REALITY IS NOT WHAT IT SEEMS

THE JOURNEY TO QUANTUM GRAVITY

CARLO ROVELLI

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The Journey to Quantum Gravity

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ABOUT THE AUTHOR

Carlo Rovelli is a theoretical physicist who has made significant contributions to the physics of space and time. He has worked in Italy and the US, and is currently directing the quantum gravity research group of the Centre de Physique Théorique in Marseille, France. His *Seven Brief Lessons on Physics* is a phenomenal international bestseller translated into forty-one languages.

Author's Note

During my entire research life, friends and curious people have asked me to explain what was going on in quantum gravity research. How was it possible to study new ways of thinking about space and time? Over and over again I have been asked to write a popular account of this research. While books on cosmology or string theory abound, a book describing the research on the quantum nature of space and time, and on loop quantum gravity in particular, did not yet exist. I have long hesitated, because I wanted to concentrate on research. Some years ago, after completing my technical book on the subject, I felt that the collective work of many scientists had moved the topic to a stage mature enough for a popular book. The landscape we are exploring is enchanting: why keep it hidden?

But I still delayed the project, because I could not 'see' the book in my head. How to explain a world without space and time? One night in 2012, during a long solitary drive from Italy to France, I realized that the only way to explain in a comprehensible manner the ongoing modifications of the notions of space and time was to tell the story from the beginning: starting from Democritus, all the way through to the quanta of space. After all, this is how I understand the story. I began to design the entire book in my mind while driving, and got increasingly excited, until I heard a police car's sirens telling me to pull over: I was driving far above the speed limit. The Italian policemen asked me politely if I was crazy to drive at that speed. I explained that I had just found the idea I'd been seeking for so long; the policeman let me go without a ticket, and wished me good luck with the book. This is the book.

This book was written and first published in Italian at the beginning of 2014. Shortly afterwards, I wrote a few articles on fundamental physics for an Italian newspaper. A prestigious Italian publisher, Adelphi, asked me for an extended version of these articles, to appear as a small booklet. This is the origin of the short book *Seven Brief Lessons on Physics*, which to my immense surprise has become an international bestseller and has opened a beautiful channel of communication between me and so many wonderful readers all over the world. The *Seven Lessons* were thus written *after* this book, and to some extent they are a synthesis of some of the topics you find here. If you have read *Seven Brief Lessons on Physics* and want to know more, to journey deeper into the strange world that book sketched, here you can find more.

While the account of established physics I give here is presented from the peculiar perspective in which I understand it, it is largely uncontroversial. However, the part of this book that describes current research in quantum gravity is my own personal understanding of the state of the art. This is the region at the boundary between what we have understood and what we do not yet understand, and is still far from achieving consensus. Some of my physicist colleagues will agree with what I write here; others won't. This is true for all presentations of ongoing research at the frontiers of knowledge, but I prefer to state it upfront and clearly. This is not a book about certainties: it is a book about the adventure of moving towards the unknown.

As a whole, this is a travel book describing one of the most spectacular journeys that humanity has taken: a journey out of our limited and parochial views of reality, towards an increasingly vast understanding of the structure of things. A magical journey out of our common-sense view of things, far from complete.

Marseille, 4 May 2016

Preface: Walking along the Shore

We are obsessed with ourselves. We study *our* history, *our* psychology, *our* philosophy, *our* gods. Much of our knowledge revolves around man himself, as if we were the most important thing in the universe. I think I like physics because it opens a window through which we can see further. It gives me the sense of fresh air entering the house.

What we see out there through the window is constantly surprising us. We have learned a great deal about the universe. In the course of the centuries we have come to realize just how very many wrong ideas we had. We thought that the Earth was flat, and that it was the still centre of our world. That the universe was small, and unchanging. We believed that man was a breed apart, without kinship to the other animals. We have learned of the existence of quarks, black holes, particles of light, waves of space, and of the extraordinary molecular structures in every cell of our bodies. The human race is like a growing child who discovers with amazement that the world consists not just of his bedroom and playground, but that it is vast, and that there are a thousand things to discover, and innumerable ideas quite different from those with which he began. The universe is multiform and boundless, and we continue to stumble upon new aspects of it. The more we learn about the world, the more we are amazed by its variety, beauty and simplicity.

But the more we discover, the more we understand that what we don't yet know is greater than what we know. The more powerful our telescopes, the stranger and more unexpected are the heavens we see. The closer we look at the minute detail of matter, the more we discover of its profound structure. Today we see almost to the Big Bang, the great explosion from which, 14 billion years ago, all the galaxies were born – but we have already begun to glimpse something beyond the Big Bang. We have learned that space is curved, but already foresee that this same space is woven from vibrating quantum grains.

Our knowledge of the elementary grammar of the world continues to grow. If we try to put together what we have learned about the physical world in the course of the twentieth century, the clues point towards something profoundly different from what we were taught at school. An elementary structure of the world is emerging, generated by a swarm of quantum events, where time and space do not exist. Quantum fields draw space, time, matter and light, exchanging information between one event and another. Reality is a network of granular events; the dynamic which connects them is probabilistic; between one event and another, space, time, matter and energy melt in a cloud of probability.

This strange new world is slowly emerging today from the study of the main open question posed in fundamental physics: quantum gravity. It's the problem of coherently synthesizing what we have learned about the world with the two major discoveries of twentieth-century physics: general relativity and quantum theory. To quantum gravity, and the strange world that this research is unfolding, this book is dedicated.

