"Jim Al-Khalili has distilled the very essence of science. This book is packed full of joy, inspiration, and real wisdom."

Alice Roberts, Professor of Public Engagement in Science, University of Birmingham

"Jim Al-Khalili eloquently reminds us of all the reasons to celebrate science. A lovely little book that will serve you well as a trusted guide in this troubled post-truth era."

Sabine Hossenfelder, physicist and author of *Lost in Math*

"*The Joy of Science* pulls back the curtain on the essential nature of science and tackles the confusions the public confronts in understanding how it's done. I highly recommend Al-Khalili's book to anyone, scientist or not, interested in thinking more scientifically."

S. James Gates Jr., coauthor of *Proving Einstein Right*

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PREFACE

As a young student in the mid-1980s, I read a book called *To Acknowledge the Wonder* by the English physicist Euan Squires. It was about the latest ideas in fundamental physics (at the time), and I still have it somewhere on my shelf nearly four decades later. While some of the material in that book is now outdated, I have always liked its title. At a time when I was contemplating a career in physics, the chance to 'acknowledge the wonders' of the physical world was what really inspired me to devote my life to science.

There are many reasons why people pursue their interests in one subject or another. In science, some enjoy the thrill of climbing into the crater of a volcano or crouching on a cliff's edge to observe birds nesting—or looking through telescopes or microscopes to see worlds beyond our senses. Some design ingenious experiments on their laboratory workbenches to reveal the secrets inside stars, or build giant underground particle accelerators to probe the building blocks

of matter. Some study the genetics of microbes so they can develop drugs and vaccines to protect us against them. Others become fluent in mathematics and scrawl pages upon pages of abstract but beautiful algebraic equations, or write thousands of lines of code that instruct their supercomputers to simulate Earth's weather or the evolution of galaxies, or even model the biological processes inside our bodies. Science is a vast enterprise, and there is inspiration, passion, and wonder everywhere you look.

But the old adage that beauty is in the eye of the beholder applies to science as well as more generally in our lives. What we regard as fascinating or beautiful is highly subjective. Scientists know as well as anyone that new subjects and new ways of thinking can be daunting. When you haven't been properly introduced to a subject, it can seem downright forbidding. However, my response would be that, if we try, we can almost always gain a better understanding of an idea or concept that might once have seemed unfathomable to us. We just have to keep our eyes and minds open and take the time we need to think

things through and absorb the information—not necessarily to the level of experts, but just enough to comprehend what we need.

Let's take as an example a simple and common phenomenon in the natural world: the rainbow.[1] We can all agree that there is something enchanting about rainbows. Is their magic diminished if I explain to you the science of how they form? The poet Keats claimed that Newton had "destroyed all the poetry of the rainbow, by reducing it to the prismatic colours." In my view, far from 'destroying its poetry,' science only enhances our appreciation of nature's beauty. See what you think.

Rainbows combine two ingredients: sunshine and rain. But the science behind the way in which they combine to create the arc of colour

1 In beginning this book by invoking the iconic rainbow, I am traveling a path well-worn by other science writers; for example, Carl Sagan (*The Demon-Haunted World: Science as a Candle in the Dark*) and Richard Dawkins (*Unweaving the Rainbow: Science, Delusion and the Appetite for Wonder*). I hope readers already familiar with these books will make allowances for my having followed in this tradition for the benefit of new readers who may be coming afresh to the example.

we see in the misty sky is as beautiful as the sight itself. Rainbows are made of broken sunlight that reaches our eyes after the Sun's rays strike a billion raindrops. As the Sun's rays enter each water droplet, all the different colours of light that make up sunlight slow down slightly to travel at different speeds, bending and separating out from each other in a process called refraction.[2] They then bounce off the backs of the droplets, returning to pass through their fronts at different points, refracting a second time as they do so and fanning out into the colours of the rainbow. If we measure the angles between the sunbeam and the different-coloured rays that emerge from the veil of raindrops in front of us—we find that they range from 40 degrees for violet light, which undergoes the most refraction and so forms the innermost colour of the rainbow, to 42 degrees for

2 Sunlight, or white light, is made of different colours, each of which has a different wavelength. When it encounters a medium, like air or water, it slows down; but each of its constituent colours slows down by a different amount, depending on its wavelength, which causes each colour to have a different angle of refraction.

red light, which undergoes the least and forms the outer rim of the rainbow (see the diagram).[3]

Even more wondrously, this arc of splintered sunlight is really just the top part of a circle—the curved surface of an imaginary cone lying on its side, whose tip is located in our eyes. And because we are standing on the ground, we only see the top half of the cone. But, if we were able to float up into the sky, we would see the entire rainbow as a complete circle.

