol him with their fraternity before their rivals at Phi Beta Delta realized what was going on. They suggested, having arrived late in Boston, that he stay the night in their house, and he agreed, not realizing that he was the subject of this tug of war. In the morning, two of the seniors from Phi Beta Delta turned up to claim their own, and after some discussion Feynman finally did become a pledge at Phi Beta Delta, feeling a warm glow at being the centre of all this attention; partly as a result, he immediately began to overcome his old self-consciousness about being a sissy that everybody laughed at. The other fraternity members soon helped to develop his social skills further, although he never became what you would call a conformist in social matters.

Just before Feynman had joined Phi Beta Delta, the fraternity had almost collapsed because of a conflict of interest between its members. About half the fraternity brothers were wild socialites, who had cars, knew all about girls and organized dances. The rest were serious academic types, who studied all the time, were socially gauche and never went to the dances. In *Surely You’re Joking*, Feynman recounts how, in order to avoid breaking apart entirely, the fraternity members had got together and agreed to help each other. Everybody in the fraternity had to achieve a certain grade level in their courses, and if one of the socialites was having difficulty then the academics were obliged to help them get up to the required standard. In return, everybody, including the academics, had to go to every dance. The socialites would help by teaching the others how to dance and other social niceties, and even by making sure that they each had a date for the evening. Apparently, the system worked beautifully, and was an ideal way for Feynman to learn how to socialize. ‘It was’, he said, ‘a good balancing act.’

Not that he didn’t have some difficulty with the lessons. It had to be explained to him, for example, that it was not done to invite waitresses to the dance, and although he still lacked the confidence to disregard their advice in this regard, he couldn’t photon seemed to know in advance about the set-up of the experiment with two holes before it passed through the apparatus. He was a pragmatist, who asked only that theories should be able to predict the outcome of experiments with reasonable accuracy, a philosophy that he tried to pass on to his students. Just how the photon got from A to B didn't matter, as long as the theory could tell you that it would indeed, if it started out from A in a certain way, end up at B.

Feynman used to listen to Cohen and Crossman discussing problems they had been set in Slater's course. After a couple of months, he was confident enough to chip in when they were worrying about how to solve some problem. 'Hey,' he said, 'why don't you try Baronally's equation?' Cohen and Crossman had never heard of 'Baronally'. The trouble was, being self-taught and only ever having seen the name in a book, he had hopelessly mispronounced the name 'Bernoulli'. But eventually communication was established. They tried the equation, and it worked. From then on, the two seniors were always ready to discuss their physics problems with Feynman, and although he couldn't do them all, he often knew some trick, like Bernoulli's equation, that would set them on the right trail. And by talking about the problems, of course, he picked up a lot more so-called advanced physics. By the end of the year, he had decided that he knew enough to tackle the course (aimed, remember, at seniors and graduate students) in his sophomore year.[2]

When he turned up to register for the course, Feynman was wearing his Reserve Officer Training Corps (ROTC) uniform, which was compulsory for first-and second-year students. All the seniors and graduate students wore their everyday clothes. They had green or brown cards to fill in to register, corresponding to their status; Feynman had a pink card. In addition, he looked even younger than he really was. It all made him feel good; he liked to be seen as the boy genius. This time, though, he wasn't alone. Another student in ROTC uniform, carrying a pink card, came and sat next to him. It was another boy genius, another sophomore, Ted Welton, who also had enough self-confidence to sign up for the advanced course.

The two prodigies cautiously got to know each other, verbally circling around one another to see if they would be rivals or friends. Feynman noticed that Welton was carrying a book on differential calculus that he had wanted to get out of the library. Welton discovered that a book he had been trying to find in the library had been taken out by Feynman. Feynman claimed he had taught himself quantum mechanics already, using Dirac's book; Welton claimed that he had learned all about the General Theory of Relativity. Each was impressed by the other. They decided that ‘cooperation in the struggle against a crew of aggressive-looking seniors and graduate students might be mutually beneficial’,[3] and soon became firm friends.

Even among the aggressive-looking seniors and graduate students, Feynman stood out. For the first semester, the course was taught by Julius Stratton, a young physicist who certainly knew his stuff (he went on to become President of MIT) but sometimes didn’t prepare his presentation with due care and attention. Whenever he got stuck in the middle of a lecture, he would turn to the audience and ask, ‘Mr Feynman, how did you handle this problem?’, and Dick would take over. ‘I note’, Welton recalled many years later, ‘that Stratton never entrusted his lecture to me or to any other student.’[4]

Quantum mechanics appeared formally in the second semester of the course, and was taught by another young physicist, Philip Morse. Feynman and Welton, having worked together through some introductory texts by then, swallowed this up and were eager for more. They asked Morse where they could go for the real quantum nitty gritty, and as a result he invited them, during their junior year, to visit him one afternoon a week, along with a promising student in his senior year, for special tuition in the subject. Eventually Morse gave them real problems to solve using quantum mechanics – such as the separation of the energy levels for the electron in a hydrogen atom. This brought home to them, forcefully, that it wasn’t just some abstract theory, but practical science which could indeed be used to solve real problems.