The book is a live coverage of the ongoing research: what we are learning, what we already know, and what we think we are beginning to understand, about the elementary nature of things. It starts from the distant origin of some key ideas that we use today to order our understanding of the world and describes the two great discoveries of the twentieth century – Einstein's general relativity and quantum mechanics – trying to put into focus the core of their physical content. It tells of the picture of the world which is emerging today from research in quantum gravity, taking into account the latest indications given by nature, such as the confirmation of the cosmological standard model obtained from the Planck satellite and the failure at CERN to observe the super-symmetric particles that many expected. And it discusses the consequences of these ideas: the granular structure of space; the disappearance of time at small scale; the physics of the Big Bang; the origin of black-hole heat – up to the role of information in the foundation of physics.

In a famous myth related by Plato in the seventh book of *The Republic*, some men are chained at the bottom of a dark cave and see only shadows cast upon a wall by a fire behind them. They think that this is reality. One of them frees himself, leaves the cave and discovers the light of the Sun, and the wider world. At first the light, to which his eyes are unaccustomed, stuns and confuses him. But eventually he can see, and returns excitedly to his companions to tell them what he has seen. They find it hard to believe.

We are all in the depths of a cave, chained by our ignorance, by our prejudices, and our weak senses reveal to us only shadows. If we try to see further, we are confused: we are unaccustomed. But we try. This is science. Scientific thinking explores and redraws the world, gradually offering us better and better images of it, teaching us to think in ever more effective ways. Science is a continual exploration of ways of thinking. Its strength is its visionary capacity to demolish preconceived ideas, to reveal new regions of reality, and to construct novel and more effective images of the world. This adventure rests upon the entirety of past knowledge, but at its heart is change. The world is boundless and iridescent; we want to go and see it. We are immersed in its mystery and in its beauty, and over the horizon there is unexplored territory. The incompleteness and the uncertainty of our knowledge, our precariousness, suspended over the abyss of the immensity of what we don't know, does not render life meaningless: it makes it interesting and precious.

I have written this book to give an account of what for me is the wonder of this adventure. I've written with a particular reader in mind: someone who knows little or nothing about today's physics but is curious to find out what we know, but also what we don't yet understand, about the elementary weave of the world – and where we are searching. And I have written it to try to communicate the breathtaking beauty of the panorama of reality which can be seen from this perspective.

I've also written it for my colleagues, fellow travellers dispersed throughout the world, as well as for the young women and men with a passion for science, eager to set out on this journey for the first time. I've sought to outline the general landscape of the structure of the physical world, as seen by the double lights of relativity and of quantum physics, and to show how they can be combined. This is not only a book of divulgation; it's also one which articulates a point of view, in a field of research where the abstraction of the technical language may sometimes obscure the wide-angle vision. Science is made up of experiments, hypotheses, equations, calculations and long discussions; but these are only tools, like the instruments of musicians. In the end, what matters in music is the music itself, and what matters in science is the understanding of the world which science provides. To understand the significance of the discovery that the Earth turns around the Sun, it is not necessary to follow Copernicus's complicated calculations; to understand the importance of the discovery that all living beings on our planet have the same ancestors, it is not necessary to follow the complex arguments of Darwin's books. Science is about reading the world from a gradually widening point of view.

This book gives an account of the current state of the search for our new image of the world, as I understand it today. It is the reply I would give to a colleague and friend asking me, 'So, what do you think is the true nature of things?', as we walk along the shore, on a long midsummer's evening.

Part One

ROOTS

This book begins in Miletus, twenty-six centuries ago. Why begin a book about quantum gravity with events, people and ideas so ancient? I hope the reader eager to get on to quanta of space will not hold this against me. For it is easier to understand ideas by starting with the roots from which they have grown, and an important number of the ideas which turned out to be effective for understanding the world originated over two thousand years ago. If we briefly retrace their birth, they become clearer, and the later steps turn out to be simpler and natural.

But there's more. Certain problems first posed in antiquity continue to be crucial to our understanding of the world. Some of the most recent ideas about the structure of space utilize concepts and issues introduced then. In speaking of these distant ideas, I put on to the table questions which are going to be central to quantum gravity. This makes it also possible, when treating of quantum gravity, to distinguish between the ideas which go back to the very origin of scientific thought, even if we are unfamiliar with them, and those which are radically new. The connection between problems posed by the scientists of antiquity, and solutions found by Einstein and quantum gravity, is, as we shall see, surprisingly close.

1. Grains

According to tradition, in the year 450 BCE, a man embarked upon a ship travelling from Miletus to Abdera. It was to be a crucial journey for the history of knowledge.

The man was probably fleeing political turmoil in Miletus, where the aristocracy was violently seizing back power. Miletus had been a prosperous and flourishing Greek city, perhaps the principal city of the Greek world before the golden age of Athens and Sparta. It had been a busy commercial hub, dominating a network of almost a hundred colonies and commercial outposts, stretching from the Black Sea to Egypt. Caravans from Mesopotamia and ships from all over the Mediterranean arrived at Miletus, and ideas circulated.

Figure 1.1 The journey made by Leucippus of Miletus, the founder of the atomist school (circa 450 BCE).

During the preceding century, a revolution in thinking which would prove fundamental to humanity had taken place in Miletus. A group of thinkers had reformulated the way questions were asked about the world, and the way answers were sought. The greatest of these thinkers was Anaximander.

