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CHAPTER 1

THE AWE OF UNDERSTANDING

While stories will always be a vital part of human culture, even in science—and our lives would be the poorer without them—modern science has now replaced many of the ancient mythologies and accompanying superstitious beliefs. A good example of how we have demystified our approach to understanding the world is the creation myths. Since the dawn of history, humankind has invented stories about the origins of our world, and deities that were instrumental in its creation, from the Sumerian god Anu, or Sky Father, to the Greek myths about Gaia being created out of Chaos and the Genesis myths of the Abrahamic religions, which are still believed as literal truths in many societies around the world. It may appear to many non-scientists that our modern cosmological theories about the origins of the universe are themselves no better than the religious mythologies they replace—and, if you look at some of the more speculative ideas in modern theoretical physics, you might agree that those who feel this way have a point. But through rational analysis and careful observation—a painstaking process of testing and building up scientific evidence, rather than accepting stories and explanations with blind faith—we can now claim with a high degree of confidence that we know quite a lot about our universe. We can also now say with confidence that what mysteries remain need not be attributed to the supernatural. They are phenomena we have yet to understand—and which we hopefully will understand one day through reason, rational enquiry, and, yes . . . physics.

Contrary to what some people might argue, the scientific method is *not* just another way of looking at the world, nor is it just another cultural ideology or belief system. It is the way we learn about nature through trial and error, through experimentation and observation, through being prepared to replace ideas that turn out to be wrong or incomplete with better ones, and through seeing patterns in nature and beauty in the mathematical equations that describe these patterns. All the while we deepen our understanding and get closer to that 'truth'—the way the world *really* is.

There can be no denying that scientists have the same dreams and prejudices as everyone else, and they hold views that may not always be entirely objective. What one group of scientists calls 'consensus', others see as 'dogma'. What one generation regards as established fact, the next generation shows to be naïve misunderstanding. Just as in religion, politics, or sport, arguments have always raged in science. There is often a danger that, all the while a scientific issue remains unresolved, or at least open to reasonable doubt, the positions held by each side of the argument can become entrenched ideologies. Each viewpoint can be nuanced and complex, and its advocates can be just as unshakable as they would be in any other ideological debate. And just as with societal attitudes on religion, politics, culture, race, or gender, we sometimes need a new generation to come along, shake off the shackles of the past, and move the debate forward.

But there is also a crucial distinction to science, when compared with other disciplines. A single careful observation or experimental result can render a widely held scientific view or long-standing theory obsolete and replace it with a new worldview. This means that those theories and explanations of natural phenomena that have survived the test of time are the ones we trust the most; they are the ones we are most confident about. The Earth goes around the Sun, not the other way around; the universe is expanding, not static; the speed of light in a vacuum always measures the same no matter how fast the measurer of that speed is moving; and so on. When a new and important scientific discovery is made, which changes the way we see the world, not all scientists will buy into it immediately, but that's *their* problem; scientific progress is inexorable, which, by the way, is *always* a good thing: knowledge and enlightenment are always better than ignorance. We start with not knowing, but we seek to find out . . . and, though we may argue along the way, we cannot ignore what we find. When it comes to our scientific understanding of how the world is, the notion that 'ignorance is bliss' is a load of rubbish. As Douglas Adams once put it: 'I'd take the awe of understanding over the awe of ignorance any day.'[1]

WHAT WE DON'T KNOW

It is also true that we are constantly discovering how much more there is that we don't yet know. Our growing understanding yields a growing understanding of our ignorance! In some ways, as I will explain, this is the situation we have in physics right now. We are currently at a moment in history when many physicists see, if not a crisis in the subject, then at least the building up of a head of steam. It feels as though something has to give. A few decades ago, prominent physicists such as Stephen Hawking were asking, 'Is the end in sight

1 Douglas Adams, *The Salmon of Doubt: Hitchhiking the Galaxy One Last Time* (New York: Harmony, 2002), 99.

for theoretical physics?'[2] with a 'theory of everything' potentially just around the corner. They said it was just a matter of dotting the 'i's and crossing the 't's. But they were wrong, and not for the first time. Physicists had expressed similar sentiments towards the end of the nineteenth century; then along came an explosion of new discoveries (the electron, radioactivity, and X-rays) that couldn't be explained by the physics known at the time and which ushered in the birth of modern physics. Many physicists today feel that we might potentially be on the verge of another revolution in physics as big as that seen a century ago with the birth of relativity and quantum mechanics. I am not suggesting that we are about to discover some fundamental new phenomenon, like X-rays or radioactivity, but there may yet be a need for another Einstein to break the current deadlock.