Feynman also swallowed up courses in chemistry, metallurgy, experimental physics and optics – anything scientific was meat and drink to him. When a new course in theoretical nuclear physics, intended for graduate students, was offered for the first time at MIT, he went along to sign up for that as well. There was a crowd of students already in the room, and Morse was sitting on the window sill. He looked up, and asked if Feynman intended to register for the course. Feynman replied that he did. Morse asked if Welton was coming along. Feynman said yes. Good, said Morse; that meant they could start. It turned out that the rules required at least three students to enrol formally on the course, for credit, before it could be given. Only one of the graduate students had been willing to sign up for it. The others were afraid that they might flunk it, damaging their grade averages, but were eager to sit in on the course as observers, without being examined on the subject, if it did take place. So two of the three officially enrolled students for the new graduate course were actually undergraduates. Feynman, in the end, found it all quite straightforward – and passed the graduate course with flying colours.

There was one outstanding oddity about the way Feynman did his science at MIT, in the light of how he later made his mark in science. He liked to solve problems 'properly', by working out the relevant equations – in the case of a ball flying through the air, for example, this would involve solving Newton's equations of motion. There was an easier way, which the students at MIT were taught, called the Lagrangian approach, after the French mathematician Joseph Louis Lagrange, who lived from 1736 to 1813 and was made a Count by Napoleon Bonaparte. The beauty of the Lagrangian approach is that it doesn't involve calculating the changing forces and accelerations affecting, in this example, the flight of a moving object instant by instant, but deals only with the overall energies involved and the elapsed time.

Sound familiar? The Lagrangian approach is, indeed, directly based on the Principle of Least Action, that Feynman had fallen in love with when it had been introduced to him by Bader in high school. Why he eschewed this approach as an undergraduate remains a mystery, but the most likely explanation is his love of both problem solving (preferably from first principles) and showing off. While his fellow students, including Welton, were solving the problems the easy way, using the Lagrangian, Feynman would solve them even more quickly (in almost all cases) the hard way, integrating the equations of motion as laid down by Newton – a technique often known as the Hamiltonian method, after the 19th-century Irish mathematician William Hamilton. This involved working with 'the Hamiltonian', an appropriate set of differential equations describing the system being investigated.

'My way would take ingenuity,' Feynman later said,[5] 'whereas the trick of the Lagrangian was that you could do it blindfold.' Shades of the old days of the Interscholastic Algebra League! The trouble was, for the problems the students were given at undergraduate level, the Lagrangian approach was simply too easy for Feynman to bother with; it hardly gave him scope to exercise his brain. But he learned the approach anyway, if only to be able to test it against the conventional methods, such as the Hamiltonian approach, and see which was really quickest in a variety of situations. And in a few years' time, when he came up against some *really* tricky problems, he was happy to use the technique to solve them.

But if Feynman found the science taught at MIT so easy that he had to make his own difficulties in order to make the problem solving more interesting, outside the sciences it was a different matter. In a letter to a friend soon after he started at MIT, Feynman described the courses he was taking as 'physics, math, chemistry, ROTC, English; in decreasing order of pleasure I get out of them'.[6] But he soon found something even worse than English that he had to struggle with in order to keep up his overall grades and be allowed to graduate.

MIT quite rightly required all their students to take (and pass) three humanities courses, in order to become at least slightly more well rounded as citizens by the time they graduated. English, like it or not, was compulsory, but to Feynman's delight he found astronomy listed as a humanities course, so that was no problem. But for his third choice, after rejecting possibilities such as French literature, he was left with philosophy, which at least sounded as if it ought to have some bearing on science. But he was wrong, at least as far as the philosophy being taught to undergraduates at MIT in the 1930s was concerned.

In *Surely You're Joking*, he explained how he scraped through the English and philosophy courses without bringing shame to the fraternity – for, of course, in these cases the boot was on the other foot, and it was Feynman who was obliged to seek help and advice from the others in order to achieve the standard that the fraternity felt was acceptable for one of its members.

In English, for example, on one occasion the assignment was to write a theme on Goethe's *Faust*. Feynman was in despair, unable to come up with anything, and threatening not to hand in any work at all. His fraternity brothers persuaded him that he had to write something – anything – just to prove that he wasn't trying to get out of doing the work. So he wrote an essay on the theme 'On the Limitations of Reason', discussing the relevance of moral values, scientific methods of reasoning and so on. But there was nothing about *Faust*. One of the fraternity brothers read the theme, and advised Feynman that what he should now do was add a few lines linking what he had said to *Faust*. It seemed ridiculous, but under pressure from his peers Feynman complied, adding half a page saying that Mephistopheles represents reason, Faust the spiritual, and that Goethe's aim in writing *Faust* was, indeed, to show the limitations of reason.

The professor was completely taken in. He commented that the introductory material was good, even if the direct references to *Faust* were rather brief, and awarded Feynman a B+. More confirmation that English was a 'dippy' subject – but the grade was up to the requirements demanded by the fraternity.

