PRAISE FOR THE WORLD ACCORDING TO PHYSICS

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THE WORLD ACCORDING TO PHYSICS

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PREFACE

This book is an ode to physics.

I first fell in love with physics when I was a teenager. Admittedly, this was partly because I realised I was good at it. The subject seemed to be a fun mix of puzzle-solving and common sense, and I enjoyed playing with the equations, manipulating the algebraic symbols, and plugging in numbers so that they revealed the secrets of nature. But I also realised that if I wanted satisfying answers to the many deep questions about the nature of the universe and the meaning of existence bubbling up in my teenage mind, then physics was the subject I had to study. I wanted to know: What are we made of? Where do we come from? Does the universe have a beginning, or an end? Is it finite in extent, or does it stretch out to infinity? What was this thing called quantum mechanics that my father had mentioned to me? What is the nature of time? My quest to find answers to these questions has led to a life spent studying physics. I have some answers to my questions now; others I am still searching for.

Some people turn to religion or some other ideology or belief system to find answers to life's mysteries. But for me, there is no substitute for the careful hypothesising, testing, and deducing of facts about the world that are the hallmark of the scientific method. The understanding we have gained through science—and physics in particular—of how the world is made up and how it works is, in my view, not just one of many equally valid ways of reaching the 'truth' about reality. It is the *only* reliable way we have.

No doubt many people never fell in love with physics, as I did. Perhaps they were turned off from studying science because they decided, or perhaps were told by others, that it is a hard—or a geeky—subject. And to be sure, getting to grips with the subtleties of quantum mechanics can bring on a headache. But the wonders of our universe can and should be appreciated by everyone, and gaining a basic understanding doesn't take a lifetime of study. In this book, I want to describe why physics is so wonderful, why it is such a fundamental science, and why it is so crucial to our understanding of the world. The grand scope and sweep of physics today are breathtaking. That we now know what (almost) everything we see in the world is made of and how it holds together; that we can trace back the evolution of the entire universe to fractions of a second after the birth of space and time themselves; that through our knowledge of the physical laws of nature we have developed, and continue to develop, technologies that have transformed our lives—this is all pretty staggering. I still find myself thinking, as I write this: How can anyone *not* love physics?

This book is intended to serve as an introduction to some of the most profound and fundamental ideas in physics. But the topics I cover are not ones you will likely have encountered at school. For some readers, the book may be a first invitation into physics—one that will entice you to learn more about it, maybe even pursue it as a lifelong journey of study and discovery, as I have. To others, who may have gotten off on the wrong foot with physics early on, it may serve as a gentle reintroduction. For many, it may provoke wonder at just how far humanity has come in its quest to understand.

To convey a working knowledge of what physics tells us about the nature of our world, I have selected an array of the most important concepts in modern physics and attempted to show how they link together. We'll survey the vast range of this conceptual landscape, from the physics of the largest cosmic scales to that of the smallest quantum level; from physicists' quest to unify the laws of nature to their search for the simplest possible physical principles governing life; from the speculative frontiers of theoretical research to the physics that underpins our everyday experiences and technologies. I will also offer readers some new perspectives: ideas that we physicists have learnt to accept, but which we haven't done a very good job of conveying to those outside our innermost circles of experts. For example, down at the subatomic scale, separated particles communicate with each other instantaneously despite being far apart, in a way that violates common don't know, and also because I suspect it is still a long way), although I will focus in chapter 8 on what we *know* we don't know.

I have no particular theory to plug, either. For example, when it comes to reconciling quantum mechanics with general relativity (the holy grail of modern theoretical physics), I do not subscribe to either of the two main camps working towards this goal: I am neither a string theory advocate nor a loop quantum gravity fan,[1] since neither theory falls within my particular specialism; and when it comes to interpreting the meaning of quantum mechanics, I am neither a 'Copenhagenist' nor a 'many worlds' enthusiast.[2] But, this won't stop me from being somewhat polemical about these issues now and then.