The Large Hadron Collider has not yet followed up on its 2012 success in detecting the Higgs boson, and thereby confirming the ex-

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2 This was the title of an article Hawking wrote in 1981: S. W. Hawking, *Physics Bulletin* **32**, no. 1 (1981): 15–17.

istence of the Higgs field (which I will discuss later); many physicists were hoping for the discovery of other new particles by now, which would help resolve long-standing mysteries. And we still don't understand the nature of the dark matter holding galaxies together or the dark energy that is ripping the universe apart; nor do we have answers to fundamental questions like why there is more matter than antimatter; why the properties of the universe are so finely tuned to allow for stars and planets, and life, to exist; whether there is a multiverse; or whether there was anything before the Big Bang that created the universe we see. There is still so much left that we cannot explain. And yet, it is hard *not* to be dazzled by our success so far. While some scientific theories may turn out to be connected to each other at a deeper level than we thought, and others may turn out to be entirely wrong, no one can deny just how far we've come.

Sometimes, in the light of new empirical evidence, we realise that we were barking up the wrong tree. Other times we simply refine an idea that turns out not to be wrong, but just a rough approximation that we improve upon to gain a more accurate picture of reality. There are some areas of fundamental physics that we might not be entirely happy with, where we know deep down that we've not heard the final word, but which we nevertheless continue to rely on for the time being because they are useful. A good example of this is Newton's universal law of gravitation. It is still referred to, grandly, as a 'law' because scientists at the time were so confident that it was the last word on the subject that they elevated its status above that of a mere 'theory'. The name stuck, despite the fact that we now know their confidence was misplaced. Einstein's general theory (note that it's called a theory) of relativity replaced Newton's law, because it gives us a deeper and more accurate explanation of gravity. And yet, we still use Newton's equations to calculate the flight trajectories of space missions. The predictions of Newtonian mechanics may not be as accurate as those of Einstein's relativity, but they are still good enough for nearly all everyday purposes.

Another example that we are still working on is the Standard Model of particle physics. This is an amalgamation of two separate mathematical theories, called electroweak theory and quantum chromodynamics, which together describe the properties of all the known elementary particles and the forces acting between them. Some physicists think of the Standard Model as nothing more than a stopgap until a more accurate and unified theory is discovered. And yet, it is remarkable that, as it stands now, the Standard Model can tell us everything we need to know about the nature of matter: how and why electrons arrange themselves around atomic nuclei, how atoms interact to form molecules, how those molecules fit together to make up everything around us, how matter interacts with light (and therefore how almost all phenomena can be explained). Just one aspect of it, quantum electrodynamics, underpins all of chemistry at the deepest level.

But the Standard Model cannot be the final word on the nature of matter, because it doesn't include gravity and it doesn't explain dark matter or dark energy, which between them make up most of the stuff of the universe. Answering some questions naturally leads to others, and physicists continue their search for physics 'beyond the Standard Model' in an attempt to address these lingering but crucial unknowns.

HOW WE PROGRESS

More than any other scientific discipline, physics progresses via the continual interplay between theory and experiment. Theories only survive the test of time as long as their predictions continue to be verified by experiments. A good theory is one that makes new predictions that can be tested in the lab, but if those experimental results conflict with the theory, then it has to be modified, or even discarded. Conversely, laboratory experiments can point to unexplained phenomena that require new theoretical developments. In no other science do we see such a beautiful partnership. Theorems in pure mathematics are proven with logic, deduction, and the use of axiomatic truths. They do not require validation in the real world. In contrast, geology, ethology or behavioural psychology are mostly observational sciences in which advances in our understanding are made through the painstaking collection of data from the natural world, or via carefully designed laboratory tests. But physics can *only* progress when theory and experiment work hand in hand, each pulling the other up and pointing to the next foothold up the cliffside.

Shining a light on the unknown is another good metaphor for how physicists develop their theories and models, and how they design their experiments to test some aspect of how the world works. When it comes to looking for new ideas in physics, there are, very broadly, two kinds of researchers. Imagine you're walking home on a dark, moonless night when you realise that there's a hole in your coat pocket through which your keys must have fallen at some point along your route. You know they have to be somewhere on the ground along the stretch of pavement you've just walked, so you retrace your steps. But do you only search the patches bathed in light beneath lampposts? After all, while these areas cover only a fraction of the pavement, at least you will see your keys if they are there. Or do you grope around in the dark stretches in between the pools of lamplight? Your keys may be more likely to be here, but they will also be more difficult to find.

Similarly, there are lamppost physicists and searchers in the dark. The former play it safe and develop theories that can be tested against experiment—they look where they can see. This means they tend to be less ambitious in coming up with original ideas, but they achieve a higher success rate in advancing our knowledge, albeit incrementally: evolution, not revolution. In contrast, the searchers in the dark are those who come up with highly original and speculative ideas that are not so easy to test. Their chances of success are lower, but the payoff can be greater if they are right, and their discoveries can lead to paradigm shifts in our understanding. This distinction is far more prevalent in physics than in other sciences.

