The Arrow of Time

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ROGER HIGHFIELD

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Contents

About the Book

Time has always been considered one of the greatest mysteries to mankind. Although it appears in all the major scientific theories of the day, science still lacks a clear picture of what it is. In particular, time has no sense of direction in many major scientific theories.

In this authoritative, controversial, yet highly accessible book, Dr Peter Coveney and Dr Roger Highfield take the reader on a guided tour of every major scientific theory in their quest to solve the mystery of time. They investigate both the physics of time – Newton's mechanics, the first mathematical model of the universe to incorporate time, Einstein's theory of relativity, quantum theory and thermodynamics – and its wider manifestations, examining the way time appears in poetry, chemistry and biology, from Marvell's winged chariot and the 'chemical clock' to the cause of jet-lag and that Monday morning feeling.

Finally, drawing together the various interpretations of time, they describe a novel way to give it a sense of direction. And they call for a new fundamental theory to take account of the Arrow of Time.

About the Authors

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Colour plates

Illustrations

THE ARROW OF TIME

A voyage through science to solve time's greatest mystery

PETER COVENEY

AND

ROGER HIGHFIELD

FOREWORD BY
ILYA PRIGOGINE
NOBEL LAUREATE

W H ALLEN

TO
SAMIA, PAT AND JIM,
AND
JULIA, DORIS AND RONALD

Time glides by with constant movement, not unlike a stream.
For neither can a stream stay its course, nor can the fleeting hour.

Ovid
Metamorphoses XV, 180

Foreword

BY

ILYA PRIGOGINE

WINNER OF THE 1977 NOBEL PRIZE FOR CHEMISTRY

IT IS A great pleasure for me to write a foreword for this book by Peter Coveney and Roger Highfield.

Is there an arrow of time? This question has fascinated Western philosophers, scientists and artists since the Presocratics. However, at the end of this century, we may ask this question in a new context. For a physicist, the scientific history of our century can be divided into three parts. First, we had the breakthrough associated with two new conceptual schemes, relativity and quantum mechanics. Secondly, the disclosure of unexpected findings, including the instability of 'elementary' particles, evolutionary cosmology and non-equilibrium structures, which include a variety of phenomena such as chemical clocks and deterministic chaos. The third – and present – period confronts us with the necessity of rethinking physics, taking into account these new developments.

A remarkable point is that all this emphasises the role of time. To be sure, in the nineteenth century the importance of time was already recognised in fields such as biology and the social sciences. But it was widely accepted that the fundamental level of physical description could be expressed in terms of deterministic, time-reversible laws. The arrow of time would then correspond only to a phenomenological level of description. However, this view is difficult to maintain today.

We now know that the arrow of time plays a critical role in the formation of non-equilibrium structures. As has been shown in recent years, the evolution of these structures can be simulated on computers programmed with dynamical laws; this makes clear that self-organising processes cannot be the effect of phenomenological assumptions, and must be inherent in some classes of dynamical systems.

We are today in a position to understand better the message of entropy, a quantity which always increases according to the Second Law of Thermodynamics and therefore gives an arrow of time. Entropy is basically a property of highly unstable dynamical systems. These are dealt with in Chapters Six and Eight of this book. Much remains to be done and numerous problems are still open. It is therefore not surprising that I do not necessarily agree with everything that is stated in this book. But I do agree with the general description which the authors advocate: the arrow of time is an exact property of important classes of dynamical systems.

These questions are so important that I warmly welcome this book which is written on a high scientific level while being accessible to a wide public. Peter Coveney was uniquely qualified to write this text, as he has himself made important contributions to the subject. Roger Highfield has brought in an element of stylistic presentation which makes the book very attractive.

In October 1989, the Nobel Conference of the Gustavus Adolphus College (St Peter, Minnesota) was devoted to a challenging theme: ‘The End of Science’. The organisers wrote: ‘there is an increasing feeling that … science, as a unified, universal, objective endeavour, is over’. They go on to say that ‘if science does not speak of extra-historical, universal laws, but is instead social, temporal and local, then there is no way of speaking of something real beyond science, that science merely reflects’. This statement opposes extra-historical laws to temporal knowledge.

