JIM BAGGOTT

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The quest to understand matter from Greek atoms to quantum fields

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OXFORD
UNIVERSITY PRESS

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Great Clarendon Street, Oxford, OX2 6DP,
United Kingdom

Oxford University Press is a department of the University of Oxford.
It furthers the University's objective of excellence in research, scholarship,
and education by publishing worldwide. Oxford is a registered trade mark of
Oxford University Press in the UK and certain other countries

First Edition published in 2017

Impression: 1

Published in the United States of America by Oxford University Press
198 Madison Avenue, New York, NY 10016, United States of America

British Library Cataloguing in Publication Data
Data available

Library of Congress Control Number: 2016960645

ISBN 978-0-19-875971-3

Printed in Great Britain by
Clays Ltd, St Ives plc

For Mike.
It’s probably your fault…

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PREFACE

> It has always been the dream of philosophers to have all matter built up from one fundamental kind of particle…
>
> *Paul Dirac*[1]

It seems so simple.

You're sitting here, reading this book. Maybe it's a hardback copy, or a paperback, or an e-book on a tablet computer or e-reader. It doesn't matter. Whatever you're holding in your hands, we can be reasonably sure it's made of some kind of *stuff*: paper, card, plastic, perhaps containing tiny metal electronic things on printed circuit boards. Whatever it is, we call it *matter* or *material substance*. It has a characteristic property that we call *solidity*. It has *mass*.

But what *is* matter, exactly? We learn in school science class that matter is not continuous, but discrete. As a few of the philosophers of ancient Greece once speculated nearly two-and-a-half thousand years ago, matter comes in 'lumps'. If we dig around online we learn that we make paper by pressing together moist fibres derived from pulp. The pulp has an internal structure built from molecules (such as cellulose), and molecules are in turn constructed from atoms (carbon, oxygen, hydrogen). We further learn that atoms are mostly empty space, with a small, central nucleus of protons and neutrons orbited by electrons.

You might have also learned that protons and neutrons are not the last word on this subject. Particles thought to be the ultimate building blocks of matter or (more likely) whose internal structures are presently simply unknown are referred to by scientists as 'elementary'. According to this definition protons and neutrons are not elementary particles. They are composites, assembled from different kinds of quark, held together by gluons.

Okay, so things are a little more complicated than we might have supposed. But surely all we're really seeing here is successive generations of scientific discovery peeling away the layers of material substance. Paper, card, plastic; molecules; atoms; protons and neutrons; quarks and electrons. As we descend through each layer of matter we find smaller and smaller constituents. This is surely hardly surprising.

But then, just as surely, we can't keep doing this indefinitely. Just as the ancient Greek philosophers once speculated, we imagine that we should eventually run up against some kind of ultimately fundamental, indivisible type of stuff, the building blocks from which everything in the universe is made.

And it doesn't seem to require a particularly bold leap of imagination to suppose that, whatever it might be, there can be only *one* fundamental type of stuff. Or, at least, one fundamental type of stuff would seem simpler, or neater. The rest—electric charge, something called colour charge, flavour, spin, and many other things besides—would then just be 'dressing'.

In 1930, the English physicist Paul Dirac called this 'the dream of philosophers'. These were simpler times. The neutron hadn't yet been discovered (it was discovered by James Chadwick in 1932) and, so far as physicists of the time understood, all matter was composed of just two kinds of elementary particle—positively charged protons and negatively charged electrons. For a time, Dirac thought he had found a way to reconcile these, and the quote that I used to open this Preface continues: 'There are, however, reasons for believing that the electron and proton are really not independent, but are just two manifestations of one elementary kind of particle.'

Alas, Dirac was wrong. What he had stumbled across in the mathematical equations of his new quantum theory of the electron was not, after all, a fundamental relationship between the proton and the electron. He had deduced the existence of an altogether different kind of matter, which become known as antimatter. The positively charged entity that his theory predicted was not the proton. It was the anti-electron (or positron), discovered in studies of cosmic rays just a couple of years later.