From time immemorial, or at least since humanity had left written texts which have come down to us, men had asked themselves how the world had come into being, what it was composed of, how it was ordered, and why natural phenomena occurred. For thousands of years they had given themselves answers which all resembled one another: answers which referred to elaborate stories of spirits, deities, imaginary and mythological creatures, and other similar things. From cuneiform tablets to ancient Chinese texts; from hieroglyphic writing in the Pyramids to the myths of the Sioux; from the most ancient Indian texts to the Bible; from African stories to those of aboriginal Australians, it was all a colourful but basically quite monotonous flow – of Plumed Serpents and Great Cows, of irascible, litigious, or kindly deities who create the world by breathing over abysses, uttering '*Fiat lux*', or emerging out of a stone egg.

Then, at Miletus, at the beginning of the fifth century before our era, Thales, his pupil Anaximander, Hecataeus and their school find a different way of looking for answers. This immense revolution in thought inaugurates a new mode of knowledge and understanding, and signals the first dawn of scientific thought.

The Milesians understand that by shrewdly using observation and reason, rather than searching for answers in fantasy, ancient myths or religion – and, above all, by using critical thought in a discriminating way – it is possible to repeatedly correct our world view, and to discover new aspects of reality which are hidden to the common view. It is possible to discover the new.

Perhaps the decisive discovery is that of a different style of thinking, where the disciple is no longer obliged to respect and share the ideas of the master but is free to build on those ideas without being afraid to discard or criticize the part that can be improved. This is a novel middle way, placed between full adherence to a school and generic deprecation of ideas. It is the key to the subsequent development of philosophical and scientific thinking: from this moment onwards, knowledge begins to grow at a vertiginous pace, nourished by past knowledge but at the same time by the possibility of criticism, and therefore of improving knowledge and understanding. The dazzling *incipit* of Hecataeus's book of history goes to the heart of this critical thinking, including as it does the awareness of our own fallibility: 'I wrote things which seem true to me, because the accounts of the Greeks seem to be full of contradictory and ridiculous things.'

According to legend, Heracles descended to Hades from Cape Tenaro. Hecataeus visits Cape Tenaro, and determines that there is in fact no subterranean passage or other access to Hades there – and therefore judges the legend to be false. This marks the dawn of a new era.

This new approach to knowledge works quickly and impressively. Within a matter of a few years, Anaximander understands that the Earth floats in the sky and the sky continues beneath the Earth; that rainwater comes from the evaporation of water on Earth; that the variety of substances in the world must be susceptible to being understood in terms of a single, unitary and simple constituent, which he calls *apeiron*, the indistinct; that the animals and plants evolve and adapt to changes in the environment, and that man must have evolved from other animals. Thus, gradually, was founded the basis of a grammar for understanding the world which is substantially still our own today.

Situated at a point of conjunction between the emergent Greek civilization and the ancient empires of Mesopotamia and Egypt, nourished by their knowledge but immersed in the liberty and the political fluidity which is typically Greek; in a social space without imperial palaces, or powerful priestly castes, where individual citizens discuss their destinies in open agoras, Miletus is the place where, for the first time, men decide collectively their own laws; where the first parliament in the history of the world gathers – the *Panionium*, meeting-place of the delegates of the Ionian League – and where for the first time men doubt that only the gods are capable of accounting for the mysteries of the world. Through discussion, it is possible to reach the best decisions for the community; through discussion, it is possible to understand the world. This is the immense legacy of Miletus, cradle of philosophy, of the natural sciences, and of geographical and historical studies. It is no exaggeration to say that the entire scientific and philosophical tradition, Mediterranean and then modern, has a crucial root in the speculations of the thinkers of Miletus in the sixth century BCE.[1]

This luminous Miletus shortly afterwards came to a calamitous end. The arrival of the Persian Empire, and a failed anti-imperial revolt, led to a ferocious destruction of the city in 494 BCE and to the enslavement of a large number of its inhabitants. In Athens, the poet Phrynichus writes the tragedy *The Taking of Miletus*, which so deeply moves the Athenians that its re-staging is prohibited, on account of it causing too much distress. But twenty years later, the Greeks repel the Persian menace; Miletus is reborn, repopulated, and returned to being a centre of commerce and ideas, radiating its thought and spirit once more.

The person with whom we began this chapter must have been moved by this spirit when, in 450, according to tradition, he embarked from Miletus for

Abdera. His name was Leucippus. Little is known about his life.[2] He wrote a book entitled *The Great Cosmology*. On his arrival in Abdera, he founded a scientific and philosophical school to which he soon affiliated a young disciple, Democritus, whose long shadow was to be cast over the thought of all subsequent times.

Together, these two thinkers have built the majestic cathedral of ancient atomism. Leucippus was the teacher. Democritus, the great pupil who wrote dozens of works on every field of knowledge, and was deeply venerated in antiquity, when people were familiar with these works. 'The most subtle of the Ancients', Seneca called him.[3] 'Who is there whom we can compare with him for the greatness, not merely of his genius, but also of his spirit?' asks Cicero.[4]

What, then, had Leucippus and Democritus discovered? The Milesians had understood that the world can be comprehended using reason. They had become convinced that the variety of natural phenomena must be attributable to something simple, and had tried to understand what this something might be. They had conceived of a kind of elementary substance of which everything was made. Anaximenes, among the Milesians, had imagined this substance could compress and rarefy, thus transforming from one to another of the elements of which the world is constituted. It was a first germ of physics, rough and elementary, but in the right direction. An idea was needed, a great idea, a grand vision, to grasp the hidden order of the world. Leucippus and Democritus came up with this idea.