Indeed, science *is* rediscovering time, and in a sense this marks an end to the classical conception of science; will it mark an end to science proper?

Indeed, as I have already mentioned, the research programme of classical science was focused on a description in terms of deterministic, time-reversible laws. Actually, this programme was never completed as, in addition to laws, we need also events, which introduce an arrow of time into our description of nature. Often the goal of classical science seemed to be near to completion; but always something went wrong. This gives to the history of science an element of dramatic tension. For example, Einstein's goal was to formulate physics as a geometry of nature. But general relativity paved the way to modern cosmology, only to meet the most striking of all events: the birth of the universe.

The law–event duality is at the heart of the conflicts which run through the history of ideas in the Western world, starting with the pre-Socratic speculations and continuing right up to our own time through quantum mechanics and relativity. Laws were associated to a continuous unfolding, to intelligibility, to deterministic predictions and ultimately to the very negation of time. Events imply an element of arbitrariness as they involve discontinuities, probabilities and irreversible evolution. We have to face the fact that we live in a dual universe, whose description involves both laws and events, certitudes and probabilities. Obviously the most decisive events we know are related to the birth of our universe and to the emergence of life.

'Will we be able some day to overcome the Second Law of Thermodynamics?' is the question that the civilisation of Asimov's *Last Question* keep asking to a giant computer. The computer answers, 'The data are insufficient.' Billions of years pass by, stars and galaxies die, while the computer, directly connected to spacetime, continues to collect data.

Finally there is no information left to be gathered any longer, nothing ‘exists’ any more; but the computer goes on computing and discovering correlations. Eventually it reaches the answer. There is no longer anyone there to learn, but the computer now knows how to overcome the Second Law. *And there was light…* For Asimov, the emergence of life or the birth of the universe is an anti-entropic, anti-natural event.

The new frame of thinking, to which this book is an excellent introduction, leads to a new physics which includes both laws and events, and brings us closer to a better understanding of the universe in which we are embedded.

Prologue

Duino, near Trieste, 5 September 1906

LUDWIG BOLTZMANN WAS on a seaside holiday in an Adriatic village. It was meant to be a relaxing break from his studies in Vienna to help him overcome a period of illness and depression. But Boltzmann was agitated.[1]

A professor since his twenties, he had battled for years to understand the sole piece of scientific evidence for one of man's most fundamental assumptions – that the passage of time is irreversible. In this grand quest he had failed. His work on entropy, a measure of change that always increases with time, was brilliant but still inconclusive. The enigma of time's direction remained a flaw at the centre of science. And for Ludwig Boltzmann, time had run out.

In spite of his appearance – a bulky man sporting a formidable beard – he was a soft and vulnerable character. He was overworked and plagued by ill-health. Now 62, he had almost completely lost his sight and he suffered agonising headaches. Wildly fluctuating moods had taken him to the brink of despair and led to a stay in an asylum near Munich. Even the smallest irritation could cause him deep distress – such as his wife's insistence today on delaying his return to Vienna by taking his suit to be cleaned.

Frau Boltzmann took the suit with her as she and her daughter set off for a swim in the Bay of Sistiana. It was then that her husband committed the ultimate irreversible act. He tied a short cord to the crossbars of a window casement and made a noose round his neck. Then, alone in his rented apartment, he killed himself.[2] His daughter Elsa returned to find him hanged.[3]

Boltzmann's suicide is one of the most vivid examples of the way time mocks and defeats those who seek to unravel its mysteries. His loss was deeply felt. George Jaffé, one of his pupils in Leipzig, wrote: 'Boltzmann's death is one of the tragic events in the history of science, like the decapitation of Lavoisier, the commitment of R. J. Mayer to a lunatic asylum and the crushing of Pierre Curie under the wheels of a truck. It is all the more tragic as it happened on the very eve of the final victory of his ideas.'[4]