I will also try not to become too embroiled in philosophical or metaphysical musings, even though there is a temptation to do so when one is discussing some of the more profound ideas at the forefront of physics, whether on the nature

1 I will of course explain what these ideas involve later.

2 Again, I will explain later.

of space and time, the various interpretations of quantum mechanics, or even the meaning of reality itself. I do not mean by this that physics does not need philosophy. To give you an idea of how philosophy feeds into my subject at the most fundamental level, you may be surprised to know that physicists cannot yet even agree on whether the job of physics is to figure out how the world *really* is, as Einstein believed—to reach some ultimate truth that is waiting out there to be discovered—or whether it is to build models of the world and to come up with our best current stab at *what we can say* about reality, a reality that we may never truly know. On this matter, I am on the side of Einstein.

To put it simply, I would argue that physics gives us the tools to understand the entire universe. The study of physics is a search for explanations, but to embark on that search we must first ask the right questions, something philosophers are very good at.

And so, we will begin our journey in a suitably humble frame of mind, one that, if we're honest, we all share—as children, as adults, and with generations past and future: one of not knowing. By thinking about what we don't yet know, we can think about how we can best find out. It is the many questions we have asked over the course of our human history that have given us an ever-more-accurate picture of the world we know and love.

So, here is the world according to physics.

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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

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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.

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 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 governof 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.

CHAPTER 2

SCALE

Unlike philosophy, logic, or pure mathematics, physics is both an empirical and a quantitative science.[1] It relies on the testing and verification of ideas through reproducible observation, measurement, and experimentation. While physicists can sometimes propose exotic or outlandish mathematical theories, the only true measure of their efficacy and power is whether they describe phenomena in the real world against which we can test them. This is why Stephen Hawking never won a Nobel Prize for his work in the mid-1970s on the way black holes radiate energy, a phenomenon known as Hawking radiation: the Nobel is only awarded to theories or discover-

1 Just for completeness, I should add that during the past couple of decades a new discipline called experimental philosophy has emerged.

ies that have been confirmed experimentally. Likewise, Peter Higgs and others who made a similar prediction had to wait half a century for the existence of the Higgs boson to be confirmed at the Large Hadron Collider.

It is also the reason why physics as a scientific discipline only began to make truly impressive advances once the tools and instruments necessary to test theories—through observation, experimentation, and quantitative measurement—had been invented. The ancient Greeks may have been brilliant at abstract thinking, developing subjects such as philosophy and geometry to a level of sophistication that is still valid today, but—Archimedes aside—they were not particularly famous for their experimental prowess. The world of physics only really came of age in the seventeenth century, thanks to a large extent to the invention of the two most important instruments in all of science: the telescope and the microscope.

If we were only able to understand the world we can see with our naked eyes, then physics would not have got very far. The range of wavelengths that can be 'seen' by the human eye is just a sliver of the full electromagnetic spectrum, and our eyes are constrained to discerning only those objects that are not too small and not too far away. While we can, in principle, see out to infinity, provided a sufficient number of photons make it to our eyes (and given an infinite amount of time for them to reach us!), this would not likely provide us with much useful detail. But, once the microscope and the telescope were invented, they opened up windows on the world that dramatically increased our understanding, magnifying the very small and bringing closer the very far away. At last, we could make observations, and detailed measurements, to test and refine our ideas.

On the 7th of January 1610, Galileo pointed his modified and improved spyglass up towards the heavens and banished forever the notion that we were at the centre of the cosmos.[2] He observed

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2 No doubt historians of science will dispute this simplistic claim. Galileo did not suddenly establish heliocentrism with his observations and really only offered suggestive facts (like Jupiter's moons).

four of the moons of Jupiter and correctly inferred that Copernicus's heliocentric model was correct—that the Earth goes around the Sun and not vice versa. By observing bodies in orbit around Jupiter, he showed that not all celestial bodies revolve around us. The Earth isn't at the centre of the cosmos, but is just another planet, like Jupiter, Venus, and Mars, orbiting the Sun. With that discovery, Galileo ushered in modern astronomy.