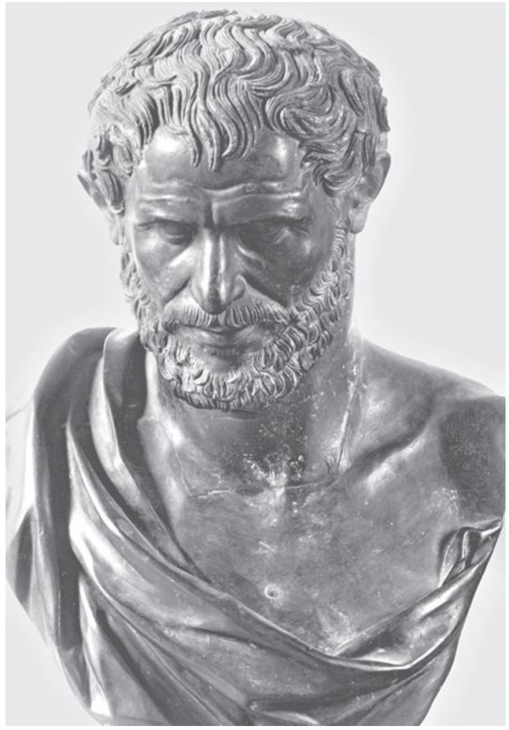

Figure 1.2 Democritus of Abdera.

The idea of Democritus's system is extremely simple: the entire universe is made up of a boundless space in which innumerable atoms run. Space is without limits; has neither an above nor a below; is without a centre, or a boundary. Atoms have no qualities at all, apart from their shape. They have no weight, no colour, no taste. 'By convention is sweet, by convention bitter, by convention hot, by convention colour; but by verity atoms and void.'[5]

Atoms are indivisible; they are the elementary grains of reality, which cannot be further subdivided, and everything is made of them. They move freely in space, colliding one with another; they hook on to and push and pull each other. Similar atoms attract each other and join.

This is the weave of the world. This is reality. Everything else is nothing but a by-product, random and accidental, of this movement and this combining of atoms. The infinite variety of the substances of which the world is made derives solely from this combining of atoms.

When atoms aggregate, the only thing that matters, the only thing that exists at the elementary level, is their shape, their arrangement, and the order in which they combine. Just as by combining the letters of the alphabet in different ways we may obtain comedies or tragedies, ridiculous stories or epic poems, so elementary atoms combine to produce the world in its endless variety. The metaphor is Democritus's own.[6]

There is no finality, no purpose, in this endless dance of atoms. We, just like the rest of the natural world, are one of the many products of this infinite dance. The product, that is, of an accidental combination. Nature continues to experiment with forms and structures; and we, like the animals, are the products of a selection which is random and accidental, over the course of eons of time. Our life is a combination of atoms, our thoughts are made up of thin atoms, our dreams are the products of atoms; our hopes and our emotions are written in a language formed by combinations of atoms; the light which we see is comprised of atoms which bring us images. The seas are made of atoms, as are our cities, and the stars. It's an immense vision; boundless, incredibly simple and incredibly powerful, one on which the knowledge of a civilization would later be built.

On this foundation Democritus wrote dozens of books articulating a vast system, dealing with questions of physics, philosophy, ethics, politics and cosmology. He writes on the nature of language, on religion, on the origins of human societies, and on much else besides. (The opening of his *Little Cosmology* is impressive: 'In this work I treat of all things.') All of these books have been lost. We know of his thought only through the quotations and references made by other ancient authors, and by their summaries of his ideas.[7] The thought which thus emerges is a kind of intense humanism, rationalist and materialist.[8] Democritus combines a keen attention to nature, illuminated by a naturalistic clarity in which every residual system of mythic ideas is cleared away, with a great attention to humanity and a deep ethical concern for life – anticipating by some two thousand years the best aspects of the eighteenth-century Enlightenment. The ethical ideal of Democritus is that of a serenity of mind reached through moderation and balance, by trusting in reason and not allowing oneself to be overwhelmed by passions.

Plato and Aristotle were familiar with Democritus's ideas, and fought against them. They did so on behalf of other ideas, some of which were later, for centuries, to create obstacles to the growth of knowledge. Both insisted on rejecting Democritus's naturalistic explanations, in favour of trying to understand the world in finalistic terms – believing, that is, that everything that happens has a purpose; a way of thinking that would reveal itself to be very misleading for understanding the ways of nature – or in terms of good and evil, confusing human issues with matters which do not relate to us.

Aristotle speaks extensively about the ideas of Democritus, and with respect. Plato never cites Democritus, but scholars suspect today that this was out of deliberate choice and not for lack of knowledge of his works. Criticism of

Democritus's ideas is implicit in several of Plato's texts, as in his critique of 'physicists', for example. In a passage in his *Phaedo*, Plato has Socrates articulate a reproach to all 'physicists' which will have a lasting resonance. He complains that when 'physicists' had explained that the Earth was round, he rebelled because he wanted to know what 'good' it was for the Earth to be round; how its roundness would benefit it. Plato's Socrates recounts how he had at first been enthusiastic about physics, but had come to be disillusioned by it:

> I had expected to be first told that the Earth was flat or round, but also that, afterwards, the reason for the necessity of this shape would be explained to me, starting from the principle of the best, proving to me that the best thing for the Earth is to have this shape. And if he had said that the Earth was at the centre of the world, then to show me how being at the centre was of benefit to the Earth.[9]

How completely off track the great Plato was here!