These ideas concerned the existence of atoms. Some commentators have portrayed Boltzmann as the victim of an intellectual 'thirty-year war' against those who did not accept the theory of atomism. His opposing army included a range of prominent nineteenth-century thinkers among whom were the Frenchmen Pierre Duhem, Auguste Comte and Henri Poincaré, the Germans Wilhelm Ostwald and Georg Helm, and others in the United States and England such as William Rankine and John Stallo. The battles between Boltzmann and his greatest adversary, fellow countryman Ernst Mach, pushed him into intellectual isolation. He once confessed to a colleague that absolutely nobody understood his most supreme theories.[5]

Eventually, Boltzmann's beliefs about atoms and molecules held sway. However, he had hoped to go even further and use them to explain the direction of time, a feature of nature which he thought about more than any other scientist.[6] It was in this daring ambition that Boltzmann was defeated by the manic depression which pushed him to commit suicide. As we shall see, he had succeeded in making a crucial connection between the two ideas. But his great dream was still unrealised at his death.

Boltzmann was not the last person to die in sad circumstances while attempting to express the arrow of time and other features of the world we inhabit in the language of atoms and molecules. As David Goodstein of the California Institute of Technology wrote in the opening lines of his book, *States of Matter*, ‘Ludwig Boltzmann, who spent much of his life studying statistical mechanics, died in 1906, by his own hand. Paul Ehrenfest, carrying on the work, died similarly in 1933. Now it is our turn … perhaps it will be wise to approach the subject cautiously.’[7]

ONE

Images of time

> Ruine hath taught me thus to ruminate:
> That Time will come and take my love away.
>   This thought is as a death which cannot choose
>   But weepe to have that which it feares to loose.
>
> William Shakespeare
> Sonnet 64, 11–14

TIME IS ONE of the greatest sources of mystery to mankind. Throughout history, human beings have restlessly puzzled over time's profound yet inscrutable nature. It is a subject which has captivated poets, writers and philosophers of every generation. But not, so it seems, the modern scientist. Contemporary science – in particular, physics – has sought to suppress if not to eliminate the role of time in the order of things. Time has been described as the forgotten dimension.[1]

We are all aware of the irreversible flow of time which seems to dominate our existence, where the past is fixed and the future open. We may yearn to turn back the clock, to undo mistakes or to relive a wonderful moment. But alas, common sense is against us: time and tide wait for no man. Time cannot run backwards.

Or can it? Disturbingly, there is little support for the common-sense view of time in many scientific theories, where time's direction makes little difference. The great edifices of modern science – Newton's mechanics, Einstein's relativity and the quantum mechanics of Heisenberg and Schrödinger – would all appear to work equally well with time running in reverse. For these theories, events recorded on a film would be perfectly plausible no matter which way the film was run through the projector. Uni-directional time, in fact, comes to appear as simply an illusion created in our minds. Frequently scientists who investigate this problem refer to our everyday sense of the flow of time, rather sneeringly, as 'psychological time' or 'subjective time'.

Could it be that somewhere in the universe the direction of time may flow against the time with which we are familiar, in a world where people rise from the grave to lose their wrinkles and eventually return to the womb? It would be a world where perfume mysteriously condenses into bottles; where ripples of water in ponds converge to eject stones; where the air in rooms spontaneously separates into its components; where wrinkled pieces of rubber expand and seal themselves into balloons; where light would shine out of astronomers' eyes to be absorbed by stars. Perhaps the possibilities do not end there. Could it be that if this line of thinking is correct, time might be thrown into reverse here on Earth? Could we all be sucked back into the past?

This contradicts all the evidence we have that time flows in a single direction. For example, compare time with space. Space surrounds us, yet time is experienced bit by bit. The distinction between right and left is trivial compared with that between past and future. We can shuffle around freely in space yet by our actions we can only affect the future, not the past. We have memory, not precognition (clairvoyants apart). Materials generally seem to decay rather than to assemble spontaneously. So it seems that although space has no preferred directional characteristics, time does.[2] It travels like an arrow. The evocative term 'the arrow of time' was first coined by the astrophysicist Arthur Eddington in 1927.[3]

In this book we shall investigate the role of time in present-day scientific theories, weigh the consequences and show how it is indeed possible to achieve a unified vision of time: a vision which is consistent with rather than in conflict with time as we directly experience it. The arrow of time may even point towards the need for a deeper and more fundamental theoretical framework to describe nature than any currently in use.

