CONTENTS

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.

Because the way we do science has served humankind so well, for so long and so successfully, I think it is worth sharing with you this way of thinking.

Before I present my case for why we should all be thinking more scientifically, I need to say something about how scientists themselves think. Scientists are as embedded in the real world as everyone else, and there are ways of thinking shared by all scientists that everyone can follow when encountering the unknown and making decisions in daily life. This book is about sharing these ways of thinking with everyone. They have always been for everyone, but somewhere along the line, that fact seems to have been lost.

Firstly, contrary to what many people think, science is *not* a collection of facts about the world. That is called 'knowledge'. Rather, science is a way of thinking and making sense of the world, which can *then* lead to new knowledge. There are, of course, many routes to gaining knowledge and insight, whether through art, poetry and literature, religious texts, philosophical debate, or through contemplation and reflection. That said, however, if you want to know about how the world really is—what physicists like me sometimes refer to as the 'true nature of reality'—then science has a big advantage, for it relies on the 'scientific method'.

THE SCIENTIFIC METHOD

When we talk about the scientific 'method', it implies there is just one way of 'doing' science. This is wrong. Cosmologists develop exotic theories that explain astronomical observations; medics carry out randomised control trials to test the efficacy of a new drug or vaccine; chemists mix compounds together in test tubes to see how they react; climatologists create sophisticated computer models that mimic the interactions and behaviour of the atmosphere, oceans, land, biosphere, and Sun; while Einstein figured out that time and space can bend in a gravitational field by solving algebraic equations and doing a lot of deep thinking. While this list hardly scratches the surface, there is a common theme 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.

There are a number of features that distinguish the scientific method from other ideologies, such as falsifiability, repeatability, the importance of uncertainty and the value of admitting mistakes, and we will be considering each of these throughout this book. But, for now, let us look briefly at a few features that the scientific method shares with other ways of thinking—ways that we would not necessarily regard as proper science—in order to show that no single one of these features *alone* is sufficient to meet the rigorous requirements of the scientific method.

In science, one should continue to test and question a claim or hypothesis even when there exists overwhelming evidence supporting it. This is because scientific theories need to be *falsifiable*—that is, a scientific theory must be capable of being proved false.[4] To offer a classic

4 In the philosophy of science, a theory is falsifiable (or refutable) if it can be contradicted or disproved by evidence, whether that be in the form of observations, laboratory measurements or mathematics and logical reasoning. The idea was introduced by the philosopher Karl Popper in the 1930s.

example, I could put forward a scientific theory that all swans are white. This theory is falsifiable, since you could prove its falsehood by observing just one swan of a different colour. If evidence is found to contradict my theory, then the theory must be either modified or discarded. The reason conspiracy theories are not proper science is because no amount of contrary evidence would dissuade their advocates. In fact, a true conspiracy theorist sees any evidence as bolstering his or her preexisting views. In contrast, a scientist takes the opposite approach. We change our minds in the light of new data, because we are trained to shun the absolute certainty of the zealot who insists that only white swans exist.

A scientific theory also needs to be testable and held up to the light of empirical evidence and data. That is, we should be able to use a scientific theory to make predictions, and then see if those predictions are borne out in experiments or observations. But again, this is not enough on its own. After all, an astrological chart also makes predictions. Does that make astrology a real science? And what if the prediction made by the astrological forecast comes true? Does that give it the seal of approval?

Let me tell you the story of the faster-than-light neutrinos. Einstein's special theory of relativity, which he published in 1905, predicts that nothing in the universe can travel faster than light. Physicists are now so confident this is true that they generally insist there must be a mistake if a measurement shows that something *is* moving faster than light. But this is exactly what was reported in 2011 in a now-famous experiment involving a beam of subatomic particles called neutrinos. Most physicists did not believe the results. Was this because they were being dogmatic and closed-minded? A layperson may well think so. Contrast this with the astrologer who claims that your stars will be aligned on Tuesday and you will receive good news, which sure enough comes true when your boss offers you a promotion. In one case, you have a theory conflicting with experimental data, and in the other, you have a theory whose prediction is borne out by events. How then can we say that relativity is a valid scientific theory and yet astrology is not?