I have sympathy for those who get frustrated by the searchers and the dreamers, who often work in esoteric areas like cosmology and string theory, for these are the people who think nothing of adding a few new dimensions here or there if it makes their maths prettier, or to hypothesise an infinity of parallel universes if it reduces the strangeness in ours. But there have been some famous examples of searchers who have struck gold. The twentieth-century genius Paul Dirac was a man driven by the beauty of his equations, which led him to postulate the existence of antimatter several years before it was discovered in 1932. Then there's Murray Gell-Mann and George Zweig, who in the mid-1960s independently predicted the existence of quarks when there was no experimental evidence to suggest such particles existed. Peter Higgs had to wait half a century for his boson to be discovered and the theory that bears his name to be confirmed. Even the quantum pioneer Erwin Schrödinger came up with his eponymous equation with nothing more than inspired guesswork. He picked the right mathematical form of equation even though he didn't yet know what its solution meant.

What unique talents did all these physicists have? Was it intuition? Was it a sixth sense that allowed them to sniff out nature's secrets? Possibly. The Nobel Prize winner Steven Weinberg believes it is the aesthetic beauty in the mathematics that has guided great theoreticians like Paul Dirac and the great nineteenth-century Scottish physicist James Clerk Maxwell.

But it is also true that none of these physicists worked in isolation, and their ideas still had to be consistent with all established facts and experimental observations.

THE SEARCH FOR SIMPLICITY

The true beauty of physics, for me, is found not only in abstract equations or in surprising experimental results, but in the deep underlying principles that govern the way the world is. This is a beauty that is no less awe-inspiring than a breathtaking sunset or a great work of art such as a Leonardo da Vinci painting or Mozart sonata. It is a beauty that lies not in the surprising profundity of the laws of nature, but in the deceptively simple underlying explanations (where we have them) for where those laws come from.[3]

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3 Of course, beauty need not only be associated with simplicity. Just as with great art or music, there can also be beauty in the sheer complexity of some physical phenomena.

A perfect example of the search for simplicity is science's long and continuing journey to discover the basic building blocks of matter. Take a look around you. Consider the sheer range of materials that make up our everyday world: concrete, glass, metals, plastics, wood, fabrics, foodstuffs, paper, chemicals, plants, cats, people . . . millions of different substances, each with its own distinctive properties: squidgy, hard, runny, shiny, bendy, warm, cold. . . . If you knew nothing of physics or chemistry, you might imagine that most materials have little in common with each other; and yet we know that everything is made of atoms, and that there is only a finite number of different kinds of atoms.

But our quest for ever-deeper simplicity does not stop there. Thinking about the structure of matter goes all the way back to the fifth century BC in ancient Greece, when Empedocles first proposed that all matter consisted of four fundamental 'elements' (his 'fourfold roots of everything'): earth, water, air, and fire. In contrast to this simple idea, and around the same time, two other philosophers, Leucippus and his pupil Democritus, proposed that all matter was composed of tiny indivisible 'atoms'. However, these two promising ideas conflicted with each other. While Democritus believed that matter was ultimately made of fundamental building blocks, he thought there would be an infinite variety of such different atoms; whereas Empedocles, who proposed that everything was ultimately made up of just four elements, argued that these elements were continuous and infinitely divisible. Both Plato and Aristotle promoted the latter theory and rejected Democritus's atomism, believing that its simplistic mechanistic materialism could not produce the rich diversity of beauty and form of the world.

What the Greek philosophers were doing was not true science as we understand it today—apart from a few notable exceptions, such as Aristotle (the observer) and Archimedes (the experimenter), their theories were often not much more than idealised philosophical concepts. Nevertheless, today, through the tools of modern science, we know that both of those ancient ideas (atomism and the four elements) were, in spirit at least, along the right lines: that all the stuff making up our world, including our own bodies, and including everything we see out in space—the Sun, the Moon, and the stars—is all made of fewer than a hundred different types of atoms. We also now know that atoms have internal structure. They are made of tiny, dense nuclei surrounded by clouds of electrons while the nucleus itself is made up of smaller constituents: protons and neutrons, which are in turn made of even more fundamental building blocks called quarks.

So, despite the apparent complexity of matter and the immeasurable variety of substances that can be made up from the chemical elements, the truth is that the ancients' quest for simplicity didn't go far enough. As we understand physics today, all the matter we see in the world is made up of not the four classical elements of the Greeks, but just three elementary particles: the 'up' quark, the 'down' quark, and the electron. That's it. Everything else is just detail.