After 1930 things just went from bad to worse. The dream became something of a nightmare. Instead of two elementary particles that might somehow be related, physicists were confronted by a veritable 'zoo' of different kinds of particles, many with seemingly absurd properties. It is a simple truth that modern science has undermined *all* our comfortable preconceptions about the physical universe, and especially the nature of material substance.

What we have discovered is that the foundations of our universe are not as solid or as certain and dependable as we might have once imagined. They are instead built from ghosts and phantoms, of a peculiar quantum kind. And, at some point on this exciting journey of discovery, we lost our grip on the reassuringly familiar concept of mass, the ubiquitous *m* that appears in all the equations of physics, chemistry, and biology.

To the ancient Greek atomists, atoms had to possess *weight*. To Isaac Newton, mass was simply *quantitas materiae*, the amount or quantity of matter an object contains. On the surface, there seem no grounds for arguing with these perfectly logical conclusions. Mass is surely an 'everyday' property, and hardly mysterious. When we stand on the bathroom scales in the morning, or lift heavy weights in the gym, or stumble against an immovable object, we pay our respects to Newton's classical conception of mass.

But when a single electron passes like a phantom at once through two closely spaced holes or slits, to be recorded as a single spot on a far detector, what happens to the mass of this supposedly ‘indivisible’ elementary particle in between? Einstein’s most celebrated equation, $E = mc^2$, is utterly familiar, but what does it really mean for mass and energy to be equivalent and interchangeable?

The so-called ‘standard model’ of particle physics is the most successful theoretical description of elementary particles and forces ever devised. In this model, particles are replaced by quantum fields. Now, how can a quantum *field* that is distributed through space and time have mass, and what *is* a quantum field anyway? What does it really mean to say that elementary particles gain their mass through interactions with the recently discovered Higgs field? If we add up the masses of the three quarks that are believed to form a proton, we get only one per cent of the proton mass. So, where’s the rest of it?

And then we learn from the standard model of inflationary big bang cosmology that this stuff that we tend to get rather obsessed about—so-called ‘baryonic’ matter formed from protons and neutrons—accounts for less than five per cent of the total mass-energy of the universe. About twenty-six per cent is dark matter, a ubiquitous but completely invisible and unknown form of matter that is responsible for shaping the large-scale structure of visible galaxies, galaxy clusters, and the voids in between. The rest (a mere sixty-nine per cent) is believed to be dark energy, the energy of ‘empty’ space, responsible for accelerating the expansion of spacetime.

How did this happen? How did the answers to our oh-so-simple questions become so complicated and so difficult to comprehend?

In *Mass,* I will try to explain how we come to find ourselves here, confronted by a very different understanding of the nature of matter, the origin of mass and its implications for our understanding of the material world.

One word of warning. The authors of works with pretentions to present popular interpretations of the conclusions of modern science tend to duck the difficult challenge of dealing with its mathematical complexity. There's the famous quote in Stephen Hawking's *A Brief History of Time*: 'Someone told me that each equation I included in the book would halve the sales.'[2] In previous books, I've tended to follow this rubric, limiting myself to a very small number of very familiar equations (see $E = mc^2$, above).

But the language of mathematics has proved to be enormously powerful in describing the laws of nature and the properties of matter. It's important to recognize that theorists will most often pursue a mathematical line of reasoning to see where it takes them, without worrying overmuch about how the mathematical terms that appear in their equations and the resulting conclusions should then be physically interpreted.

In the early years of the development of quantum mechanics, for example, the Austrian theorist Erwin Schrödinger bemoaned a general loss of what he called *anschaulichkeit,* of visualizability or perceptibility, as the mathematics became ever denser and more abstract. Theorists, supported by experiment or observation, may be able to prove that this mathematical equation represents some aspect of our physical reality. But there's absolutely no guarantee that we'll be able to interpret its concepts in a way that aids comprehension.

So, I've chosen in this book to reveal a little more of the mathematics than usual, simply so that interested readers can get some sense of what these concepts are, how physicists use them, and how they sometimes struggle to make sense of them. In doing this

I'm only going to scratch the surface, hopefully to give you enough pause for thought without getting too distracted by the detail.*

If you can't always follow the logic or don't understand the physical meaning of this or that symbol, please don't be too hard on yourself.