As it turned out, physicists were right not to give up so easily on relativity theory, because the team that had carried out the neutrino experiment soon discovered that a fibre optic cable had been attached improperly to their timing device, and fixing it eliminated the faster-than-light results. The fact is that if this experiment *had* been correct and neutrinos do indeed travel faster than light, then thousands of other experiments that proved the contrary would have had to be wrong. But there was a rational explanation for the surprising experimental results, and the theory of relativity held firm. Yet we trust it not because it survived refutation by an (ultimately wrong) experimental result, but because so many other experimental results have confirmed the correctness of the theory. In other words, the theory is falsifiable, and it is testable, and yet it continues to stand strong, fitting in with so much of what we know to be true about the universe.

In contrast, a correct astrological prediction is sheer luck, since no physical mechanism could possibly explain it. For instance, since the astrological signs were invented, the view of the sky has changed due to a shift in Earth's axis; so, you were not born under the sign you likely thought you were anyway. More importantly, our modern astronomical understanding of the true nature of stars and planets has rendered any theoretical basis for assigning meaning to astrological signs useless. In any case, if astrology *were* true, and distant stars, whose light takes many years to reach us and whose gravitational effects are far too weak to be felt on Earth, could influence future events within the mind-bogglingly complex affairs of humankind, then this would mean that all of physics and astronomy would have to be discarded, and we would need a new, irrational and supernatural explanation for all the phenomena that science currently explains so well and on which the modern world, including all of its technology, is built.

Another feature of the scientific method that one often hears is that science is *self-correcting*. But since science is just a process—a way of approaching and seeing the world—it is wrong to think that this implies science itself has some kind of agency. What the statement really means is that *scientists correct each other*. Science is carried out by people. And we all know that people are fallible, especially since, as we've discussed, the world is a complex and confusing place. So, we test each other's ideas and theories, we argue and we discuss, we interpret each other's data, we listen, we modify, we extend—sometimes we give up entirely on an idea or experimental result if other scientists, or even we ourselves, show it to be flawed. Crucially, we see this as a strength, not a weakness, for we don't mind being proven wrong. Naturally, we want our own theories or interpretations of the data to be correct, but we don't cling to them when there is strong evidence to the contrary. If we're wrong, we're wrong, and we cannot hide from that—and it would be embarrassing to even try. That's why we do our best to subject our own ideas to the toughest criticism and tests we can think of before we announce them, and even then, we 'show all our workings' and we quantify our uncertainty. After all, even if we've looked everywhere for a black swan and haven't seen one, that does not mean there isn't one out there somewhere that we simply have not found yet.

When it comes to deciding whether or not something is 'proper' science, I am not claiming that there is a list of criteria against which to judge it—boxes to tick off in order to differentiate between science and non-science—for there are plenty of examples scattered throughout science that do not adhere to one or more of the criteria of the scientific method. I can immediately think of several examples in my own field of physics. Is superstring theory—the mathematical idea that all matter is composed of tiny strings vibrating in higher dimensions—not proper science because we don't (yet) know how to test it and therefore cannot claim it to be falsifiable? Is the Big Bang theory and the expansion of the universe not proper science because it is not repeatable? The enterprise of science and how we do it is far too broad to be neatly packaged, and it should not be considered as something hermetically sealed away, separated from other pursuits, such as history, art, politics or religion. This book is not about articulating separations or detailing distinctions, nor is it about uncovering the faults and shortcomings of the scientific method. Rather I aim to distil what is best about science and its method, and how it can be used as a power for good if applied to other walks of life.

There are, of course, many ways in which scientific research carried out in the real world can be improved. For example, if mainstream science is predominantly carried out, and its validity is decided upon, by white men in the Western world, doesn't this mean it is tainted, even shaped by certain prejudices, whether intentionally or unintentionally? Surely, if there is little or no diversity of views, and all scientists see, think, and question the world in a similar way, then they will not, as a community, be as objective as they maintain they are, or at least aspire to be. The solution is that there should be far greater diversity in the practice of science: in gender, ethnicity and social and cultural backgrounds. Science works because it is carried out by people who pursue their curiosity about the natural world and test their and each other's ideas from as many varied perspectives and angles as possible. When science is done by a diverse group of people, and if consensus builds up about a particular area of scientific knowledge, then we can have more confidence in its objectivity and truth. A democratized science can help to protect against the emergence of dogma, whereby an entire community of scientists in a particular field accepts a set of assumptions or ideas as being absolute without ever questioning them further, to the extent that dissenting voices are suppressed or dismissed. However, there is an important distinction to be made between dogma and consensus, for sometimes the two can be confused. Established scientific ideas have earned the right to be widely accepted and trusted, even though they could one day be improved upon or replaced, because they have so far survived the myriad and diverse questions and tests to which they've been subjected.