And yet the job of physics is more than just classifying what the world is made of. It is about finding the correct explanations for the natural phenomena we observe and the underlying principles and mechanisms that account for them. While the ancient Greeks might have debated passionately about the reality of atoms or the abstract connection between 'matter' and 'form', they had no idea how to explain earthquakes or lightning, let alone astronomical events such as the phases of the Moon or the occasional appearance of comets—although this didn't prevent them from trying.

We have come a very long way since the Greeks of antiquity, and yet there is also plenty that we still have to understand and explain. The physics I will cover in this book is mostly the stuff we are confident about. Throughout, I will explain *why* we are confident and point out what is speculative and where there may be some wiggle room. Naturally, I anticipate that some parts of the story will become out-of-date in the future. Indeed, an important discovery might be made the day after this book's publication that revises some aspect of our understanding. But that is the nature of science. *Mostly*, what you will read about in this book is established beyond reasonable doubt to be the way the world *is*.

In the next chapter, I explore the idea of scale. No other science so brazenly addresses such a vast range of scales, of time, space, and energies, as physics does, from the unimaginably tiny quantum world to the entire cosmos, and from the blink of an eye to eternity.

After gaining an appreciation for the scope of what physics can explain, we will begin on our journey in earnest, starting with the three 'pillars' of modern physics: relativity, quantum mechanics, and thermodynamics. In order to paint the picture of our world that physics has given us, we must first prepare the canvas, and in this case the canvas is space and time. Everything that happens in the universe comes down to events that take place somewhere in space and at some moment in time. And yet, we will see in chapter 3 that we cannot separate the canvas from the painting. Space and time themselves are an integral part of reality. You may be shocked to discover just how different the physicist's view of space and time is from our everyday, commonsense one, for it relies on Einstein's general theory of relativity, which describes the nature of space and time and defines how we think about the fabric of the cosmos. Once this canvas is ready, we can proceed to prepare our paints. In chapter 4, I define what a physicist means by matter and energy, the stuff of the universe: what it consists of, how it was created, and how it behaves. One can think of this chapter as a companion to the previous one, because I also describe how matter and energy are intimately related to the space and time in which they exist.

In chapter 5, I plunge into the world of the very small, zooming in and shrinking down to study the nature of the fundamental building blocks of matter. This is the quantum world, our second pillar of modern physics, where matter behaves very differently from our everyday experiences, and where our grip on what is real becomes increasingly tenuous. And yet . . . our understanding of the quantum is far more than a flight of fancy or mere intellectual diversion; without an understanding of the rules governing the building blocks of matter and energy, we would not have been able to build our modern technological world.

In chapter 6, we zoom out of the quantum world to see what happens when we put many particles together to make up larger, more complex systems. What do physicists mean by order, disorder, complexity, entropy, and chaos? Here, we encounter the third pillar of physics, thermodynamics—the study of heat, energy, and the properties of matter in bulk. We are led inevitably to ask what makes life itself so special. How is living matter so different from nonliving matter? After all, life must be subject to the same laws of physics as everything else. In other words, can physics help us understand the difference between chemistry and biology?

In chapter 7, I explore one of the most profound ideas in physics, the notion of unification: the way we have sought, and found, over and over again, universal laws that bring together seemingly disparate phenomena in nature under one unifying description or theory. I conclude the chapter with a look at some of the front-runners for an all-encompassing physical 'theory of everything'.

By chapter 8 we will have reached the limit of what we currently understand about the physical universe and can finally dip our toes in the vast ocean of the unknown. I explore some of the mysteries we are currently struggling with and speculate upon whether we are close to solving them.

In the penultimate chapter, I discuss how the interplay of theory and experiment in physics has led to the technologies on which our modern world is built. For example, without quantum mechanics, we would not have been able to understand the behaviour of semiconductors or invent the silicon chip, on which all of modern electronics is founded, and I would not be typing these words on my laptop. I will also take a look into the future and predict how current research into quantum technologies is going to revolutionise our world in unimaginable ways.

In the final chapter, I explore the notion of scientific truth, particularly in a 'post-truth' society in which many people remain suspicious of science. How does the process of science differ from other human activities? Is there such a thing as absolute scientific truth? And if the job of science is to seek out deep truths about nature, how should scientists convince wider society of the value of the scientific enterprise: the forming and testing of hypotheses, and rejecting them if they do not fit the data? Will science ever come to an end one day when we know all there is to know? Or will the search for answers continue to lead us deeper down an ever-expanding abyss?

I promised you in the preface that I would try not to get too tangled up in philosophical musings, and yet here I am doing just that, and this is still only the Introduction. So, I will take a deep breath and start us off again, gently, with a sense of scale.

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