There's a good chance nobody else really understands it, either.

It's a real pleasure to acknowledge the efforts of Carlo Rovelli, who made some helpful and encouraging comments on the draft manuscript. Now I've never really expected family or friends to read my stuff, although it's always nice when they do (especially when they then say nice things about it). Obviously, I'm thankful to my mother for lots of things, but on this occasion I'm especially grateful, as she took it upon herself to read every word and provide helpful suggestions on how I might make these words simpler and more accessible. Now my mum has had no formal scientific education (she graduated with a degree in history from Warwick University in England when she was seventy-four), but she has boundless curiosity and enthusiasm for knowledge about the world. My hope is that if my mum can follow it…

I must also acknowledge my debts to Latha Menon, my editor at Oxford University Press, and to Jenny Nugee, who helped to turn my ramblings into a book that is hopefully coherent, no matter what it's made of.

Jim Baggott
October 2016

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* Actually, I set myself the following constraints. No equations in the main text with more than two or at most three variables plus a constant ($E = mc^2$ has two variables, E and m, and one physical constant, c). There's a little more mathematical detail in the Endnotes for those interested enough to dig deeper.

LIST OF FIGURES

ABOUT THE AUTHOR

Jim Baggott is an award-winning science writer. A former academic scientist, he now works as an independent business consultant but maintains a broad interest in science, philosophy, and history, and continues to write on these subjects in his spare time. His previous books have been widely acclaimed and include:

Origins: The Scientific Story of Creation, Oxford University Press, 2015
Farewell to Reality: How Fairy-tale Physics Betrays the Search for Scientific Truth, Constable, London, 2013
Higgs: The Invention and Discovery of the 'God Particle', Oxford University Press, 2012
The Quantum Story: A History in 40 Moments, Oxford University Press, 2011
Atomic: The First War of Physics and the Secret History of the Atom Bomb 1939–49, Icon Books, London, 2009, re-issued 2015 (short-listed for the Duke of Westminster Medal for Military Literature, 2010)
A Beginner's Guide to Reality, Penguin, London, 2005
Beyond Measure: Modern Physics, Philosophy and the Meaning of Quantum Theory, Oxford University Press, 2004
Perfect Symmetry: The Accidental Discovery of Buckminsterfullerene, Oxford University Press, 1994
The Meaning of Quantum Theory: A Guide for Students of Chemistry and Physics, Oxford University Press, 1992

PART I

ATOM AND VOID

In which the concept of the atom is introduced by the philosophers of ancient Greece and evolves from indivisible, indestructible bits of matter to the atoms of chemical elements as we know them today.

1

THE QUIET CITADEL

> This dread and darkness of the mind cannot be dispelled by the sunbeams, the shining shafts of day, but only by an understanding of the outward form and inner workings of nature.
>
> *Lucretius*[1]

I propose to start from some clear and simple beginnings, and follow the breadcrumbs of observation, experiment, and logical reasoning into the heart of the mystery of matter. We'll begin with the kinds of things we might deduce for ourselves just by observing the world around us and pondering on its nature, without the benefit of having access to a fully equipped physics laboratory or a handy high-energy particle collider.

Now, I've managed to convince myself that this means starting with the philosophers of ancient Greece. I say this not because I think they can necessarily inform our understanding today—it goes without saying that the ancient Greek philosophers didn't have the benefit of a modern scientific education. All they could do was apply a little logic and imagination to the things they could perceive with their unaided senses, and this, I think, is a great place to start.

We owe much of our common preconceptions of the nature of matter to the physical world imagined by the ancient Greeks, and especially those we refer to as the *atomists*. These were Leucippus of Miletus (or Abdera or Elea, according to different sources), who is thought to have lived in the middle of the fifth century Before the Common Era (BCE); his pupil Democritus of Abdera (born around 460 BCE); and their intellectual heir Epicurus of Samos (born over a century later, around 341 BCE), who revived, adapted, and incorporated this early version of the atomic theory into a formal philosophy. In truth, our knowledge of precisely what these philosophers said or how they structured their arguments is in some places rather vague. Epicurus argued that Leucippus may not have even existed and that the credit for devising the atomic theory belongs solely to Democritus. Only about 300 fragments of the writings attributed to Democritus have survived. That may sound like a lot, but they pale in comparison with the list of works compiled by the third-century CE biographer Diogenes Laërtius, in his book *Lives of the Eminent Philosophers*.