Time in literature

The common-sense view of time finds its most eloquent expression in some of the great works of literature.[4] Uni-directional time gives us the idea of transience, superbly captured in the title of Proust's autobiographical novel *A la recherche du temps perdu.* Uppermost in such authors' minds is the knowledge that we have only a finite – and short – amount of time to live and that there can be no going back. Moments must be snatched as time continues its ineluctable progress, each moment appreciated with poignant intensity. The mystery of life is made all the more wonderful owing to its very ephemerality, while our sense of time's irreversibility is heightened by death. It is no coincidence that the symbolic figure of Father Time shares his attributes of a scythe and an hour-glass with death's skeletal Grim Reaper, who will mow us all down when our time is done.

The flow of time is described in literature and poetry again and again. One of the most striking meditations upon it can be found in the writings of the Persian philosopher-poet Omar Khayyám (d. 1123), immortalised by Edward Fitzgerald's free-ranging translation:

> The Moving Finger writes; and, having writ,
> Moves on: nor all your Piety nor Wit
>   Shall lure it back to cancel half a Line,

Nor all your Tears wash out a Word of it.[5]

Here irreversibility is revealed as the ultimate source of the pathos of human life. Unspoken, but implicit, is the final triumph of death. And here we have a link with science, for the fact that every living creature dies is the most tangible evidence for the flux of time. It is a crucial issue if we are to make sense of the world about us. In the words of Arthur Eddington: ‘In any attempt to bridge the domains of experience belonging to the spiritual and physical sides of our nature, time occupies the key position.’[6]

Cultural time

The idea of directional time has not always been with us. The tides, solstices, seasons and the cyclic movements of the heavenly bodies led many primitive societies to regard time in terms of organic rhythms, as essentially cyclic in nature. They thought that since time was inseparable from the circular movement of the heavens, time itself was circular. Day follows night, new moon follows old, summer follows winter, so why not history? The Maya of Central America believed that history would repeat itself every 260 years, a period of time called the *lamat*, or fundamental element, of their calendar. They also believed in cyclic catastrophies: when a group of invading Spaniards landed in 1698 members of one tribe, the Itza, fled because they believed the cycle had turned full circle and calamity had come.[7] They were right, but not by prediction or even coincidence: the Spanish knew what to expect because their missionaries had learnt of the Mayas’ belief in cyclic time eighty years earlier.

The cyclic pattern of time was a common feature in Greek cosmological thought. Aristotle observed in his *Physics* that ‘there is a circle in all other things that have a natural movement and coming into being and passing away. This is because all other things are discriminated by time and end and begin as though conforming to a cycle; for even time itself is thought to be a circle.'[8] The Stoics believed that when the planets returned to the same relative positions as at the beginning of time the cosmos would be renewed again and again. Nemesius, Bishop of Emesa in the fourth century AD remarked: 'Socrates and Plato and each individual man will live again, with the same friends and fellow citizens. They will go through the same experiences and the same activities. Every city, village and field will be restored, just as it was. And this restoration of the universe takes place not once, but over and over again – indeed to all eternity without end.'[9] It was as though historical events were decked around a great celestial wheel. This notion of eternal return reappeared in modern mathematical form as 'the Poincaré recurrence', named after Henri Poincaré, one of the world's foremost mathematicians, who was active at the turn of the twentieth century.