Philosophy, though, was beyond mere dippiness. According to Feynman, the professor who gave those classes, an old man with a beard, mumbled so much that Dick could not understand a word he was saying. To pass the time in class, Feynman used to drill holes in the sole of his shoe, using a one-sixteenth drill bit that he carried in his pocket, twisting it between his fingers. The crunch came when it was time to write a theme at the end of the course.

The only words that Feynman could recall from the weeks of lectures were ‘stream of consciousness’. That gave him the idea of writing about what happens to the stream of consciousness when you go to sleep – how does it switch off?

Formulated that way, the project became a scientific experiment. There were four weeks to go before the theme had to be handed in, and every afternoon (as well, of course, as every night) Feynman would go to his room, lie down and go to sleep, while trying to observe mentally what was happening. He noticed, among other things, that as he dropped off to sleep the flow of ideas still seemed to his consciousness to be logically connected, even as they became more jumbled. He watched his mind ‘turning off’, and wrote a theme about his experiences. To round it off, he ended with a little verse:

I wonder why. I wonder why.
I wonder why I wonder.
I wonder *why* I wonder why
I wonder why I wonder!

At the end of the course, instead of a final lecture the professor picked out a few of the better themes to read to the class. To Feynman, sitting twisting his drill bit into the sole of his shoe, it was the same old gibberish. As far as he could tell, the professor was mumbling something along the lines of ‘Mum bum wugga mum bum … ‘Dick had no idea what the theme was about. The professor came to another theme, and read on: ‘Mugga wugga mum bum wugga wugga …’ Neither Dick nor his drill bit had a clue what it was about, until the professor got to the end, and recited:

Uh wugga wuh. Uh wugga wuh.
Uh wugga wugga wugga.
Uh wugga *wuh* uh wugga wuh
Uh wugga wugga wugga.

It was only then that Feynman realized his contribution had been singled out for praise.[7] He got an A for his theme, without having understood anything the professor had tried to teach during the course. In English, he had at least been aware of the plot of *Faust*, and made some effort to mention it in his theme. His belief that philosophy was completely idiotic was reinforced, but again he had achieved a good enough grade.

In fact, during his time at MIT Feynman didn’t do anything outside science unless he had to. ROTC was compulsory, so he joined; but he didn’t join any other clubs or societies. The fraternity dances were compulsory, so he went along, and well. This must have been a great relief to Melville. The scientist Feynman was assigned to was Wheeler. He was 28, and Feynman 21, when they met for the first time. Perhaps over-conscious of his own relative youth, Wheeler (who was a first-rate scientist and had already worked for a couple of years with Niels Bohr's group in Copenhagen) tried to establish what he regarded as the proper professor–student relationship from the outset.

The full flavour of the first encounter between Feynman and Wheeler doesn't always come across in books about him, but it was a highly significant meeting of minds that set the scene for a fruitful collaboration between two scientists who were both open to new ideas in physics, no matter how wild. It was obvious to anyone who knew him, even slightly, that Feynman had this crazy kind of genius. But Wheeler has always seemed, from the outside, to be a much more sober kind of person. He wears suits and ties, he is calm and respectable, he doesn't play the bongo drums or crack safes. But behind the façade lies one of the best ideas brains of the past 60 years, an expert on exotica such as black holes (he coined the term in its astronomical sense) and parallel realities. Reading some of Wheeler's scientific papers, it is hard to believe that the bizarre images they conjure up spring from the mind of a man who looks like the head of an old-fashioned bank.

As a pompous and somewhat self-important 28-year-old, though, who had yet to make his own mark on science, Wheeler felt that his time was too valuable to squander overmuch on new graduate students. He made an appointment to see Feynman at certain times every week, and told him that each meeting would last for a certain time. It is easy to imagine the freewheeling Feynman's internal reaction to this rigid timetabling. At the start of the first of these formal meetings, Wheeler made a show of pulling out his expensive pocket watch and placing it on the table, so that he would know when Feynman's time was up – and so that Feynman would know his place in the pecking order. Well, thought Dick, two can play at that game. Before the next meeting, he bought a cheap pocket watch of his own, which he brought along and laid on the table alongside Wheeler's watch, as if to say that his time was just as valuable as Wheeler's, even if it was measured on a cheap watch.

If Wheeler had really been the pompous ass he was pretending to be, or if Feynman had gone along with the pomposity without questioning it, their relationship might never have developed beyond the formal. As it was, both men saw the humour of the situation, and collapsed into fits of laughter reminiscent of the scenes round the dinner table at Far Rockaway – corpsing, like actors unable to continue with their lines. Every time they tried to get down to business, one of them would start giggling again and set the other off. The two men became firm friends, and when the time came Feynman had no hesitation in choosing Wheeler as his thesis adviser. The pattern of their first encounter continued throughout their student–teacher relationship: ‘Discussions turned into laughter, laughter into jokes and jokes into more to-and-fro and more ideas.’[13]