According to Diogenes, Democritus wrote extensively on physics, cosmology, and mathematics, and on ethics and music. His obsession with the human condition, and especially our sense of happiness or cheerfulness, led him to become known as the 'laughing philosopher'. Much of what we know of Democritus' work comes to us second-hand, from the commentaries of later philosophers, some of whom (such as Aristotle, born in 384 BCE) were vocal, though seemingly respectful, *opponents* of the atomic theory.

The situation is a little better when it comes to the writings of Epicurus. He penned several summaries of his work (called epitomes), including one on his physical theory written to his pupil Herodotus, and this, it would seem, is quoted in full by Diogenes. The Epicurean philosophy was also the inspiration for Roman poet and philosopher Titus Lucretius Caro's epic poem *De Rerum Natura* (translated variously as 'On the Nature of Things' or 'On the Nature of the Universe'), which was published around

55 BCE and which appears to be a relatively faithful adaptation of Epicurus' own thirty-seven-volume magnum opus, *On Nature*.*

It may yet be possible to learn more of Epicurus' particular brand of atomism from his own writings. A handsome villa in the Roman city of Herculaneum, thought to belong to Julius Caesar's father-in-law and sitting half-way up Mount Vesuvius, was buried in ash and debris in the eruption of 79 CE. Excavations in the eighteenth century uncovered an extensive library, containing more than 1,800 papyri (the 'Herculaneum papyri').[2] This is believed to be the personal library of the philosopher Philodemus of Gadara, born around 110 BCE. Philodemus studied in the Epicurean school in Athens, and many of the papyri contain key parts of *On Nature*, though these are badly damaged and many gaps remain.

Enough of the history. Let us now examine the logic. To be fair to these ancient thinkers, let's try temporarily to forget what we know about our modern world. We're going to indulge in a little armchair philosophizing, and we don't want to be distracted by the trappings of our modern existence. Let's imagine ourselves strolling barefoot along an Aegean beach in fifth-century BCE Western Thrace in Greece, about 17 kilometres northeast of the mouth of the Nestos River (see Figure 1). It's a fine day. The Sun is shining and a gentle breeze blows inland. As we stroll, we're preoccupied with a single question.

How is the world put together?

Before we can really begin to address this question we need to establish some ground rules. Living as we do in fifth-century BCE Greece, our lives and many of our daily rituals are governed by

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* In the opening passage of Book II of *On the Nature of the Universe* (Penguin, London, first published 1951), Lucretius compares the joy of philosophical reflection to standing aloof in 'a quiet citadel, stoutly fortified by the teaching of the wise', gazing down on struggling humanity. I suspect this is the earliest depiction of an 'ivory tower' as you're likely to find.

Figure 1. Greece and Western Asia Minor.

a need to pay our respects to the gods. Let's agree that, irrespective of our own personal beliefs and prejudices, we will seek an answer to our philosophical question that does not rely ultimately on some kind of divine intervention. As we look around us, we see blue sky, a sandy beach, a restless sea and, on a distant hill, a flock of sheep grazing on green grass. No gods.

If we deny that the gods have any role in creating and shaping the material world, then we eliminate the element of unpredictability, chance causation and the sense of 'anything goes' that might otherwise be identified with the 'will of the gods'. We then allow ourselves an opportunity to discern something of the world's underlying *natural* order.

Setting legend and superstition aside, it is our common experience that there are no miracles. Objects in the material world don't suddenly appear, from nowhere or from nothing. And, although they undoubtedly change over time, objects likewise don't suddenly vanish into thin air. This means that we can move on quickly to our first important logical deduction. *Nothing can come from nothing.*[3]

Let's go further. Just as we see no evidence for the gods intervening in the material world, so too we see no evidence for any influence of what we might call the human soul or spirit. Again, this doesn't mean to imply that the soul or spirit doesn't exist or isn't in some way connected to the way the mind works. It's just that these appear to be quite distinctly different things. Whatever it is and however it works, it is my experience that my mind (soul, spirit) does seem to be rather firmly fixed in my head or in my body, and can't go wandering off into the external material world, at least while I'm still living. What this means is that we're heading in the direction of a firmly *materialist* or *mechanistic* philosophy. Our external material world is shaped *only* by non-sentient, physical mechanism.