Is there a limit to divisibility?

The greatest physicist of the second half of the twentieth century, Richard Feynman, wrote at the beginning of his wonderful introductory lessons on physics:

> If, in some cataclysm, all scientific knowledge were to be destroyed, and only one sentence passed on to the next generation 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 an enormous amount of information about the world, if just a little imagination and thinking are applied.[10]

Without needing anything from modern physics, Democritus had already arrived at the idea that everything is made up of indivisible particles. How did he do it?

He had arguments based upon observation; for example, he imagined, correctly, that the wearing down of a wheel, or the drying of clothes on a line, could be due to the slow flight of particles of wood or of water. But he also had arguments of a philosophical kind. Let's focus on these, because their potency reaches all the way to quantum gravity.

Democritus observed that matter could not be a continuous whole, because there is something contradictory in the proposition that it should be so. We know of Democritus's reasoning because Aristotle reports it.[11] Imagine, says Democritus, that matter is infinitely divisible, that is to say, it may be broken down an infinite number of times. Imagine then that you break up a piece of matter ad infinitum. What would be left?

Could small particles of extended dimension remain? No, because if this were the case the piece of matter would not yet be broken up to infinity. Therefore, only points without extension would remain. But now let us try to put together the piece of matter starting from these points: by putting together two points without extension you cannot obtain a thing with extension, nor can you with three, or even with four. No matter how many you put together, in fact, you never have extension, because points have no extension. Therefore, we cannot think that matter is made of points without extension, because no matter how many of these we manage to put together, we never obtain something with an extended dimension. The only possibility, Democritus concludes, is that any piece of matter is made up of a *finite* number of discrete pieces which are indivisible, each one having *finite* size: the atoms.

The origin of this subtle mode of argumentation pre- dates Democritus. It comes from the Cilento region in the south of Italy, from a town now called Velia, which in the fifth century BCE was a flourishing Greek colony called Elea. Parmenides lived there, the philosopher who had taken to the letter – perhaps too much – the rationalism of Miletus and the idea born there that reason can reveal to us how things can be other than they appear. Parmenides had explored an avenue to truth via pure reason alone, a path which led him to declare that all appearances are illusory, thus opening a direction of thinking that would progressively move towards metaphysics and distance itself from what would come to be known as 'natural science'. His pupil Zeno, also from Elea, had brought subtle arguments to bear in support of this fundamentalist rationalism, which refutes the credibility of appearances radically. Among these arguments there was a series of paradoxes that became celebrated as 'Zeno's paradoxes'; they seek to show how all appearance is illusory, arguing that the commonplace notion of motion is absurd.[12]

The most famous of Zeno's paradoxes is presented in the form of a brief fable: the tortoise challenges Achilles to a race, starting out with a ten-metre advantage. Will Achilles manage to catch up with the tortoise? Zeno argues that rigorous logic dictates that he will never be able to do so. Before catching up, in effect, Achilles needs to cover the ten metres, and in order to do this he will take a certain amount of time. During this time, the tortoise will have advanced a few centimetres. To cover these centimetres, Achilles will have to take a little more time but, meanwhile, the tortoise will have advanced further, and so on, ad infinitum. Achilles therefore requires *an infinite number of such times* to reach the tortoise, and an *infinite number of times*, argues Zeno, is *an infinite amount of time*. Consequently, according to strict logic, Achilles will take an infinite time to reach the tortoise; or rather, we will never see him do so. Since, however, we do see the swift Achilles reaching and overtaking as many tortoises as he likes, it follows that what we see is irrational, and therefore illusory.

Let's be honest: this is hardly convincing. Where does the error lie? One possible answer is that Zeno is wrong because it is not true that by accumulating an infinite number of things one ends up with an infinite thing. Think of taking a piece of string, cutting it in half, and then again in half, and again, ad infinitum. At the end, you will obtain an infinite number of small pieces of string; the sum of these, however, will be finite, because they can only add up to the length of the original piece of string. Hence, an infinite number of strings can make a finite string; an infinite number of increasingly short times may make a *finite* time, and the hero, even if he will have to cover an infinite number of distances, ever smaller, will take a *finite* time to do so, and will end up catching the tortoise.

It seems that the paradox is resolved. The solution, that is, is in the idea of the continuum – arbitrarily small times may exist, an infinite number of which make up a finite time. Aristotle is the first to intuit this possibility, which was subsequently developed by ancient and modern mathematics.[fn1]

But is this really the correct solution in the *real* world? Do arbitrarily short strings really exist? Can we really cut a piece of string an *arbitrary* number of times? Do infinitely small amounts of time exist? This is precisely the problem that quantum gravity will have to face.

According to tradition, Zeno had met Leucippus and had become his teacher. Leucippus was therefore familiar with Zeno's riddles. But he had devised a *different* way of resolving them. Maybe, Leucippus suggests, nothing arbitrarily small exists: there is a lower limit to divisibility.

The universe is granular, not continuous. With infinitely small points, it would be impossible ever to construct extension – as in Democritus's argument, reported by Aristotle and mentioned above. Therefore, the extension of the string must be formed by a *finite* number of finite objects with *finite* size. The string *cannot* be cut *as many times as we want*; matter is not continuous, it is made of individual 'atoms' of a finite size.

Whether this abstract argument is correct or not, its conclusion – as we know today – contains a great deal of truth. Matter does indeed have an atomic structure. If I divide a drop of water in two, I obtain two drops of water. I can divide each one of these two drops again, and so on. But I cannot continue to infinity. At a certain point I have only one molecule, and I have finished. No drops of water exist smaller than a single molecule of water.

