1 A revolution in time

My solution was really for the very concept of time, that is, that time is not absolutely defined but there is an inseparable connection between time and the signal velocity. Five weeks after my recognition of this, the present theory of special relativity was completed.

Albert Einstein, Kyoto Address, 1922

Einstein’s revolution

The famous Russian scientist Lev Landau used to keep a list of names, in which he graded physicists into ‘leagues’. The first division contained the names of physicists such as Niels Bohr, Werner Heisenberg and Erwin Schrödinger, the founding fathers of modern quantum physics, as well as historical ‘giants’ such as Isaac Newton. He was rather modest about his own classification, grading himself 2½, although he later promoted himself to a 2. Most working physicists would be happy even to make it into Landau’s fourth division: David Mermin, a well-known and perceptive American physicist, once wrote an article entitled ‘My life with Landau: homage of a 4½ to a 2’. What is the point of this story? The point is that any book about relativity is inevitably also about Albert Einstein, and Einstein was a remarkable physicist by any standard. Landau, in fact, created a special ‘superleague’ containing only one physicist, Einstein, whom he classified uniquely as a ½. Thus, the popular opinion that Einstein was the greatest physicist since Newton is widely shared among professional physicists.

When Einstein wrote about ‘The wonderful events which the great Newton experienced in his younger days...’, and commented that, to Newton, Nature was ‘an open book’, he could well have been writing about himself. Newton’s miraculous years of discovery occurred during the Great Plague in 1665–66, when he retired to work in isolation at his home in the Lincolnshire village of Woolsthorpe. For Einstein, the miraculous years of daring innovation were spent in Switzerland, quietly working at the Patent Office.
Office in Berne. Without any contact with the professional physics community, Einstein, in 1905, published not only the papers that spelled out the special theory of relativity, but also papers that laid the foundation for quantum theory. It was for his work on quantum theory that he won the Nobel Prize for Physics some years later – not for relativity. It is perhaps not surprising that Einstein, after 1905, should wonder whether his creative days were over. He wrote to his close friend Maurice Solovine: ‘Soon I will arrive at the stationary and sterile age where one laments over the revolutionary mentality of the young.’ Actually, Einstein was still only in his mid-twenties, and his supreme achievement – the creation of the theory of general relativity – was yet to come. Although Einstein obtained his first intuitive glimpse of a new theory of gravity in 1907, it took him ten more years of hard work to transform this into the theory of general relativity that we know today. In the following chapters, we shall attempt to explain what physicists understand by both ‘special’ and ‘general’ relativity, and to give some idea of the revolution each brought to the way in which physicists view the world.

It was not until after the First World War that Einstein, then a professor in Berlin, suddenly acquired world-wide fame. His prediction of the bending of light passing near the Sun was confirmed by a British expedition sent to photograph the total eclipse of the Sun in 1919. Headlines in The Times proclaimed ‘Revolution in Science – New Theory of the Universe – Newtonian Ideas Overthrown’. Before we have a look at what Einstein said about the world, we should perhaps remember what turbulent times these were in Europe. The Russian Revolution was still sending shock waves around the world, and even the art world was experiencing an unparalleled upheaval with the birth of the Dada movement. Curiously, both these revolutions had connections with Switzerland, where Einstein had completed his physics education. Was the parallel birth in Berne of relativity and the revolutions in politics and art just a coincidence? Zurich must have been a stimulating and exciting place for a young student in those days – certainly a long way from the ‘safe’ image we have of Switzerland today.

The sociologist Lewis Feuer has indeed suggested that Einstein’s theories of relativity were nurtured by the revolutionary culture of Zurich. The name relativity is perhaps a clue, since, in many ways, it is strangely
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Zurich – hot-bed of revolution

Lenin and many other revolutionaries had found safe havens in Switzerland because of its policy to grant political asylum. In the eyes of many of the leaders of other European countries, this made peaceful, democratic Switzerland a very dangerous place. Indeed, in 1873, the Czarist Russian government had demanded that students ‘immediately abandon the terrible city of Zurich’. And perhaps they were right to be worried – it was from Zurich, in the spring of 1917, that Lenin and a band of his associates were allowed, with the connivance of the German authorities, to leave for Russia in a sealed train.