A graduate student at Princeton had plenty of choice in his work, both of his thesis supervisor (if the professor he wanted was willing to take him on) and in the courses he attended. In fact, there were no formal course requirements at all (sheer bliss after the labours of English and philosophy at undergraduate level), although the student had to pass tough preliminary examinations, complete a satisfactory thesis based on original research, and defend that thesis in a rigorous oral examination. Among the classes Feynman chose to attend was a graduate-level course in biology, a subject he was to dabble in at an even higher level later in his career; there was, quite frankly, nothing he could learn from the graduate courses in physics. The research students helped each other out with their problems, though, and that way they learned a lot about what was going on in physics in general, not just the area covered by their own thesis topic. On one occasion early in his time at Princeton Feynman was able to calculate, using quantum theory, the value of a parameter that one of his fellow students needed in order to explain certain details of the way an atomic nucleus captures an electron, in the process known as inverse beta decay. It was the first time that he had made a calculation that was needed in connection with a current experiment at the cutting edge of physics.

Just as he hadn’t been worried that the Greeks had discovered the rules of geometry before he had, Feynman wasn’t concerned about what use, if any, his fellow student made of the calculation. ‘The important thing was that I did it, that was the beginning of the real stuff, and it felt good.’[14] As ever, the important thing, to Feynman, was solving the problem. Throughout his career, he would be almost entirely unconcerned about publishing his discoveries. The important thing was that *he had done it*. He couldn’t resist problem solving, and when faced with a problem he was largely unconcerned about whom he was talking to. As a research student, he had no hesitation in questioning even Albert Einstein, who by then was based at the Institute for Advanced Study, in Princeton, and gave a seminar at the university. The name and the reputation didn’t mean a thing. There was just some guy, a fellow scientist, giving a talk, and if something he said didn’t sound right then Feynman would question him until it did make sense.

There was another way in which Feynman lacked respect (in the best possible way) for authority, linked to his love of problem solving. He wanted to work out *everything* for himself, from first principles.[15] That way, he could be sure he had got it right, instead of, perhaps, wasting valuable time developing someone else's ideas, only to find that those ideas had been wrong in the first place. He was encouraged in this attitude by the last sentence in the 1935 edition of Dirac's book on quantum physics, which said, 'it seems that some essentially new physical ideas are here needed' – a sentence he quoted to himself as a kind of mantra for the rest of his life. Whenever Feynman was stuck with a physics problem he was working on, even in the 1980s, he would walk around muttering 'it seems that some essentially new physical ideas are here needed' while trying to find a way out of the impasse.[16]

The sentence made such an impression on Feynman, when he first read it, because Dirac himself was admitting that quantum theory as understood in the 1930s was incomplete and imperfect, and that new ideas were needed. So, surely, the last thing to do was to try to use these old ideas as the starting point for a new version of quantum physics. Better, thought Feynman, to start entirely from scratch, build his own quantum theory, and see if the problems that so puzzled Dirac and his contemporaries could be solved that way. This idea had been firmly planted in Feynman's mind while he was still at MIT; it flowered at Princeton, and came to fruition, as we shall see, in his masterwork after the Second World War.

But all that still lay far in the future when the young graduate student was struggling to come to terms with the social scene at Princeton. Princeton was deliberately designed as an imitation of the old colleges of Oxford and Cambridge, both in its architecture and its social style – and its imitation English accents. Feynman was assigned a room in the Graduate College, an impressive, ivy-clad building complete with a Great Hall with stained glass windows and a Flail Porter to guard the door of the college. He was more than a little nervous about what he had let himself in for, especially since his colleagues at MIT had been teasing him about how horrified Princeton would be by this rough diamond from Brooklyn. He had hardly got settled in his room, on the Sunday he arrived, when he was invited to join the Dean for tea – a regular Princeton ritual – that afternoon. The event was very formal, Feynman was very nervous and didn't know anybody. It was there, his mind preoccupied with trying to work out where he should go, and whether he ought to sit down, that he was offered tea by the Dean's wife, who asked if he would like cream or lemon in it. 'Both please', he replied absentmindedly, leading to the famous response 'Surely you're *joking*, Mr Feynman!' that later became the title of his first bestselling popular book.

But Princeton wasn't all formality and imitation English manners; it had a first-class physics school, to which Feynman had been attracted by noticing how often the address appeared on papers in the *Physical Review*. He imagined the Princeton cyclotron (an early form of particle accelerator) as a huge and impressive instrument, polished with care and attended by acolytes in gleaming white coats (rather like the 'scientists' you see in a soap powder commercial today). But when he went over to the physics building, the day after the Dean's tea incident, to see the great machine for himself, he found something else entirely; a homely device tucked away in a basement and surrounded by wires and cables and water pipes, with bits of wax stuck over it where things were being fixed, and water dripping from some of the pipes. It was just like his own childhood 'laboratory' on a larger scale – a real research instrument, where people tinkered 'hands on' and persuaded the machine to perform its tricks. Nothing could be more different from the formal face of Princeton typified by the Dean's tea, and Feynman fell in love with the cyclotron on the spot, happy to be reassured that he had indeed come to the right place to do his kind of physics.