A moment's reflection as we continue our stroll leads us to conclude that there exists an astonishing variety of different *forms* of matter. Look around. We see rock, soil, sand, water, air, living creatures. Drawn up on the beach ahead of us is a small wooden fishing boat, abandoned for now by its owner. We can see why. It is holed just below the waterline. A crude attempt at repair has reduced some of the wooden hull to a fine sawdust, which has gathered on the sand beneath and is now catching in the breeze. No object in the material world can be created from nothing and, logic suggests, objects can never be reduced to nothing. Left to itself the sawdust will disperse, scattered to the winds. But, you now suggest, the matter that was once solid wood and is now sawdust has simply changed form, and although it will blow away it doesn't disappear. I tend to agree.

The sawdust shows that, as a result of some mechanical action, the solid wood of the boat's hull can be finely divided. But then, what if we could divide the sawdust even more finely? And then divide it some more? Couldn't we keep on doing this, endlessly dividing the matter into smaller and smaller pieces, *ad infinitum*? Wouldn't we end up dividing it completely into nothing, and so contradicting our earlier conclusion?

This reminds you of a famous paradox devised by one of our contemporaries, Zeno of Elea. The one about the race between the Greek hero Achilles and the tortoise. I've heard it before, but you tell the story well and it is worth repeating. It is clear that Achilles and the tortoise are unevenly matched. But Achilles has a strong sense of honour and fair play, and he agrees to give the tortoise a head start, no doubt confident of ultimate victory. So, Achilles waits until the tortoise has reached a certain position—half-way to the finish line—before setting off. But by the time Achilles has reached half-way, the tortoise will inevitably have moved on a certain additional distance. By the time Achilles has reached that additional distance, the tortoise will have moved on a little further. We can go on like this for ever, it seems. Each time Achilles reaches the point where the tortoise was, the tortoise has moved a little further ahead. It seems that Achilles will never overtake the tortoise.

At the heart of Zeno's paradox lies the seemingly innocent observation that a line can be divided into an infinite number of distinct points. But if there's an infinity of points between start and finish, then no kind of motion through each and every point can be conceived that will allow us to get from start to finish in a *finite* time. Zeno is a pupil of Parmenides of Elea, and philosophers of the Eleatic school argue that, contrary to appearances, all change is an illusion. There is no motion because motion is simply impossible. This, according to Parmenides, is the 'way of truth'. Appearances, in contrast, are deceptive and so cannot be trusted. He calls this the 'way of opinion'. Hmm…

We ponder on this for a while. We debate some more and agree that it's really rather illogical bordering on absurd to deny ourselves access to everything we can learn about the material world by engaging our senses. Why not trust them? Why not rely on how things appear? But then how do we resolve Zeno's paradox?

You're struck by a thought. You explain that the paradox is actually based on a confusion. Whilst it is correct to suggest that a continuous line can be *mathematically* divided into an infinity of points, this does not mean that a distance or an area or a volume in the real world can be *physically* so divided. What if the material world is *not* continuous and endlessly divisible, but is instead composed of discrete, indivisible, or uncuttable parts? You use the Greek word *atomon,* or *a-tomon,* meaning an entity that cannot be cut or divided.

It's an intriguing line of argument, and it leads us to another conclusion. Matter cannot be divided endlessly into nothing: it can be divided only into its constituent atoms.[4]

I sense some problems, however. We perceive change in the external material world because matter changes over time and changes from one form into another. (Think about the lake that freezes over with ice in the winter.) But underpinning all the different kinds of matter are indestructible atoms, right? Ah, but if the atoms are indestructible and unchangeable, and therefore eternal, just *how* can they be responsible for the change that we perceive?