You cannot touch a rainbow. It has no substance; it does not exist in any particular part of the sky. A rainbow is an intangible interaction between the natural world and our eyes and brains. In fact, no two people see the same rainbow. The one we see is made from those rays of light that have entered our eyes alone.

3 The type of rainbow I have described is called a primary rainbow. We can sometimes also observe outer, fainter secondary rainbows, which are produced when the Sun's rays undergo two, rather than one, internal reflections within each raindrop. In these cases, we see only the rays of colour that emerge at angles of between 50 and 53 degrees. But in secondary rainbows, due to this double reflection, the colours are reversed, with red on the inside and violet on the outside.

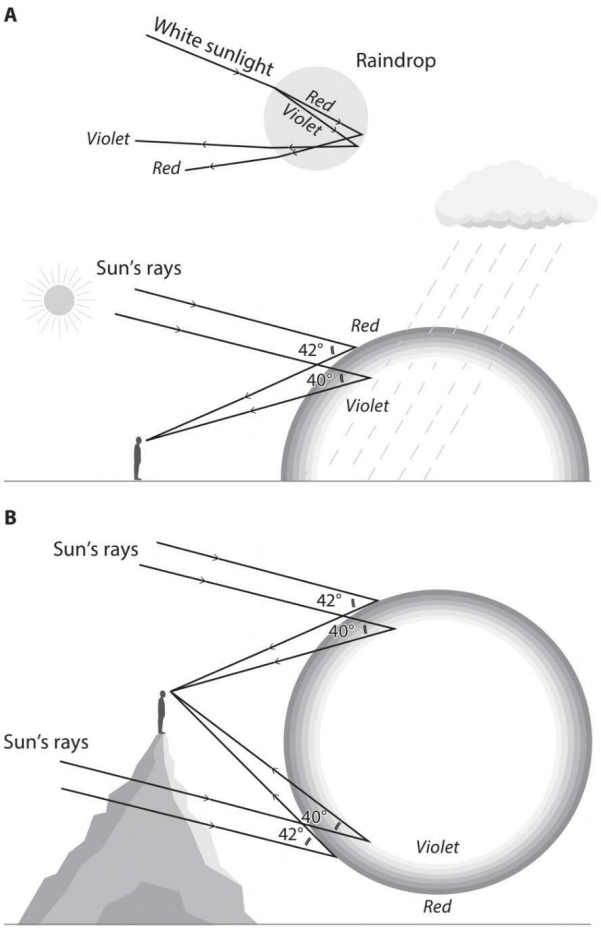

DIAGRAM OF A RAINBOW

So, each of us experiences his or her own unique rainbow, created by nature for us and us alone. This, for me, is what a scientific understanding can give us: a richer, more profound—and more personal—appreciation of the world; one we would never had had without science.

Rainbows are so much more than just a pretty arc of colour, just as science is so much more than hard facts and lessons in critical thinking. Science helps us see the world more deeply, enriches us, enlightens us. My hope is that this book will welcome you to a world of light and colour, truth and profound beauty—a world that will never fade as long as we all keep our eyes and minds open and share what we know with each other. The closer we look, the more we can see and the more we can wonder. I hope you will join me in acknowledging the wonder—the joy of science.

INTRODUCTION

As I write these words in the spring of 2021, and while we all continue to reel from the impact of the Covid pandemic, we are witnessing a seismic shift in the way people around the world view science: its role and value to society, how scientific research is carried out and its claims tested, and indeed how scientists conduct themselves and communicate their discoveries and results. In short, and albeit in the most devastating and tragic of circumstances, science and scientists are today under scrutiny like never before. Certainly, the race to understand the SARS-CoV-2 virus and to find ways of defeating it have highlighted the fact that humanity cannot survive without science.