How do we know this today? Evidence has accumulated over centuries, much of it from chemistry. Chemical substances are made up of combinations of a few elements and are formed by proportions (of weight) given by whole numbers. Chemists have constructed a way of thinking about substances as composed of molecules made up of fixed combinations of atoms. Water, for example – H_2O – is composed of two parts hydrogen and one part oxygen.

But these are only clues. Still at the beginning of the last century numerous scientists and philosophers did not consider the atomic hypothesis to be credible. Among them was the renowned physicist and philosopher Ernst Mach, whose ideas on space would come to have great importance for Einstein. At the end of a lecture by Ludwig Boltzmann at the Imperial Academy of Science in Vienna, Mach publicly declared, ‘I do not believe that atoms exist!’ This was in 1897. Many, like Mach, understood chemical notation only as a conventional method of summarizing laws of chemical reactions – not as evidence that there actually were molecules of water composed of two atoms of hydrogen and one of oxygen. You can’t see atoms, they would say. Atoms will never be seen, they would say. And then, they asked, how big would an atom be? Democritus could never measure the size of his atoms …

But somebody else could. The definitive proof of the ‘atomic hypothesis’ had to wait until 1905. It was found by a rebellious twenty-five-year-old, who had studied physics but had not been able to find employment as a scientist and was making ends meet by working as an employee in the patent office in Berne. I will speak a lot about this young man in the rest of this book, and about the three articles he sent to the most prestigious physics journal of the time, the *Annalen der Physik*. The first of these articles contained the definitive proof that atoms exist, and calculated their dimensions, solving the problem posed by Leucippus and Democritus twenty-three centuries earlier.

Figure 1.3 Albert Einstein.

The name of this twenty-five-year-old, obviously, is Albert Einstein.

How does he do it? The idea is surprisingly simple. Anyone could have arrived at it, from the time of Democritus onwards, if he had had Einstein's acumen and a sufficient mastery of mathematics to make what was not an easy calculation. The idea goes like this: if we observe attentively very small particles, such as a speck of dust or a grain of pollen, suspended in still air or in a liquid, we see them tremble and dance. Pushed by this trembling, they move, randomly zigzagging, and so they drift slowly, gradually moving away from their starting point. This motion of particles in a fluid is called Brownian motion, after Robert Brown, a biologist who described it in detail in the nineteenth century. The typical trajectory of a particle dancing in this manner is illustrated in figure 1.4. It is as if the small particle is receiving blows randomly from each side of it. In fact, it isn't 'as if' it were being hit, it really is hit. It trembles because it is hit by individual molecules of air, which collide with the particle at times from the right and at times from the left.

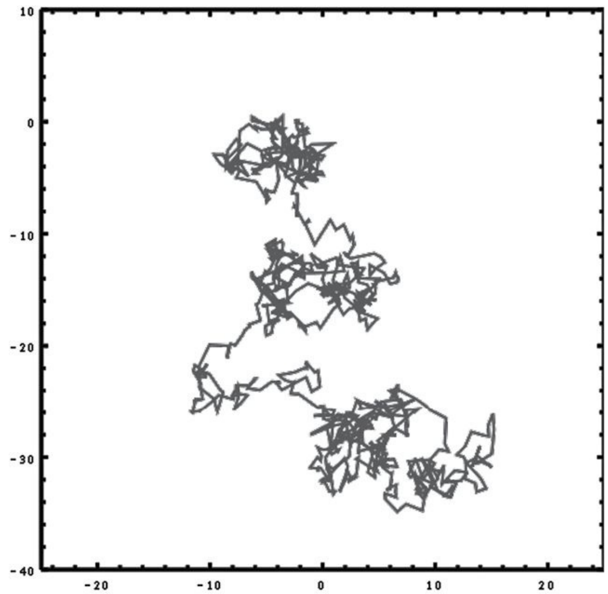

Figure 1.4 Typical Brownian motion.

The subtle point is the following. There are an enormous number of molecules of air. On average, as many hit the granule from the left as those that hit it from the right. If the air's molecules were infinitely small and infinitely numerous, the effect of the collisions from right and from left would balance and thus cancel out at each instant, and the granule would not move. But the finite size of the molecules – the fact that these are present in *finite* rather than infinite number – causes there to be *fluctuations* (this is the key word): that is to say, the collisions never balance out *exactly*; they only balance out *on average*. Imagine for a moment the molecules were very few in number and large in size: the granule would clearly receive a blow only occasionally; now one on the right, then one on the left … Between one collision and the other it would move here and there to a significant degree, like a football kicked by boys running around a playing field. The smaller the molecules, on the other hand, the shorter the interval between collisions and the better the hits from different directions balance and cancel each other out. And the less the granule moves.

It is indeed possible, with a little mathematics, to work back from the amount of movement of the granule, which can be observed, to the dimensions of the molecules. Einstein does this, as I mentioned above, at the age of twenty-five. From observations of granules drifting in fluids, from the measurement of how much these 'drift' – that is, move away from a position – he calculates the dimensions of Democritus's atoms, the elementary grains of which matter is made. He provides, after 2,300 years, the proof of the accuracy of Democritus's insight: matter is granular.