Graduate College also had its advantages, since people from all disciplines were living together under one roof, and Feynman could get involved in deep discussions with researchers from other fields. Sometimes he sat at dinner with the philosophers (winding them up by demonstrating the shallowness of their debates), sometimes with the biologists and often with the mathematicians. He learned that he was able to keep track of time accurately for long periods by counting in his head, and competed with John Tukey, who later became an eminent statistician, in performing this trick while engaged in other tasks, such as reading, or running up and down stairs. They discovered that they did their mental counting in different ways. Feynman 'heard' a voice counting off the seconds in his head, while Tukey 'saw' the numbers marching past. As a result, Feynman could read a book while still keeping his mental count, but Tukey could not, because the reading part of his brain was busy. On the other hand, Tukey could talk while counting, but Feynman could not (so he could not read out loud), because the verbal part of his brain was busy.[17] It was only much later that Feynman realized that this was an important discovery about the working of the mind, showing how the same end could be achieved in different ways, and was original enough for it to have been published in a psychology journal in the 1940s.[18]

At Wheeler's house, where Feynman often worked with Wheeler, he would amuse Wheeler's two small children with jokes and tricks, including demonstrating how to tell if the contents of a tin can are liquid or solid by tossing the can in the air and watching the way it wobbles in its flight.[19] When a professor of psychology visited Princeton to lecture on hypnosis, Dick was the first to volunteer to be hypnotized (to his surprise, it worked). And his drumming became more practised.

Feynman was happy, his work was going well (as we discuss in the next chapter) and in many ways the future seemed assured. In spite of Melville's fears (he also called on Wheeler during Richard's time at Princeton, this time asking outright whether anti-Jewish prejudice might affect Richard's career and being firmly told 'no'), there would clearly be no problem about Richard's finding a job after completing his PhD, and as soon as he was no longer a student he and Arline could marry. Long before the end of Richard's first year at Princeton, the authorities were well aware that they had something special on their hands. In a reference endorsing Feynman's application for a Proctor Fellowship, on 17 May 1940, H. P. Robertson, the Professor of Mathematical Physics, described him as a 'most promising student' and said that 'at the corresponding stage in their careers', Richard's showing was 'better than that of John Bardeen'.[20] Bardeen later became the first person to win the Nobel Prize in Physics twice, which is some indication of how special Feynman was as a graduate student. He would certainly have no problem making a career in physics. But there were two clouds on the horizon.

The war in Europe had begun almost exactly at the time Feynman was joining Princeton, in the autumn of 1939. Over the following months, the United States became increasingly involved in the war effort as a 'neutral' supporter of the British cause, and it seemed increasingly likely that at some stage the country would formally join in the fight against Hitler. Few of Feynman's peers had any doubts that this would be the right thing to do; many eminent Jewish scientists (including Einstein) were now based in America precisely because they had had to flee from Hitler's Germany, and the war could be understood in black and white terms (and was, indeed, being presented that way in government propaganda), as 'good guys against bad guys'.

Like many of his contemporaries, Feynman increasingly felt that he ought to do something to help the war effort. When he had been at MIT, he had repeatedly tried to get a summer job at the Bell Laboratories, failing (it seems likely with hindsight) because of an unspoken objection to his Jewish background. In the spring of 1941, at the fourth or fifth time of asking, he was accepted, and felt very happy. But then a General visited Princeton, to give a talk about the importance of physics in the

Feynman family went to stay in Atlantic City for a holiday, and Dick joined them for the weekend. Everyone was swimming in the pool, having a great time, but Arline had to get out and lie down because of her tiredness.

After a while, the lump changed slightly, Arline developed a fever and was taken into hospital. The illness was initially misdiagnosed, first as typhoid, then as Hodgkin’s disease. Meanwhile Feynman, reading up the symptoms in the medical library at Princeton, decided that they matched those of tuberculosis of the lymphatic glands. But the textbook said ‘this is very easy to diagnose’, so he decided that that couldn’t be the problem, or the doctors would have found it.[25] Either way, Hodgkin’s disease or TB, the disease was, in those days, almost certainly fatal. Feynman wanted to tell Arline the truth, but was prevailed upon by her family to join in a ‘white lie’ that it was only glandular fever, and that she would soon recover.

For a time, Arline did get slightly better, and returned home, where she guessed that the illness was much more serious when she heard her mother crying. To his immense relief, Richard was able to tell her the truth (as the doctors saw it at the time), and the couple began to re-plan their future in the light of this new development.

By now, Richard was nearing his final year at Princeton, and had been awarded a scholarship, one of the stipulations of which was that it could not be held by a married student. His first reaction to the news of Arline’s death sentence – she had been given a maximum of two years to live was that he wanted to marry her at once, and look after her for her final years. Incredibly, when Feynman asked permission for the ‘no marriage’ rule to be waived in this very special case, it was refused. He would have to choose between the scholarship and marriage, and without the scholarship he couldn’t afford to live while completing his PhD. Feynman seriously considered giving up the thesis and seeking a job with Bell Labs, or somewhere similar. But then, at last, came the final, correct diagnosis of Arline’s condition. It was indeed tuberculosis of the lymphatic glands.