You ponder this question for a while, then suddenly snap your fingers. Change happens because the atoms are *constantly moving,* colliding with each other and forming different associations with each other that represent the different forms that matter can take. Okay, I can live with that. But what, can I ask, are these atoms supposed to be moving *in*? I sense you're on a roll. You come right back and announce with conviction that the *solid atoms are moving in empty space,* also known as the 'void'.[5] This kind of thing will doubtless sow some seeds for future philosophical argument. (Aristotle was firmly against the idea of the void and is credited with the declaration that 'nature abhors a vacuum'.) But we'll run with it for now.

So, just by looking at the world around us and thinking logically about its construction and the nature of change we've come to the conclusion that all matter exists in the form of atoms moving restlessly in space. With a little more intellectual effort we can sharpen this basic description to fit a few more of our observations.

We can suppose that by mixing different proportions of 'hard' atoms and empty space we can construct the wonderful variety of material substance in all its forms, which the Ancient Greeks reduced to four basic 'elements'—earth, air, fire, and water.[6] Although he did not acknowledge any influence of Leucippus or Democritus on his work, the great philosopher Plato (born around 428 BCE*) developed an elaborate atomic theory. He represented each of the four elements by a geometrical (or so-called 'Platonic') solid, and argued in the *Timaeus* that the faces of each solid could be further decomposed into systems of triangles, representing the elements' constituent atoms. Rearrange the patterns of triangles—rearrange the atoms—and it is possible to convert one element into another and combine elements to produce new forms.[7]

Plato fixed on triangles, but the early atomists (and, subsequently, Epicurus) argued that atoms must possess different *shapes,* some more rounded, with gentle curves, some more angular, sharp-edged, and 'spiky', with barbs and hooks. As the atoms collide they stick together to form composites (I guess what we would today call molecules). The different textures of the resulting

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* Or 427 or four years later.

combinations are ultimately responsible for the properties and behaviours of the material substances thus formed.

The release of films of atoms from these substances cause us to have sensory perceptions. We perceive colour through the ‘turning’ or changing positions of the atoms that enter our eyes, the texture of the atoms on our tongues cause taste sensations, and so on. The atomists did not imagine the atoms in such combinations to be held together by any kind of force, but rather by the interlinking of their shapes. For example, Lucretius suggested that that bitter taste of seawater could be attributed to the presence of ‘rough’ atoms. These rough atoms can be filtered out by passing seawater through layers of earth (as they have a tendency to ‘stick’ to earth), allowing the ‘smooth’ atoms through and so giving a much more palatable fluid.[8]

Democritus suggested that there was no limit to the number of different possible shapes that atoms could possess, and that they could, in principle, be of any size. Epicurus was more circumspect. He argued that there must be a limit to the number of shapes. And atoms are small beyond the limits of perception—if we can see it then it’s not of atomic size.

This is all very fine, but if the atoms are supposed to be perpetually moving, what is it that is *making* them do so? Aristotle (who was a student of Plato) didn’t buy it.[9] The early atomists never really explained what causes such motion, even though this is absolutely essential to the theory.

Epicurus provided something of an answer by crediting the atoms with *weight* which causes a ‘downward’ motion through the infinite cosmos, as can be observed in the behaviour of any and all substantial things on Earth. The atoms are kept in motion either by their own weight or by the impacts of collisions with other atoms.[10] But anyone who has ever been caught in a heavy downpour will have noticed how raindrops can sometimes appear to fall vertically. If the atoms are not subject to any other force except for a kind of gravity that pulls them downward, then why wouldn't they simply fall straight down, so avoiding chance collisions? According to later commentators, Epicurus admitted that they sometimes 'swerve':

> When the atoms are travelling straight down through empty space by their own weight, at quite indeterminate times and places they swerve ever so little from their course.[11]

This argument doesn't hold up well under scrutiny, and in fairness I should point out that although we've no reason to doubt later sources, no such comment can be found in the surviving writings of Epicurus himself.