But it wasn't just a revolution in astronomy that Galileo would bring about. He also helped put the scientific method itself on a firmer foundation. Building on the work of the medieval Arab physicist Ibn al-Haytham, Galileo 'mathematised' physics itself. In developing mathematical relationships that describe, and indeed predict, the motions of bodies, he showed beyond doubt that, as he put it, the book of nature 'is written in mathematical language.'[3]

3 A quote from Galileo's famous book, *The Assayer* (Italian: *Il Saggiatore*), published in Rome in 1623.

in 1905 in a famous paper for which he won the Nobel Prize many years later (and not for his work on the theories of relativity, as you may have thought). Today, this process of knocking electrons out of materials is called photoemission and is the way we turn sunlight into electricity in solar cells.

In the 2016 experiment, two special lasers were used. The first fired an almost unimaginably short pulse of ultraviolet laser light at a jet of helium gas. The duration of this pulse was a mere ten thousandth of a trillionth of a second, or 100 attoseconds (10^{-18} seconds).[5] The second laser was lower in energy (its frequency being in the infrared range) and its pulse duration was a little longer than the first. Its job was to capture the escaping electrons, allowing the researchers to calculate how long it had taken them to be knocked out. The researchers found that this was even quicker: a mere tenth of the duration of the first laser pulse. What is inter-

5 There are more attoseconds in a single second than there have been seconds since the Big Bang.

esting about this result is that the knocked-out electrons actually drag their heels a little. You see, helium atoms each contain two electrons, and the ones that are knocked out feel the influence of the partner they leave behind, which, ever so slightly, delays the ejection process. It is staggering to think that a physical process taking just a few attoseconds can actually be measured like this in the lab.

In my own field of nuclear physics, there are processes that are even faster than this, although these cannot be measured directly in the lab. Instead, we develop computer models to explain the different structures of atomic nuclei and the processes that take place when two nuclei collide and react. For example, the first step in nuclear fusion—when two heavy nuclei come together like coalescing drops of water to make an even heavier nucleus—involves the very rapid reorganization of all the protons and neutrons from both nuclei into the new combined nucleus. This quantum process takes less than a zeptosecond (10^{-21} seconds).

At the other extreme of the time scale, cosmologists and astronomers have been able to work out the age of (our part of) the universe so precisely that we are now confident that the Big Bang took place 13.8242 billion years ago (give or take a few million years). Our confidence in the accuracy of this value may sound arrogant to some—and even unbelievable to those who still cling to the medieval idea that the universe is only six thousand years old—so let me explain how we come to this figure.

Let me first make two important assumptions, which I will discuss in more detail later on, but will now just say that they are both supported strongly by observational evidence: (1) that the laws of physics are the same everywhere in our universe, and (2) that space looks the same in all directions (the same density and distribution of galaxies). This gives us confidence that we can use the observations we make from Earth, or via satellite observatories in orbit around the Earth, to learn about the entire cosmos. Doing this has allowed us to work out the age of the universe in several different ways.

For example, we can learn a lot by studying the stars in our galaxy. We know how long stars can live, depending on their size and brightness, which determines how fast they burn via thermonuclear fusion. This means we can work out the age of the oldest stars, which sets a lower limit on how old our galaxy is, which in turn gives us a lower limit on the age of the universe. Since the oldest stars are about 12 billion years, the universe cannot be younger than that.

Then, by measuring the brightness and colour of the light entering our telescopes from distant galaxies, we can work out how fast the universe is expanding, both now and in the past. The further out we look, the further back in time we are probing, since the light we see will have taken billions of years to reach us and is thus bringing us information about the distant past. And if we know how fast the universe has been expanding, we can wind back the clock to a time when everything was squeezed together in the same place: the moment of the universe's birth.