Time's arrow aroused deep fear – even terror – because it implied instability, flux and change. It also pointed towards the end of the world rather than to rebirth and renewal. In his work on time's arrows and cycles, *The Myth of the Eternal Return*, the Romanian anthropologist and historian of religion Mircea Eliade maintained that most people throughout mankind's existence have clung to the comfort of time's cycle, where the past is the future, there is no real 'history' and mankind is resigned to rebirth and renewal. Significantly, he wrote: 'The life of archaic man … although it takes place in time, does not record time's irreversibility; in other words, [it] completely ignores what is especially characteristic and decisive in a consciousness of time.'[10]

It was the Judaeo-Christian tradition which had established 'linear' (irreversible) time once and for all in Western culture. 'Christian thought tended to transcend, once and for all, the old themes of eternal repetition,' wrote

Eliade.[11] Through the Christian belief in the birth and death of Christ and the Crucifixion as unique events, unrepeatable, Western civilisation came to regard time as a linear path that stretches between past and future. Before the advent of Christianity only the Hebrews and the Zoroastrian Persians preferred this progressive view of time.[12]

Irreversible time profoundly influenced Western thought. It prepared the human mind for the idea of progress, for the concept of 'deep time', the shocking discovery by geologists that human evolution is only a late and brief episode in the Earth's history. It paved the way for Darwin's theory of evolution, our union through time with more primitive creatures. In short, the emergence of the idea of linear time and the intellectual evolution which it entailed have underpinned modern science and its promise of improvement of life on Earth.

Aspects of time in biology are analogous to both cyclical and linear cultural experience. Cyclical time appears in cell division and the orchestra of different rhythms in our bodies, ranging from high-frequency nerve impulses to leisurely cycles of cell turnover. And the notion of irreversible time is manifested by ageing in the passage from birth to death. Ordinary clocks also express both these facets of time. They compound a succession of pendulum swings or crystal oscillations to reveal 'the time', which on Earth is expressed as a 12- or 24-hour cycle. The flow of time is manifested indirectly by dissipation: the running down of batteries, slackening of the mainspring or the falling of weights.

Time in philosophy

Time has been the subject of repeated speculative investigation by philosophers. The mathematician Gerald

Whitrow, in his influential work, *The Natural Philosophy of Time*,[13] highlights how the ideas of Archimedes and Aristotle represent two extreme views of time: Aristotle regarded time as intrinsic and, unlike Archimedes, fundamental to the universe. Their debate has continued in one form or another through the centuries.

In Plato's cosmological work *Timaeus*, time was born when a divine worksmith imposed form and order on primeval chaos. *Timaeus* begins with the distinction between Being and Becoming, two concepts which reappear in various guises in modern scientific theories. For Plato, the world of Being is the real world 'apprehensible by intelligence with the aid of reasoning, being eternally the same', while that of Becoming (the realm of time) 'is the object of opinion and irrational sensation, coming to be and ceasing to be, but never fully real'.[14] He was making the same distinction as between a journey (becoming) and its destination (being), claiming only the latter was real. This distinction, in which the physical world, including time, has only a secondary reality, dominated Plato's entire philosophy.

In this view Plato was preceded by Parmenides who believed that reality was both indivisible and timeless. His pupil, Zeno of Elea in southern Italy, teased us with his famous paradoxes aimed at undermining our whole concept of time. One of the best known is usually referred to as that of Achilles and the tortoise,[15] claiming to show that motion is impossible if time can be infinitely subdivided. Achilles is pictured chasing a tortoise: during the time it takes Achilles to reach the point from which the tortoise started out, the latter has advanced a (small) distance; in the time Achilles takes to cover that distance, the tortoise has again moved on; and so on *ad infinitum*.[16]

Opinions differ on the significance of this and the other of Zeno's paradoxes. In the 24 centuries since their formulation, they have been either written off as absurd or treated as most profound in the massive literature they have generated. In his careful analysis, Whitrow concludes that there are but two ways in which the paradoxes may be resolved. Either one can seek to deny the notion of 'becoming', in which case time assumes essentially space-like properties; or one must reject the assumption that time, like space, is infinitely divisible into ever smaller portions.[17]

Just as the colour red can induce different subjective impressions on different observers but is nonetheless an essential component of sight, the philosopher Immanuel Kant maintained that while time is an essential component of our intellect, it is devoid of objective reality: 'Time is not something objective. It is neither substance nor accident nor relation, but a subjective condition, necessary owing to the nature of the human mind.'[18] Kant's 'subjectivist' viewpoint finds close parallels in the way some scientists attempt to explain time in present-day science. One very simple and obvious way out, and one which has been popular with idealists in all ages – Parmenides, Plato, Spinoza, Hegel, Bradley and McTaggart – is to say that time is riddled through and through with contradictions, and hence cannot be real. A withering remark on this kind of metaphysical evasion came from the logician M. Cleugh: 'Merely to say that because time is self-contradictory it must be appearance only, is, so far from solving the problems, not even an answer to them.'[19]