Though there will always be those who fear science and treat it with suspicion, I see among the vast majority of the world's population a new appreciation for and trust in the scientific method, as ever more people realize that the fate of humanity rests not so much in the hands of

politicians, economists or religious leaders, but in the knowledge that we gain about the world through science. Equally, scientists are coming to appreciate that it is not enough to keep the findings of our research to ourselves. We must also put in the effort to explain, as honestly and transparently as possible, how we work, what questions we ask and what we have learned, and to show the world how our newly discovered knowledge can best be put to good use. Today, in a very real sense, all our lives depend on the thousands of virologists, geneticists, immunologists, epidemiologists, mathematical modellers, behavioural psychologists and public health scientists around the world working together to defeat a deadly microscopic organism. But the success of the scientific enterprise also depends on the public's willingness, both collectively and as individuals, to make informed decisions for ourselves, as well as for our loved ones and the broader societies we live in, that make good use of that knowledge gained by scientists.

The continuing success of science—be it in tackling the biggest challenges facing humanity

in the twenty-first century, such as pandemics, climate change, eradicating disease and poverty, or in creating wondrous technologies, sending missions to Mars and developing artificial intelligence, or simply learning more about ourselves and our place in the universe—all depends on a relationship of openness and collaboration between scientists and non-scientists. This can only happen if politicians pull back from the all-too-prevalent current attitudes of isolationism and nationalism. Covid-19 is no respecter of national borders, cultures, race or religion. None of the biggest problems facing us as a species is. Therefore, just like scientific research itself, tackling such problems must also be a collective, collaborative enterprise.

Meanwhile, nearly eight billion human inhabitants on the planet still have to navigate through their daily lives, make decisions and act on them, often while stumbling through a dense fog of confusing information . . . and misinformation. How then can we take a step back and see the world, and ourselves, more objectively? How can we sort through all the complexity and do better for ourselves and for each other?

The truth is that complexity isn't new. Misinformation and confusion aren't new. Huge gaps in our knowledge aren't new. The world we face is daunting, confusing, even overwhelming at times. None of this should be news to us, of course. In fact, science is built on this very premise; humans came up with the scientific method precisely to deal the difficulties of making sense of a confusing and complex cosmos. In our daily lives, every one of us—scientists and non-scientists alike—encounters a world bursting with information, which is constantly reminding us of our own ignorance. What can we do about it? Indeed, *why* should we do something about it?

In this book, I have put together a short, all-purpose guide to thinking and living a little more scientifically. Before reading on, you might take a moment to ask yourself this: Do I want to find out about the world as it really is? Do I want to make decisions based on that knowledge? Do I want to mitigate a fear of the unknown with a sense of promise, potential, and even excitement? If you are tempted to say "yes" to any of

the above questions, and even if (or dare I say, especially if) you don't yet know how you feel about them, then maybe this book can help.

As a practicing scientist I do not profess to impart any profound wisdom, and I certainly hope there is no hint of superiority or condescension in the tone of this book. My aim is simply to explain how thinking scientifically can offer you some control over the complex and conflicting information that the world throws at you. This book does not contain lessons in moral philosophy, nor a list of life skills or therapeutic techniques to help you feel happier or more in control of your life. What I have to say comes from the core of what science is and the ways in which it is practiced: an approach that is tried and tested and that has served humankind well over our centuries-long quest to understand the world. Yet, at a deeper level, the reason it has served us so well is that it was built to help people like you and me make sense of complexity or gaps in our knowledge, and generally to arm us with a confidence and a better sense of perspective when we encounter the unknown.

running through it. One could say that all of the above activities involve a curiosity about some aspect of the world—the nature of space and time, the properties of matter, the workings of the human body—and a desire to learn more, to reach a deeper understanding.

But isn't this too general? Surely, historians are curious too. They too look for evidence in order to test a hypothesis or uncover some previously unknown fact about the past. Should we then regard history as a branch of science? And what about the conspiracy theorist who claims that the Earth is flat? Is he or she not just as curious as a scientist, just as keen to find rational evidence that supports a claim? Why then would we say that they are not being 'scientific'? The answer is that, unlike scientists, or indeed historians, flat-Earth conspiracy theorists would not be prepared to reject their theory when presented with irrefutable evidence to the contrary, such as NASA images from space showing our planet's curvature. Clearly, just being curious about the world does not mean someone is thinking scientifically.