The situation by then was so desperate that, in spite of Feynman’s anger at his own failure to press the possibility of this diagnosis on the doctors (although it is hard to see how they would have taken much notice of him), the couple regarded this diagnosis as good news. After all, according to the doctors it might mean that Arline would live for another five years. So the immediate pressure to marry was eased, and Richard did keep the scholarship, finish his PhD and get started on the road that would lead him to Los Alamos to work on the Manhattan Project.

Feynman came under enormous pressure from his family and friends not to go through with the marriage. Chief among the opposition, Melville still thought that marriage, even to a healthy bride, would damage Richard’s career prospects, while Lucille was more concerned that he would catch TB and die. But there was never any doubt in Richard’s own mind that he was doing the right thing, even though he and Arline understood that they could only ever have a limited physical relationship, and could not even kiss for fear of contagion. The decision to go ahead with the marriage as soon as he had received his PhD led to a rift between Richard and his parents which was never really healed, but he never regretted the decision.

By the time Dick had been awarded his PhD, Arline was permanently hospitalized, staying at the state hospital on Long Island. He arranged for her to move to a charitable hospital called the Deborah Hospital, at Browns Mills (near Fort Dix), in New Jersey, close to Princeton. He borrowed a stationwagon from a friend at Princeton, and fixed it up, as he described in *What Do You Care*, ‘like a little ambulance’, with a mattress and sheets in the back for Arline to rest on. On 29 June 1942, the couple had a romantic ride on the Staten Island Ferry, and got married in the borough of Richmond (sealing the ceremony with a chaste kiss on the cheek); then the groom delivered his bride to the Deborah Hospital, and left her there, where he could visit her every weekend.

For a while, the newly married, newly qualified Dr Feynman stayed on at Princeton, working on the fringes of what was now called the Manhattan Project. Arline, an indomitable character, kept her spirits up in hospital by writing daily letters to Dick, initiating crazy projects (more of these in Chapter 5), and planning for what she knew was a mythical future of normal married life. Once, she sent Dick a box of pencils, each one emblazoned in gold with the message ‘RICHARD DARLING, I LOVE YOU! PUTSY’. He was pleased, but embarrassed. The message was nice, and (as Arline had known) he needed pencils. Such stuff was in short supply, and too valuable to waste. But he didn’t want one of the professors noticing the legend. So he got a razor blade and neatly cut the message off of the pencil he was using. But Arline was ahead of him.

Next morning, he received a letter from her, beginning ‘WHAT’S THE IDEA OF TRYING TO CUT THE NAME OFF THE PENCILS?’, and ending ‘WHAT DO *YOU* CARE WHAT OTHER PEOPLE THINK?’ He left the rest of the pencils intact, ignoring the gentle ribbing that resulted when colleagues picked them up. It was a message that he took to heart, carrying it with him to Los Alamos and beyond, right up to his involvement with the *Challenger* inquiry. But before we go into all that, it is time to take stock of the scientific work with which Feynman made his initial reputation, as an undergraduate at MIT and then as a research student at Princeton.

Notes

1. Mehra.
2. Mehra.
3. Quoted by James Gleick in *Genius* (see Bibliography).
4. From an unpublished memoir by Welton, written in 1983; quoted by Mehra.
5. Mehra.
6. Mehra.
7. *Surely You're Joking*.
8. Mehra.
9. *Most of the Good Stuff*.
10. See letters between Smyth and Morse, and Smyth and Slater, Princeton archive (Seeley G. Mudd Manuscript Library).
11. Philip Morse, *In at the Beginnings*, MIT Press (1977).
12. Joan Feynman, correspondence with JG, January/February 1996.
13. Wheeler, *in Most of the Good Stuff*.
14. Mehra.
15. This was, in fact, a characteristic he shared with Einstein; see *Einstein: A Life in Science*.
16. Ralph Leighton, comment to JG, December 1995.
17. *What Do You Care*.
18. Leighton, comment to JG, December 1995.
19. Wheeler, in *Most of the Good Stuff*.
20. Princeton archive.
21. Mehra.
22. Report in the Princeton archive.
23. See Wheeler's contribution to *Most of the Good Stuff*.
24. See *No Ordinary Genius*.
25. *What Do You Care*.

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[*] For those who are not familiar with the American educational system, a freshman is a first-year undergraduate, a sophomore is a second-year student, a junior is a third-year student on a four-year course, and a senior is a final-year undergraduate.

4 Early works

Although Feynman failed to get much intellectual stimulation from being forced to attend classes in English and philosophy during his time as an undergraduate at MIT, he had ample opportunity to stretch his mind by attending any classes that did interest him, even if they did not count officially towards his degree. One of the classes he attended in his senior year was taught by Manuel Vallarta, who had an interest in cosmic rays – high-energy particles that reach the Earth from space. These ‘rays’ come equally from all directions – they are isotropic – but the stars of our Galaxy, the Milky Way, are distributed far from uniformly across the sky. The obvious inference is that cosmic rays do not come from within our Milky Way Galaxy, but from the Universe at large, beyond the Milky Way. But even if cosmic rays did come in to the Galaxy uniformly from all directions, surely, Vallarta thought, they ought to be scattered by the stars of the Milky Way, and end up with an uneven pattern on the sky. He discussed the puzzle with Feynman, and suggested that the bright undergraduate might like to work on the puzzle of the isotropy of cosmic rays.