Boltzmann dubbed metaphysics a 'migraine of the human mind'.[20] 'The most ordinary things are to philosophy a source of insoluble puzzles,' he remarked. 'With infinite ingenuity it constructs a concept of space or time and then finds it absolutely impossible that there be objects in this space or that processes occur during this time… To call this logic seems to me as if somebody for the purpose of a mountain hike were to put on a garment with so many long folds that his feet become constantly entangled in them and he would fall as soon as he took his first steps in the plains. The source of this kind of logic lies in excessive confidence in the so-called laws of thought.'[21] Boltzmann criticised several philosophers virulently, singling out Hegel, Schopenhauer and Kant: 'To go straight to the deepest depth, I went for Hegel; what unclear thoughtless flow of words I was to find there! My unlucky star led me from Hegel to Schopenhauer … Even in Kant there were many things that I could grasp so little that given his general acuity of mind I almost suspected that he was pulling the reader's leg or was even an imposter.'[22]

Time: Newton and Einstein

But if philosophy has failed us, what of time in science? The invention of the first successful pendulum clock in the middle of the seventeenth century by Christiaan Huygens[23], and the progressive increase in the precision of 'timekeeping' that followed, fostered the image of a mechanical and predictable side to nature. The technological development of clocks disentangled time from human events and helped to create belief in an independent world of science.[24] The 'classical' science that emerged in the seventeenth and eighteenth centuries portrayed a universe in which free will and capricious chance were redundant, a universe that to all intents and purposes was a cosmic machine.

We can trace the birth of a truly scientific time back to Sir Isaac Newton, who discovered mathematical expressions for the movement of bodies. His achievement was breathtaking: mathematical description could describe the motion of objects ranging from apples to moons, fusing celestial and terrestrial mechanics. The dazzling ability of his expressions to describe the movement of the heavens using only a few assumptions, and their aesthetic appeal, rapidly brought about acceptance of his ideas.[25] Thus Newton laid the foundations of modern physics.

Newton was no doubt influenced by the mathematician Isaac Barrow who, on resigning as the Lucasian professor at Cambridge in 1669, saw to it that Newton succeeded him. Barrow had remarked that 'because mathematicians frequently make use of time, they ought to have a distinct idea of the meaning of that word, otherwise they are quacks'.[26] Yet in spite of the grandeur of Newton's scientific achievement, time was only incorporated in his equations as a primitive, undefined quantity. It was, like space, absolute. That is to say, all events could be regarded as having a distinct and definite position in space and occur at a particular moment in time. Everywhere, from the Greenwich Observatory to the tip of a distant spiral galaxy, was connected by the same moment of 'now'. As Newton said in his *Principia*, 'Absolute, true, and mathematical time of itself and from its own nature … flows equably without relation to anything external.'[27]

Newton's mechanics promises vast predictive power, allowing one instant to provide all possible information about the past and future of the universe. Take the positions and speeds of all the stars in our universe at any instant and plug these values into a cosmic computer that solves Newton's equations. Frozen in that instant is the past and the future: the computer could calculate the positions and speeds of the stars at all times. But what his equations fail to do is to decide which direction of time constitutes the actual past and future of our universe. Instead they strip time of its sense of direction, leaving no room for its relentless march onward. We could highlight this symmetrical time with a film of planetary motions taken by, say, the *Voyager 2* space probe, which was launched to explore the outer solar system in 1977. Such motions were the first to be reduced to mathematical law by Newton. Yet the film would be consistent with his laws of celestial mechanics whether it was run forwards or backwards. This belief in a deterministic world, where time has no direction and the past and future are preordained, has played a pre-eminent role in the development of physics. Its power is shown in a remarkable statement made by Einstein when he learnt of the death of his lifelong friend and confidant Michelangelo Besso. In a letter written on 21 March 1955 Einstein seized upon this unshakable conviction in the 'timelessness' of the laws of physics to offer some comfort for Besso's family. Death was not so final, he suggested: 'For we convinced physicists, the distinction between past, present and future is only an illusion, however persistent…'[28] Perhaps the letter was also designed to comfort Einstein himself, for he added that Besso 'has preceded me briefly in bidding farewell to this strange world'. Einstein died a month later.