The Dada art movement began in Zurich in 1916 as a revolt against the traditional values that were embraced by a society that could countenance the mass slaughter which took place during the First World War. Dada was deliberately provocative and outrageous and it sought to shock people out of a state of complacency. The name, meaning ‘a child’s wooden hobbyhorse’, is thought to have been chosen at random from a German–French dictionary. The movement was launched at a nightclub called the Cabaret Voltaire by the playwright Hugo Ball and the singer Emmy Hennings. The public outcry was such that the ‘cabarets’ were soon stopped, but Dada, like Marxist-Leninism, continued to flourish and spread across the world. Eventually, some of the Dada artists joined with others to form the Surrealist art movement, of whom Salvador Dali was a prominent member.

Figure 1.3  The laboratory at the Zurich Federal Institute of Technology where Einstein was an undergraduate. (Permission granted by ETH – Bibliothek.)
inappropriate. All too often Einstein’s theory is over-simplified to mean that ‘everything is relative’. Einstein himself is guilty of using this aspect of relativity theory when writing in *The Times*:

> By an application of the theory of relativity to the taste of readers, today in Germany I am called a German man of science and in England I am represented as a Swiss Jew. If I come to be regarded as a bete noire, the descriptions will be reversed and I shall become a Swiss Jew for the Germans and a German man of science for the English.

*The Times* retorted:

> We concede him his little jest; but note that, in accordance with the general tenor of his theory, Dr. Einstein does not supply an absolute description of himself.

The theory of relativity has no connection with either the social or moral relativity as expressed by the revolutionary movements in politics or art. Indeed, since relativity theory makes very specific and definite predictions that agree with experimental observations, ‘absolute theory’ would be an equally valid name. It is intriguing to speculate that Einstein, who had great empathy with the oppressed of the world, may have unconsciously had the idea of social relativity in his mind when naming his startling new vision of the physical world. In this sense, it might be said that the theory of relativity born in the quiet Berne patent office is the most abiding achievement of the revolutionary movements that emerged from Switzerland at the turn of the century. The story of how this revolution challenged, and continues to challenge, our preconceived ideas about space and time is the theme of this book.

Einstein wrote in his autobiography:

> ...sometimes we ‘wonder’ quite spontaneously about some experience. This ‘wondering’ seems to occur when an experience comes into conflict with a world of concepts that is already fixed in us.

Relativity causes much ‘wonder’ in the struggle to come to terms with its ideas. The problem lies in trying to reconcile Einstein’s view of time and space with our own intuition drawn from our experiences in everyday life. Relativistic ideas are so alien to us that they seem unbelievable. Like quantum mechanics, relativity makes predictions seemingly entirely at odds with our own experiences. However, as in the case of quantum theory, scientific experiment validates the predictions of Einstein’s relativity theory. We have no option, therefore, but to modify and enlarge our thinking to include these ideas. To convince the reader that the strange predictions of relativity have been carefully checked and are verified daily in many ways in the world around us is the central purpose of this book.
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...
How did Einstein discover relativity? The crucial insight that led Einstein to the theory of relativity only arrived after much hard work and after he had attained a deep understanding of both the successes and limitations of the ‘classical’ theories of Newton and Maxwell. Curiously, Einstein explained his discovery in terms of his ‘slow’ development:

The normal adult never bothers his head about space-time problems. Everything there is to be thought about it, in his opinion, has already been done in early childhood. I, on the contrary, developed so slowly that I only began to wonder about space and time when I was already grown up. In consequence I probed deeper into the problem than an ordinary child would have done.

In particular, at the age of sixteen, Einstein puzzled over the consequences of travelling at the speed of light. Nothing in nineteenth century science limited the maximum speed attainable, so this fantasy seemed possible, if a little impractical. However, just thinking about the implications of travel at light speed posed several intriguing problems. One of these we have called ‘Einstein’s Mirror’: what would you see if you and the mirror you were
looking into were both moving at the speed of light? This is an example of a ‘thought’ experiment – usually known in physics as a ‘gedanken’ experiment, from the German for thought. Einstein used such imaginary experiments to great effect all his life, including in his famous (but ultimately unsuccessful) attempts, in an exchange of letters with Niels Bohr, to prove that quantum mechanics was inconsistent. An account of Einstein’s role in the foundation of quantum mechanics is contained in the companion volume to this book, *The Quantum Universe*.