If we accept that atoms are endlessly in motion, how do we reconcile this with the fact that large, observable objects are still, or move only slowly? The atomists argued that we don't see the motion because we simply can't. Remember that flock of sheep grazing on the distant hillside as we strolled along the beach? It serves as an example. From this distance, we can't discern the movements of individual sheep. We see only a vague—and seemingly stationary—white blur on the green hillside.[12]

One last challenge. Why should we believe in the reality of atoms if they are so small that we can never see them? Isn't this just the same as believing in gods or any other construction of the imagination that we could invoke to explain observed phenomena, but for which we can gather no evidence using our senses? The atomists advise us to stick to our mechanistic instincts. Although we can't see these invisible entities, there is plenty of visible evidence which alerts us to their existence. There are effects for which atoms must be the cause.

Just look at many natural phenomena, such as wind, odour, humidity, or evaporation. We're all too familiar with such things, although we cannot see the agencies that cause them. Likewise, we're aware of the imperceptible wearing down of a ring worn on a finger, or a ploughshare in a furrow, or the cobblestones under your feet, or the right hands of bronze statues at the city gates worn thin by the greeting touch of travellers, although we cannot see the particles that are lost through such slow decay. Nature must work through the agency of invisible atoms.[13]

Perhaps there's even more direct evidence. Imagine a quiet space, inside an ancient building. A high window admits a beam of sunlight which lightens the darkness. As we look more closely we notice a multitude of tiny particles dancing in the beam. What's causing this dance of the dust motes? Isn't this evidence of invisible atomic motions?[14]

It's hard to fault this logic although, of course, this is not the right conclusion. Dust motes dance in a sunbeam because they are caught in currents of air, not because they are buffeted by the chaotic motions of atoms. It's just a question of *scale*. But this description would be perfectly appropriate when applied to fine grains of pollen suspended in a fluid, whose random, microscopic motions were observed and reported by Scottish botanist Robert Brown in 1827 and which is now collectively called *Brownian motion*. In 1905, a young 'technical expert, third class' working at the Swiss patent office in Bern published a paper explaining how Brownian motion is visible evidence for the random movements of the invisible atoms or molecules of the fluid. His name was Albert Einstein (and we'll get to him soon enough).

So, according to the ancient atomists matter is composed of atoms moving restlessly in the void. Different forms of matter are constructed from different mixtures of atoms and void, and from different combinations of atoms. Changes in these combinations and mixtures cause matter to change from one form to another, and films of atoms released from material objects cause sensory perceptions. The atoms possess properties of size, shape, position, and weight, and sometimes 'swerve' into each other as they fall, but are so small as to be invisible to our eyes.

This is all perfectly logical and wonderfully well argued. But there remains a problem with this structure that threatens to undermine it completely. We've arrived at these conclusions by trusting that our perceptions of the external world provide us with a faithful representation, on which we can apply our logic with confidence. However, the atomists agreed that although these perceptions are in some way *caused* by atoms that exist in reality, the sensations that result—colour, taste, odour, and so on—are not 'real' in this same sense. The atoms themselves have no sensory properties—for example, atoms cause the sensation of colour or a bitter taste but they are not in themselves coloured, or bitter. The sensations we experience are constructs of our minds and exist only in our minds. There will be a lot more on this topic in Chapter 2.

But surely everything we know or can deduce is shaped by these very perceptions. If we accept that they exist only in the internal workings of our minds, then it seems we are denied access to the external reality that we're trying so hard to create a structure for. It seems that on this point the laughing philosopher was really rather pessimistic: 'We know nothing in reality;' he declared, 'for truth lies in an abyss.'[15]

Five things we learned

1. Matter is 'substantial'. It cannot suddenly appear from nothing and it cannot be divided endlessly into nothing.

2. Therefore all matter must consist of ultimate, indivisible components which we call atoms.
3. Atoms move endlessly in empty space—the void. Different forms of matter are composed of mixtures of atoms with different shapes and different proportions of hard atoms and void.
4. Atoms move because they possess weight. As they fall they sometimes 'swerve' and collide with each other.
5. Atoms possess the properties of size, shape, position (in the void), and weight. They also cause sensory perceptions in our minds, of colour, taste, odour, and so on, although the atoms themselves do not possess these properties directly.