Newton's theory of motion is now known to fail when applied to bodies moving with speeds close to that of light, to vast masses, including black holes, when gravitational forces become enormous, and to the smallest of length scales involving atomic and sub-atomic particles. But the two great revolutions of twentieth-century theoretical physics that rule in these regimes – Einstein's relativity and quantum mechanics – are also built on the same directionless notion of time. They too remain unable to bridge the gap between the irreversible time of history and literature, and the symmetrical time of Newton's laws.

That is not to say that they did not throw up many fascinating new ideas about time. Einstein's theories of relativity shattered Newton's common-sense concept of absolute time – that any event in the universe should be considered to take place at a particular point in space and at a given instant in time which is the same everywhere. Instead, Einstein put forward the idea of a four-dimensional existence in spacetime (three dimensions of space plus one of time) rather than the evolution of a three-dimensional existence in time.[29] Our perception of time can be warped by illness or by drugs. But Einstein's theory of relativity shows that it also depends on one's point of view – the faster a clock travels, the slower it ticks. In the wake of relativity, even the possibility of time travel was to achieve a certain level of scientific respectability, through the work of Kurt Gödel, one of the greatest ever logicians.

Nevertheless, Einstein's remarkable relativity theories are silent on the one-sided nature of time. As with Newton, the structure of his equations makes it possible to know the past and the future of any system – say the rotation of a star round a black hole or the evolution of the universe itself – if one has a precise knowledge of it at any instant. But there is still no clue as to which is the past and which the future. Fundamental doubts are also raised by the embarrassing presence in the mathematics of 'singularities', where the description of space, time and matter breaks down. The best known singularity is the so-called Big Bang, the super-dense fireball of creation widely believed to have spawned the universe. At this singularity, where vast energies are condensed into a single point, observable quantities in the theory blow up into infinities and hence become meaningless. As the cosmologist Dennis Sciama remarked: 'General relativity contains within itself the seeds of its own destruction.'[30]

Quantum time

In our hunt for a scientific basis for the direction of time, the quantum theory governing the atomic and molecular world looks more promising. It gives a highly successful (although quite baffling) description of the vagaries of atoms and molecules. It can explain the behaviour of lasers, sub-atomic particles in nuclear reactors, electrons in computers and much more. Perhaps, upon a quantum description of the vast agglomerations of atoms and molecules which make up the world, one could construct a description of the arrow of time so keenly felt by our senses. This idea follows an honourable tradition. Ever since the Golden Age of Greek civilisation, the philosophical legacy of describing the world in terms of its component atoms and molecules – atomistic reductionism – has been paramount in the development of scientific thought.

A glimpse of a quantum arrow of time does emerge from two tantalisingly elusive elements we will encounter in Chapter Four – the strange case of a sub-atomic particle called the long-lived kaon and the mystery which surrounds interpreting the very act of measurement in quantum theory. Nevertheless, the core of quantum theory follows other 'fundamental' theories in making no distinction between the two directions of time. Like Einstein's relativity, quantum theory also has deep intrinsic difficulties – it can explode into unpleasant infinities when put to work on real problems, such as the way light is absorbed and emitted by atoms. Although physicists have learned ingenious tricks to sidestep these problems, one has the feeling that they provide further evidence that something is badly amiss.

Thus quantum mechanics and Einstein's theory of gravitation sit uneasily side by side. In the long run, some scientists, such as Roger Penrose of Oxford University, believe that a proper unification of the two would produce a quantum theory of gravity (or some entirely new theory) in which an arrow of time would finally be made explicit. Such a development seems some way off and would quite possibly still be unsatisfactory. For there is a serious