Einstein solved his mirror problem with his creation of ‘special relativity’. With the example of the mirror moving at the speed of light Einstein had put his finger on the key to the whole problem. Even though Einstein was not the only scientist to be concerned with the problem of light and how its velocity might be affected by the motion of the observer, it was Einstein, and Einstein alone, who realized that the solution to the problem involved a radical re-thinking of the concept of time. The first seven chapters of this book will be devoted to exploring the consequences of this new vision of space and time. This is the content of Einstein’s ‘special relativity’ theory, and we will show how it finds routine application in physics, chemistry and medicine. In particular, the huge particle accelerators in
Europe, the USA and Russia depend on special relativity for their very operation and design.

The situation was rather different for the theory of 'general relativity': essentially a theory of gravity. In a sense, one can say that Einstein's special theory modified Newton's laws of motion and that his general theory modified Newton's theory of gravity. Einstein described the inspiration which led to his theory of general relativity as 'the happiest thought of my life'. He explained his happy thought as follows:

I was sitting in a chair in the patent office at Berne when all of a sudden a thought occurred to me: 'If a person falls freely he will not feel his own weight.' I was startled. This simple thought made a great impression on me. It impelled me towards a theory of gravitation.

This image of a ‘falling man’ preoccupied Einstein for many years. After eight years of intense effort and imagination, he was able, in 1915, to convert this image into the fully-fledged theory of general relativity. The new theory quick-
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ly found observational success with the British eclipse expedition mentioned earlier. Although it was this success that caught the imagination of the popular press and catapulted Einstein onto the world stage, unlike special relativity, general relativity found very few other areas of application: it became rather like a ‘temple’ of modern physics, revered and respected, but seldom visited. All this changed dramatically in the 1960s. Developments in atomic clocks, space travel and radio astronomy breathed new life into the subject, and new and more accurate tests of Einstein’s ideas were devised and undertaken. Quasars and pulsars were discovered, and a new generation of physicists began to explore seriously the implications of the strange ‘black holes’ predicted by the general theory. The discovery of the microwave background radiation in 1965 and its interpretation as a relic of the ‘Big Bang’ creation of the universe, led to renewed interest in the use of Einstein’s general theory of relativity as a tool for modern cosmology. Experiments are in progress at the time of writing that attempt to detect the gravitational waves predicted by Einstein. It is because of all these new ‘post-Einstein’ developments that his general theory is now firmly in the vanguard of modern experimental and theoretical research. These topics form the basis for chapters 8–10.

No book about relativity would be complete without at least a passing look at the problem that occupied a large part of the remainder of Einstein’s research life. This was his dream of a ‘unified theory’ of all natural laws. During Einstein’s lifetime, this research was not in the mainstream, and was very distant from the exciting applications of quantum mechanics and nuclear physics. Today, however, such a search is now an active research area for theoretical physicists. Einstein made the geometry of space-time the key to gravity in general relativity. The extension of similar geometrical ideas to other areas of physics has been one of the important consequences of Einstein’s efforts. Chapter 10 describes the state of these attempts as they exist in the late 1990s.

Time and clocks

*It might appear possible to overcome all the difficulties attending the definition of ‘time’ by substituting ‘the position of the small hand of my watch’ for ‘time’. And in fact such a definition is satisfactory when we are concerned with defining time exclusively for the place where the watch is located; but it is no longer satisfactory when we have to…evaluate the times of events occurring at places remote from the watch.*

Albert Einstein, *The electrodynamics of moving bodies*, 1905

Many people have had the experience of returning from some routine chore with no conscious recollection of having completed it. This is common when driving, for example, when part of the mind seems to take over driving the car while the conscious mind is occupied with other things: control is only reasserted if something unusual happens. Miraculously, the task has been
accomplished on 'automatic pilot', without conscious attention. One strange feature of this experience is the absence of any sense of the passage of time. This 'time gap' phenomenon makes apparent what is significant for our sense of time: conscious attention to a series of physical or mental changes which act as time markers. Is 'time' purely reducible to an ordered sequence of events such as the passage of day and night, or to the biological processes of ageing? Or is 'time' some more fundamental inner property of Nature?

If we turn over an hour-glass, the interval of time taken for the sand to run out is assumed to be the same, no matter how often we repeat the process. (In practice, although we may try to duplicate the same event, things can go wrong – such as the sand becoming damp and sticking.) The essence of a clock is that it is a device that repeats the same action and