'FOLLOWING THE SCIENCE'

Sociologists will argue that to truly understand how science works we need to embed it in the broader contexts of human activities, whether they be cultural, historical, economic or political.

To simply talk about 'how we do science' from the perspective of a practitioner like me is, they would say, too naïve, for science is more complicated than that. They will also insist that science is not a value-neutral activity since all scientists have motives, biases, ideological stances and vested interests, just like everyone else, whether it is to secure a promotion, enhance a reputation or establish a theory they have spent years developing. And even if the researchers themselves don't have biases or motives, then their paymasters and funders will. Needless to say, I find such an appraisal overly cynical. While those who carry out the science, or indeed those who pay their salaries, will almost inevitably *not* be value-free, the scientific knowledge that they gain *should be*. And this is because of the way the scientific method works: self-correcting, building on firm foundations of what has already been established as factually correct, being subject to scrutiny and falsification, reliant on reproducibility, and so on.

But then I would say that, wouldn't I? After all, I want to persuade you of my own objectivity and neutrality. And yet I too cannot be entirely objective, nor value-free, however much I may think I am or try to be. But the subjects I study—the theory of relativity, quantum mechanics or the nuclear reactions taking place inside stars—are all value-neutral descriptions of the external world, as are genetics, astronomy, immunology and plate tectonics. The scientific knowledge we have gained about the natural world—the description of nature itself—would be no different if those who had discovered it spoke different languages, or had different politics, religions or cultures—provided, of course, that they are honest and truthful and carry out their science well and with integrity. Of course, our research priorities—the questions we might ask—depend on what is considered important at that time in history or in that part of the world, or on whoever has the power to decide what is important and what (and whose) research to fund; these decisions can be culturally, politically, philosophically, or economically driven. For example, physics departments in poorer countries are more likely to fund research in theoretical physics than experimental physics since laptops and whiteboards are cheaper than lasers and particle accelerators. These decisions about what questions to pursue and what research to fund can also be subject to bias; and so the more diversity we can foster among those in positions of leadership and power the more the scientific enterprise can protect itself against bias when determining which veins of research are more or less promising or potentially impactful. All this said, what is ultimately learned about the world—the knowledge itself, achieved by doing good science—should not depend on who has carried out that science. A scientist located at an elite institution may reach a different result from a scientist located at another institution that is not regarded as elite; but one has no inherent claim on a more accurate result than the other. By the nature of science and the accumulation of evidence, the truth will out.

Many who are suspicious of the motives of scientists argue that science, as a process, can never be 'value-free'. To some extent, as we've discussed, they are correct. However much we scientists might think that our pursuit of knowledge and truth is objective and pure, we must acknowledge that the ideal of *all* science being value-free is a myth. Firstly, there are values *external* to science, such as ethical and moral principles about what we should or should not be studying, and social values, such as public interest concerns. Such external values must play a role in the decisions about what science should be funded and conducted—and, of course, those decisions can be subject to bias, which we must be mindful of and work against. Secondly, there are values *internal* to science, such as honesty, integrity and objectivity, which are the responsibility of the scientists carrying out the research. This is not to say that scientists should not also have a say in shaping or debating those external values, for they have a responsibility to consider the consequences of their research, both in terms of how it may be applied and in terms of the policies it might shape and the public's reaction to it. Sadly, all too often scientists will argue among themselves as to whether science can in principle be value-free, confusing the value-free pursuit of pure knowledge about the world—in astrophysics, for example—with the inevitably value-laden research in fields such as environmental science or public health policy.[5]

But assuming that we can agree that science in the real world is not entirely value-free, and that the knowledge gained through the process of good science is, let us go on to explore a few of the challenges that the public sometimes has with the perception of science, both justified and unjustified.

Scientific progress has undoubtedly made our lives immeasurably easier and more comfortable. With the knowledge that has been revealed through science, we have been able to cure diseases, create smartphones and send space missions to the outer Solar System. But this success can sometimes have the adverse effect of giving people false hope and unrealistic expectations. Many can be so blinded by the success of science

5 For an excellent account of this issue, see the book by Heather Douglas, *Science, Policy, and the Value-Free Ideal* (Pittsburgh: University of Pittsburgh Press, 2009).

that they will believe any report or marketing trick that sounds remotely 'scientific', whatever the source and however bogus the product may be. This is not their fault, for it is not always straightforward to tell the difference between real scientific evidence and misleading marketing based on unscientific notions.