2

THINGS-IN-THEMSELVES

> Though we cannot know these objects as things in themselves, we must yet be in a position to at least think [of] them as things in themselves; otherwise we would be landed in the absurd conclusion that there can be appearance without anything that appears.
>
> *Immanuel Kant*[1]

I want to reassure you that this business about perception and the nature of external reality which so exercised Democritus is not some philosophical mire of our own making. It is not something from which we can extricate ourselves only by engaging in seemingly interminable nit picking. It is a fundamental problem that will have a profound impact on our understanding of matter and it will be a recurring theme. I fear that anyone suffering the delusion that science is free from this kind of philosophical wrangling is most likely in for bit of a shock.

I propose in this chapter to move on quite quickly from the ancient Greek atomists to some of the great philosophers of the seventeenth and eighteenth centuries. Now, in doing so I don't want to give you the impression that nothing of consequence was discussed, debated, or written by philosophers in the sixteen centuries that passed in between. But I think it's fair to say that much of the attention of Western philosophers during this period was absorbed by the challenge of reconciling the philosophies of ancient Greece and Rome with the theologies of the 'Abrahamic' religions of Christianity, Judaism, and Islam.[2]

Some of the tenets of ancient Greek philosophy were preserved, even as the Roman Empire began its slow decline, initially by a few scholars with some facility in the Greek language. Not all of these scholars were wholly sympathetic, however. For example, the second-century CE Christian philosopher Quintus Septimius Florens Tertullianus (Tertullian, sometimes referred to as the 'father of Western theology'), despised Greek philosophy, declaring the Greeks to be the 'patriarchs of heretics'.[3]

The Greeks' pronouncements on the nature of the soul, resurrection, and the creation simply didn't fit the demands of a theology based on the notion of an all-powerful, omniscient, omnipresent, Christian God. It was perhaps inevitable that philosophical inquiry into the nature of the material world would get dragged into the debate. 'Natural philosophy' became inextricably tangled with theological questions, such that the lines we draw today between these disciplines became greatly blurred, or even non-existent.

But the emphasis on scholarship slowly returned, first through schools established by monasteries and cathedrals, some few of which eventually developed in the twelfth and thirteenth centuries into universities. The rise of academic philosophy and theology helped to renew interest in the ancient Greeks, even though formal teaching of some of their works was generally forbidden (e.g., the teaching of Aristotle's metaphysics and natural science was prohibited by the statutes of the University of Paris in 1215).

This burgeoning interest in a selection of the ancient Greek texts proliferated new translations. By the middle of the thirteenth century the climate had changed sufficiently to allow the Italian Catholic priest and theologian Thomas Aquinas to set about the task of rehabilitating Aristotle. The resulting 'Thomist' philosophy is Aristotle blended with many other sources, ancient and medieval. This was only a partial or selective rehabilitation: Aquinas served two spells as regent master of theology at the University of Paris, so Thomism is really a theology or a philosophy with a distinctly Christian gloss. In this way, Aristotle's pronouncements on the nature of matter, his Earth-centred cosmology based on perfect circular motion, caused by a prime mover, became enshrined in Christian religious orthodoxy.

So, what *did* Aristotle have to say about the nature of material substance? He had struggled to reconcile Democritus' rather passive, unchanging atoms with the observation of a very lively, actively changing material reality. And, as we have seen, he rejected completely the notion of the void. The atomists' rebuttal of Parmenides and Zeno arguably required that space and time should also be conceived to be 'atomic' in nature, with ultimate limits on how finely units of space and units of time can be divided.* Aristotle preferred to think of space and time as continuous, and any object taking up room in a continuous three-dimensional space is in principle infinitely divisible, thereby making atoms impossible. But he was nevertheless still sympathetic to the idea that a substance could be reduced to some kind of smallest constituent. It was just that the atomists had gone too far. They had been *too* reductionist in their approach.

His solution was an alternative structure based on the idea of *natural minima,* meaning the smallest parts into which a substance can be divided without losing its essential character. Now, natural minima are in principle *not* atoms, at least in the sense that the Greek atomists understood the term. Natural minima can in principle be divided. It's just that when they are divided beyond a

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* This idea is firmly back with us today—see the Epilogue.