Feynman was able to solve the puzzle in a fairly straightforward manner, proving that if cosmic rays from the Universe at large do indeed enter our Galaxy isotropically, then they will still be seen coming from all directions when they reach the Earth. The influence of the stars of the Milky Way is far too small to disturb the pattern. One interesting feature of Feynman’s proof is that it involved dealing mathematically not just with cosmic ray particles coming into the Galaxy from outside, but with a kind of hypothetical mirror image set of particles moving out from the Galaxy into deeper space. The kind of scattering Vallarta was worried about mainly involves the magnetic fields of stars, which interact with electrically charged particles. So the probability of an electron (with negative charge) coming into the Galaxy along a particular path is the same as the probability of a positron (with positive charge) going out of the Galaxy along the same path.

In fact, some cosmic rays are now known to originate within our Galaxy, but that does not affect the validity of Feynman’s argument – those cosmic rays which do originate from outside the

Milky Way (essentially the ones with most energy, which is why they were the first to be studied) behave just as he calculated on their way to Earth. Vallarta was sufficiently impressed by Feynman's proof that he offered to tidy it up and submit it to the *Physical Review* for publication, under their joint names. He explained to Feynman that although he (Vallarta) had made only a small contribution to the paper, his name should appear first on it, because he was the more senior scientist. It was Feynman's first experience of this kind of jockeying for academic credit, but he was hardly in a position to object, and the paper appeared in the *Physical Review* on 1 March 1939, with the authorship 'Vallarta and Feynman'.

But Feynman would have the last laugh. In 1946, Werner Heisenberg published a book on cosmic rays in which he discussed just about every worthwhile paper ever published on the topic. The Vallarta and Feynman paper didn't quite fit in anywhere, but right at the end of the book Heisenberg discussed the possibility of the influence of stellar magnetic fields in changing the direction of cosmic rays and, in his very last sentence, concluded that 'such an effect is not expected according to Vallarta and Feynman'. The next time Feynman met up with Vallarta, he gleefully asked if he had seen Heisenberg's book. Vallarta already knew what was coming. 'Yes', he said. 'You're the last word in cosmic rays.'[1]

Feynman had time to do research – albeit in a modest way – in his senior year because by then he was only serving out time as far as the requirements for his degree were concerned. The rules said you had to serve four years as an undergraduate before receiving the Bachelor's degree. Feynman had long since learned everything required of a physics student, and more, but he hadn't completed the statutory four years. In fact, unknown to Feynman at the time, Philip Morse had actually suggested to the authorities at MIT that Feynman should be allowed to graduate a year early, after three years instead of four; but the proposal had been turned down. All that was left was for Feynman to write his senior thesis – no small task at the end of the 1930s, when students were expected to do original work on a specific problem suggested to them by a supervisor. The supervisor was supposed to be aware of the broad sweep of the development of science, and able to pinpoint a tiny area, equivalent to adding one brick to the tower of knowledge, where the undergraduate could make a genuine contribution. Feynman's senior thesis started out like that, but ended up as a much more far-reaching piece of work.

The problem John Slater set Feynman was to work out why quartz expands much less than other substances, such as metals, when it is heated. Feynman quickly became intrigued by the a distance, a direct interaction between charges, albeit with a delay.[*] On this picture, one electron shakes, and a certain time later another electron shakes as a result (the time delay depends on the distance to the second electron and the speed of light). But there is no way for the first electron to interact with itself. This was the state of the idea when Feynman arrived in Princeton. He hadn't worked out a proper theory along these lines; it was no more than a half-baked idea. But, as Feynman recounted in Stockholm in 1965, he had fallen 'deeply in love' with the notion, and 'I was held to this theory, in spite of all difficulties, by my youthful enthusiasm' ('youthful enthusiasm', of course, sums up Feynman's approach to all of his work, and life in general, whatever his chronological age). There was, though, a 'glaringly obvious' fault with the idea, as he pointed out in that Nobel address. A charged particle such as an electron *must*, in fact, interact with itself to a certain extent, to account for a phenomenon known as radiation resistance.

All objects resist being pushed about – this is the property known as inertia. In a frictionless environment, such as the inside of a spaceship falling freely in orbit around the Earth, any object will sit still (relative to the walls of the spaceship) until it is given a push, then it will keep moving at a steady speed in a straight line (that is, at constant velocity) until it is given another push (perhaps by bouncing off the wall). The key thing is that it takes a force to make something accelerate – which, to a physicist, means to change its speed or its direction of motion, or both. This is encapsulated in Newton's Laws of Motion, which became the basis of classical mechanics more than 300 years ago, and which still provide an entirely adequate description of the way things work for most everyday purposes, whether that involves designing a bridge that won't fall down or a spaceship that will fly to the Moon.