The nature of things

> Sublime Lucretius's work will not die,
> Until the day the world itself passes away.
>
> – Ovid[13]

I often think that the loss of the works of Democritus in their entirety[fn2] is the greatest intellectual tragedy to ensue from the collapse of the old classical civilization. Take a look at the list of his works in the footnote; it is difficult not to be dismayed, imagining what we have lost of the vast scientific reflections of antiquity.

We have been left with all of Aristotle, by way of which Western thought reconstructed itself, and nothing by Democritus. Perhaps, if all of the works of Democritus had survived, and nothing of Aristotle's, the intellectual history of our civilization would have been better …

But centuries dominated by monotheism have not permitted the survival of Democritus's naturalism. The closure of the ancient schools such as those of Athens and Alexandria and the destruction of all the texts not in accordance with Christian ideas were vast and systematic, at the time of the brutal anti-pagan repression following from the edicts of Emperor Theodosius, which, in 390–1 declared that Christianity was to be the only and obligatory religion of the empire. Plato and Aristotle, pagans who believed in the immortality of the soul or in the existence of a Prime Mover, could be tolerated by a triumphant Christianity. Not Democritus.

But a text survived the disaster, and has reached us in its entirety. Through it, we know a little about ancient atomism and, above all, we know the spirit of that science. It is the splendid poem *De rerum natura* (*The Nature of Things*, or *On the Nature of the Universe*), by the Latin poet Lucretius.

Lucretius adheres to the philosophy of Epicurus, a pupil of a pupil of Democritus. Epicurus is interested more in ethical than scientific questions and does not have Democritus's depth. He sometimes translates Democritean atomism a little superficially. But his vision of the natural world is substantially that of the great philosopher of Abdera. Lucretius decants in verse the thought of Epicurus and the atomism of Democritus, and in this way a part of this profound philosophy was saved from the intellectual catastrophe of the Dark Ages. Lucretius sings of atoms, the sea, the sky, of nature. He expresses in luminous verse philosophical questions, scientific ideas, refined arguments.

… I will explain by what forces nature steers the courses of the sun and the journeyings of the moon, so that we shall not suppose that they run their yearly races between the heaven and earth of their own free will … or that they are rolled round in furtherance of some divine plan …[14]

The beauty of the poem lies in the sense of wonder which pervades the vast atomistic vision – the sense of the profound unity of things, derived from the knowledge that we are all made of the same substance as are the stars, and the sea:

… we are all sprung from heavenly seed. All alike have the same father, from whom all-nourishing mother earth receives the showering drops of moisture. Thus fertilized, she gives birth to smiling crops and lusty trees, to mankind and all the breeds of beasts. She it is that yields the food on which they all feed their bodies, lead their joyous lives and renew their race …[15]

There is a sense of luminous calm and serenity about the poem, which comes from understanding that there are no capricious gods demanding of us difficult things, and punishing us. There is a vibrant and airy joyfulness, beginning with the marvellous opening verses dedicated to Venus, a radiant symbol of the creative force of nature:

Before you the winds flee, and at your coming the clouds forsake the sky. For you the ocean levels laugh, the sky is calmed and glows with diffused radiance.[16]

There is a deep acceptance of the life of which we are an integral part:

Do you not see that nature is clamouring for two things only, a body free from pain, a mind released from worry and fear for the enjoyment of pleasurable sensations?[17]

And there is a serene acceptance of the inevitability of death, which cancels every evil and about which there is nothing to fear. For Lucretius, religion is ignorance; reason is the torch that brings light.

Lucretius's text, forgotten for centuries, was rediscovered in January 1417 by the humanist Poggio Bracciolini, in the library of a German monastery. Poggio had been the secretary of many popes, and was a passionate hunter of ancient books, in the wake of the celebrated rediscoveries made by Francesco Petrarch. His rediscovery of a text by Quintilian modified the course of the study of law throughout the faculties of Europe; his discovery of the treatise on architecture by Vitruvius transformed the way in which fine buildings were designed and constructed. But his triumph was rediscovering Lucretius. The actual codex found by Poggio has been lost, but the copy made by his friend Niccolò Niccoli (now known as the Codex Laurenziano 35.30) is still preserved in its entirety in Florence's Biblioteca Laurenziana.

The ground was already surely prepared for something new when Poggio gave Lucretius's book back to humanity. Already, from Dante's generation, it had been possible to hear markedly new accents:

> Your eyes went shooting through my heart
> to wake my dormant thought.
> Look now, I'm desperate and distraught
> with love that tears my life apart.[18]

But the rediscovery of *De rerum natura* had a profound effect upon the Italian and European Renaissance,[19] and its echo resounds, directly or indirectly, in the pages of authors ranging from Galileo[20] to Kepler,[21] and from Bacon to Machiavelli. In Shakespeare, a century after Poggio, atoms make a delightful appearance:

> MERCUTIO O, then I see Queen Mab hath been with you:
> She is the fairies' midwife, and she comes
> In shape no bigger than an agate-stone
> On the forefinger of an alderman,
> Drawn with a little team of atomies
> Over men's noses as they lie asleep …[22]

Montaigne's *Essays* include at least a hundred quotations from Lucretius. But the direct influence of Lucretius extended to Newton, Dalton, Spinoza, Darwin – and all the way up to Einstein. The very idea of Einstein's that the existence of atoms is revealed by the Brownian motion of minute particles immersed in a fluid may be traced back to Lucretius. Here is a passage in which Lucretius provides a 'living proof' of the notion of atoms:

> This process is illustrated by an image of it that is continually taking place before our very eyes. Observe what happens when sunbeams are admitted into a building and shed light on its shadowy places. You will see a multitude of tiny particles mingling in a multitude of ways in the empty space within the light of the beam, as though contending in everlasting conflict, rushing into battle rank upon rank with never a moment's pause in a rapid sequence of unions and disunions. From this you may picture what it is for the atoms to be perpetually tossed about in the illimitable void. To some extent a small thing may afford an illustration and an imperfect image of great things. Besides, there is a further reason why you should give your mind to these particles that are seen dancing in a sunbeam: their dancing is an actual indication of underlying movements of matter that are hidden from our sight. There you will see many particles under the impact of invisible blows, changing their course and driven back upon their tracks, this way and that, in all directions. You must understand that they all derive this restlessness from the atoms. It originates with the atoms, which move of themselves. Then those small compound bodies that are least removed from the impetus of the atoms are set in motion by the impact of their invisible blows and in turn cannon against slightly larger bodies. So the movement mounts up from the atoms and gradually emerges to the level of our senses, so that those bodies are in motion that we see in sunbeams, moved by blows that remain invisible.[23]

Einstein resuscitated the 'living proof' presented by Lucretius, and probably first conceived of by Democritus, and made it solid by translating it into mathematical terms, thus managing to calculate the size of the atoms.

The Catholic Church attempted to stop Lucretius: in the Florentine Synod of December 1516 it prohibited the reading of Lucretius in schools. In 1551, the Council of Trent banned his work. But it was too late. An entire vision of the world which had been swept away by medieval Christian fundamentalism was re-emerging in a Europe which had reopened its eyes. It was not just the rationalism, atheism and materialism of Lucretius that were being proposed in Europe. It was not merely a luminous and serene meditation on the beauty of the world. It was much more: it was an articulate and complex structure of thinking about reality, a new mode of thinking, radically different from what had been for centuries the mind-set of the Middle Ages.[24]

The medieval cosmos so marvellously sung by Dante was interpreted on the basis of a hierarchical organization of the universe which reflected the hierarchical organization of European society: a spherical cosmic structure with the Earth at its centre; the irreducible separation between Earth and heavens; finalistic and metaphorical explanations of natural phenomena. Fear of God, fear of death; little attention to nature; the idea that forms preceding things determine the structure of the world; the idea that the source of knowledge could only be the past, in revelation and tradition …

There is none of this in the world of Democritus as sung by Lucretius. There is no fear of the gods; no ends or purposes in the world; no cosmic hierarchy; no distinction between Earth and heavens. There is a deep love of nature, a serene immersion within it; a recognition that we are profoundly part of it; that men, women, animals, plants and clouds are organic threads of a marvellous whole, without hierarchies. There is a feeling of deep universalism in the wake of the splendid words of Democritus: 'To a wise man, the whole earth is open, because the true country of a virtuous soul is the entire universe.'[25]

There is, too, the ambition of being able to think about the world in simple terms. Of being able to investigate and understand the secrets of nature. To know more than our parents. And there are extraordinary conceptual tools on which Galileo, Kepler and Newton will build: the idea of free rectilinear motion in space; the idea of elementary bodies and their interactions, out of which the world is constructed; the idea of space as a container of the world.

And there is the simple idea of the finite divisibility of things. The granular quality of the world. The idea which stops the infinite between our fingers. This idea is at the root of the atomic hypothesis, but it will also return with augmented force with quantum mechanics, and today is revealing itself to be powerful again – as the keystone of quantum gravity.

The first person to make the parts of the mosaic which begin to emerge from Renaissance naturalism cohere – and to reprise the Democritean vision, immensely reinforced, placing it at the centre of modern thought – will be an Englishman, the greatest scientist of all time and the first protagonist of the following chapter.

2. The Classics

Isaac and the little moon

If in the previous chapter I appeared to be saying that Plato and Aristotle have only done harm to the development of science, I would like to correct this impression. Aristotle's studies of nature – of botany and zoology, for example – are extraordinary scientific works, grounded upon meticulous observations of the natural world. The conceptual clarity, the attention to the variety of nature, the impressive intelligence and the openness of mind of the great philosopher made him an authority for centuries to come. The first systematic physics that we know of is Aristotle's, and it is not bad physics at all.

Aristotle presents it in a book entitled, precisely, *Physics*. The book didn't take its title from the name of a discipline: it was the discipline which got its name from Aristotle's book. For Aristotle, physics works as follows. First, it is necessary to distinguish between the heavens and Earth. In the heavens, everything is made up of a crystalline substance which moves in a circular motion and turns eternally around the Earth in great concentric circles, with the spherical Earth at the centre of everything. On the Earth, it is necessary to distinguish between forced motion and natural motion. Forced motion is caused by a thrust and ends when the thrust ends. Natural motion is vertical – upwards or downwards – and depends both on the substance and the location. Each substance has a 'natural place', that is to say, a proper altitude to which it always returns: earth at the bottom, water a little way above it, air a little higher still, and fire even higher. When you pick up a stone and let it fall, the stone moves downwards because it wants to return to its natural level. Air bubbles in water, fire in the air; and children's balloons move upwards, seeking their natural place.

Do not smile at this theory, or dismiss it, because it is very sound physics. It's a good and correct description of the motion of bodies immersed in a fluid and subject to gravity and friction, namely, the real things we meet in our everyday experience. It's not wrong physics, as is frequently said.[fn3] It's an approximation. But the physics of Newton, too, is an approximation of general relativity. And probably everything that we know today as well is an