Understandably, most people tend not to worry too much about the scientific process itself, only about what science can achieve. For example, when scientists claim to have discovered a new vaccine, the public wants to know if it is safe and it works, and they will either trust that the scientists involved know what they are doing, or they will be suspicious (of the scientists' or their paymasters' motives). Chances are, it will only be other scientists in the field who will delve into whether the research was carried out at a reputable lab, whether the vaccine has been through rigorous randomised clinical control trials, and whether the research is published in a reputable journal and has been through the proper peer review process. They will also want to know if the results claimed are repeatable.

It also doesn't help the public to make up their minds about what or whom to trust when scientists disagree, or when they express uncertainty about their results. While this is perfectly normal in science, many people nevertheless wonder how they can believe anything scientists say if the scientists themselves are never quite sure. Not properly communicating the importance of uncertainty and debate in science is one of the main problems we face today when explaining how we develop our scientific understanding of the world.

It can become even more confusing for the public when the advice—particularly on issues relating to public health—is not only conflicting, but reaching them from sources outside the scientific community, such as the media, politicians, online posts, or after having been spread over social media. In reality, even genuine scientific discoveries reach the public after having been through a number of filters, whether the lab or university press officer who has had to distil a simplified message from a complex scientific paper, the journalist looking for a headline, or the amateur science enthusiast who posts information online. This might range from what precautions to take during a pandemic, to the risks of vaping or the benefits of flossing. And as the story develops and spreads, so too will opinions about it—both informed and uninformed—so that we end up mostly believing what we want to believe anyway. Instead of making careful, evidence-based rational judgements, many people will accept something as true if it fits in with their preconceived prejudices and ignore what they don't want to hear.

Before I move on, I should also say a few words about the advice scientists give to governments, the purpose of which is to inform policy decisions. While scientists can provide all the evidence they have, from the results of laboratory experiments or computer simulations, clinical trial data, graphs and tables, to the conclusions they are able to draw from their results, in the end what is done with this scientific advice is down to the politicians. I should make clear that scientists should always advise on the basis of their specific area of expertise. Thus, epidemiologists, behavioural scientists and economists may all have views on what is best for the population when fighting Covid, and the politicians must then weigh up costs and benefits of what may sometimes be conflicting advice. An epidemiologist might estimate the number of excess deaths due to Covid associated with delaying going into lockdown by one week, while an economist might calculate that that delay avoids loss to GDP which might lead to an equivalent or greater number of deaths. Both experts will have based their conclusions on model predictions that may well be highly accurate given the data and model parameters used, and yet they predict different conclusions. It is then the role of policymakers and politicians to choose what they regard as the best course of action. The public also has choices to make. The more individuals in a population are given access to those conclusions in a transparent way, and take up the challenge of learning to understand them, the more they will be empowered to make informed choices—in daily life and as part of the democratic process—that will benefit them and their loved ones.

Science, unlike politics, is not an ideology or belief system. It is a process. And we know that politicians base policy decisions on more than just the scientific evidence. So even if the science is clear-cut, when it comes to the complexity of human behaviour, decision-making is never value-free. Nor, I have to admit with some reluctance, should it be.

Politicians, like most people, almost always follow the science that aligns with their preferences and ideologies. They will cherry-pick the conclusions that fit their purposes, often influenced by public opinion, which is in turn shaped by how the facts are presented in the media or official government guidelines or by scientists themselves in the first place. Basically, the relationship between science, society and politics involves complex feedback loops. And lest you think I am being overly critical of politicians, I am the first to acknowledge that scientists are not elected, and it is therefore not our job as scientists to say what policies should be put in place. All we can do is communicate as clearly as possible and provide guidance based on the best scientific evidence available at the time. We may personally feel very strongly about an issue, but that should not colour the advice we give. In a democracy, whether we support a particular government or not, it is the elected politicians in the end who have to make the decisions and be held accountable for those decisions, not the scientists—although there is no doubt that society would benefit immeasurably if we had more scientifically trained politicians, and more scientific literacy generally.

Luckily, this book is not about the complicated relationship between science, politics and public opinion, but about how we can import the best features of the scientific process into our wider decision-making and opinion-forming processes in daily life. The scientific method is a combination of curiosity about the world, a willingness to question, to observe, to experiment and to reason, and of course to modify our views and learn from experience if what we discover does not follow our preconceived thinking.

Here then is a brief guide to how we can all think and behave more rationally. Each chapter is a piece of advice, distilled from some particular aspect of the scientific method. We may find that sharing a more scientific approach to thinking about the world can lead us to a better place.

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INDEX