Just why things have inertia – where inertia 'comes from' – is not explained by Newton's laws, and Einstein tried to build inertia into his General Theory of Relativity, without entirely succeeding (but see Chapter 14). But that doesn't matter for now. What does matter is that if you try to accelerate a charged particle, perhaps by shaking it to and fro with a magnetic field, you discover that it has an extra inertia, over and above the inertia you would find for a particle with the same mass but no electric charge. This extra inertia makes it harder to move the charged particle.

Now this is not just some exotic phenomenon only of interest to physicists. The most common reason for shaking electrons to and fro is to make them radiate electromagnetic energy, in line with Maxwell's equations. This is what goes on in the broadcast antennas of TV and radio stations. It takes energy to make the electrons in the antenna oscillate and radiate the signal you want to broadcast, and it takes more energy (requiring a more powerful transmitter) than it would to shake equivalent uncharged particles, which do not radiate, by the same amount. Hence the name radiation resistance. The effect of radiation resistance can be seen in the electricity bills of every TV and radio station.

One curious feature of the classical description of electrons (the same is true for all other charged particles) and electromagnetic fields is that the interaction between each electron and the field (the self-interaction) actually has two components. The first component looks as if it ought to represent ordinary inertia, but is infinite for a point charge. But the second term exactly gives the force of radiation resistance. So the snag with Feynman's original idea, that an electron could not act on itself at all, was that even if the idea could be made to work it would remove both terms in the expression, getting rid not just of the unwanted infinity but also of the radiation resistance. This was the state of play when he started thinking seriously about the idea once again at Princeton.

Feynman needed some interaction to act back on the electron and give it radiation resistance when it was accelerated, and he wondered whether this back-reaction might come from other electrons (strictly speaking, any other charged particles) rather than from the 'field'. As physicists do when trying to get to grips with such problems, he considered the simplest possible example – in this case, a universe in which there were only two electrons. When the first charge shakes, it produces an effect on the second charge, which shakes in response (this, of course, is how the receiver in your radio or TV set works, as electrons in it respond to the shaking of the electrons in the broadcast antenna). But now, because the second charge is shaking there must be a back-reaction which shakes up the first charge. Perhaps this could account for radiation resistance. Feynman calculated the size of the effect, but it didn't work out properly to account for radiation resistance. Baffled, but still in love with the idea, it was at this point that he took it to Wheeler to discuss.

What Feynman didn't know was that Wheeler had been interested in the idea of action at a distance for some time, and that this had a respectable pedigree as a backwater of physics.[3] So the professor didn't dismiss his student's idea as crazy, but set out with him to work through the calculations. To Feynman's embarrassment, Wheeler pointed out the big flaw with his calculation. It takes a certain time for the second electron to respond to the shaking of the first electron, and the same amount of time before the first electron responds to the shaking of the second electron. So the reaction back on the first electron would occur some time after it had been shaken in the first place – not at the right time to cause radiation resistance. What Feynman had actually described and calculated, albeit in an unconventional manner, was simply ordinary reflection of light.

But Wheeler didn't stop there. Maxwell's equations, he pointed out, actually have two sets of solutions. One corresponds to a wave moving outward from its source and forward in time at the speed of light; the other (usually ignored) corresponds to a wave converging on its 'source' and moving backwards in time at the speed of light (or, if you like, moving forwards at *minus* the speed of light, –*c*). This is rather like the way in which the equations of quantum mechanics can be solved to give a solution corresponding to positive-energy electrons and a solution corresponding to negative-energy electrons. Dirac's equation, published in 1928, was still the crowning glory of quantum mechanics at the beginning of the 1940s, so it did not seem completely crazy for the two young physicists to take the second solution to Maxwell's equations seriously. The waves corresponding to the usual solution of the equations are called retarded waves, because they arrive somewhere at a later time than they set out on their journey (the journey time is 'retarded' by the speed of light); the other solution corresponds to so-called advanced waves, which arrive before they set out on their journey (the journey time is 'advanced' by the speed of light). If the back-reaction from the second electron only involved advanced waves, Wheeler realized, its influence on the first electron would arrive exactly at the right time to cause radiation resistance, because it would have travelled the same distance at the same speed, but backwards in time.

Wheeler set Feynman the task of calculating what mixture of advanced and retarded waves would be required to produce the correct form of radiation resistance. Between them, Wheeler and Feynman also proved that in the real Universe, full of charged particles, all the interactions would cancel out in the right way to produce the same radiation resistance that they had calculated for the simple case.

A key ingredient of their model is that a wave has both a magnitude and a 'phase' – if two waves are the same size, but one is precisely out of step with the other, so that the first wave produces a peak where the second wave produces a trough, they are out of phase, and cancel each other. If the two waves march precisely in step, so that the two peaks are on top of each other, they are in phase, and produce a combined wave twice as big as either wave on its own. As a result, it turned out that you need a mixture of exactly half advanced waves and half retarded waves

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