CHAPTER 1

What is Future-Proof Science?

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1. Science and scepticism

This book is about identifying scientific claims we can be confident will last forever. By 'forever' I mean so long as the human race continues, and assuming the scientific endeavour continues in a serious way, without some sort of apocalypse. For most purposes it is convenient to think ahead just 1000 years. A lot has happened in the development of human thought in the past 1000 years, needless to say. But I want to claim, and I want to argue, that some of our current ideas *will* still be with us in 1000 years, so long as the human race persists and that thing we call 'science' is not abolished by some well-meaning government body. This will strike many readers as hubristic, no doubt. It may well be asked, "Who could dare to claim to know the minds of humankind 1000 years from now?" But a persuasive argument can be made, I believe, that *many* such scientific ideas can be identified, and so I hope to persuade many of those readers with a genuinely open mind, including those who start reading this book with a certain degree of scepticism. I agree that it is surprising – amazing, even – that we can rationally be confident that certain scientific ideas will remain intact 1000 years from now. Or even 5000 years from now. But in fact this is a reasonable thing to believe.

There are (at least) two very different reasons a scientific idea could last forever:

(i) We are stuck in a rut of human thinking out of which we will never escape. Our idea is totally wrong (or mostly wrong) but we are somehow prevented from seeing that, or even if we do see it we are unable to replace it with something better/truer.

(ii) Science has hit upon the truth, and all that remains is for scientists to build upon and develop the correct idea they already have. No feasible scientific developments could bring them to reject the idea.

It is the latter option, (ii), that I mean to refer to with the phrase 'future-proof science'. This isn't to say that (i) is impossible, and we'll take it quite seriously in some later chapters. But what I mainly wish to argue is that some scientific ideas should be called 'facts', and they should be called 'facts' because they are true ideas – the universe really is the way the theory says it is (allowing for small adjustments). Moreover, we have overwhelming evidence for this, to such an extent that no feasible scientific developments could overturn it. For example, it couldn't ever be the case that we have the right idea, and lots of evidence, but somehow (by sheer bad luck perhaps?) we go on to accumulate lots of *contrary* evidence that is sufficient to overturn the correct idea we started with.

In short, this book argues that we have come to know things through science, beyond all reasonable doubt. Certain knowledge claims – the product of scientific labour – are justified, where by 'knowledge claims' I mean assertions of fact without any significant hedging or caveats. I hope even sceptics will grant that this is *possible*. Sometimes we can have knowledge where we didn't have it before. To give an example, we can come to know why the sky does not run out of rain. Further, it can be the case that we don't just have a *theory* about the rain, but that, over time, we have so much evidence for the 'water cycle theory' that it is not unreasonable to say that we are certain, and it is a fact. We stop talking about 'the water cycle theory', and simply talk about 'the water cycle'. If we meet a sceptic, it would not be *unreasonable* (though it may come across as patronising or arrogant) to say, "I'm certain; I know that I'm right about this." Of course, in social interactions it is often much preferred to 'agree to disagree', to respect somebody's opinions and beliefs. It is often much preferred to dial down one's confidence and say something like "I think there's good evidence for this", as opposed to "I know this is true". But what may *seem* like objectionable hubris to your audience can sometimes be fully justified: it may be no exaggeration to say that you are sure (beyond reasonable doubt) that you are correct, and an alternative view is wrong, however uncomfortable it may feel to say this.[1]

I think it's worth expanding on this point about social discomfort a little further. In many cases we face difficult dilemmas vis-à-vis how we express our degree of confidence. For example, suppose you visit a music festival, and you're laid on the grass one evening staring up at the stars with a new friend. You hear them say, "I guess we'll never know what those twinkly dots of light really are". You might feel so awkward about contradicting your new friend, that you actually reply, "Yeah, I guess not", even though (let's assume) you studied astrophysics at university, and feel 100% sure that scientists *do* know what stars are. The problem is, you just can't think of any way to contradict the person without coming across as patronising. It also doesn't really matter if you 'let it go' in this particular context.

In other contexts, this tendency to 'let it go' or 'agree to disagree' absolutely must be resisted. Sometimes it is crucially important to distinguish clearly between items of human knowledge, and issues that are unsettled and open for discussion, without hiding that distinction behind social niceties. If we swap the musical festival example for the Covid-19 pandemic, and we swap the statement for "I

[1] The concept of future-proof science is not inconsistent with 'epistemic humility'; see e.g. Kidd (2020) for a useful entry to the literature on humility and science.

guess we just can't know whether the AstraZeneca vaccine is safe", it becomes far more important to respond honestly instead of simply answering "Yes, you might be right about that", or similar. Indeed, if you know a lot of about vaccine testing, it would be wrong *not* to challenge the statement; you might even end up saving the person's life. And in science generally there are plenty of high-stakes contexts where absolute honesty is paramount, and social niceties must be put to one side. To illustrate: scientists could not 'agree to disagree' with CFC companies in the 1980s on the question whether CFCs were causing ozone depletion. If scientists had agreed with the CFC companies that they couldn't really prove the link between CFCs and ozone, and didn't really know, and there was room for rational doubt, that would have been a death sentence – at the hand of skin cancer – for thousands of individuals who are alive today. A similar story can be told about the HIV-AIDS link (Godfrey-Smith 2021, pp. 311-2), and there were indeed many unnecessary deaths in this case – this isn't all merely hypothetical.

At the same time there is of course a sense in which we are never 100% certain; a certain degree of doubt is always possible. Suppose I strike the keys of the laptop and I say to myself, "Do I really know I am typing right now? Do I really know that I am attempting to write the opening chapter of a book?" It's certainly *possible* that I am wrong. For example (as Descartes famously urged in the 17th century) I could be having the most vivid dream I've ever had. Or perhaps I am not asleep, but my senses – sight, sound, touch – are being manipulated in a way that is totally hidden from me (as in *The Matrix*). Or perhaps (back with Descartes again) even my thoughts are being manipulated, by some 'evil demon' or similar powerful being.

If we accept that these are (remote) possibilities, even for a case as rudimentary as whether I know that I am striking keys on my laptop, then it may be urged that I shouldn't say I am *sure*. I shouldn't say I am *certain*. At least not 100%. And if not for everyday facts such as this, then *definitely* not for scientific ideas – such as the causal link between CFCs and ozone depletion – which are *much* further removed from everyday experience and the testimony of the senses. The problem with taking this line should be obvious however: if it is insisted that we aren't sure about scientific ideas on *these* grounds, then we have to accept that we are never sure about anything. In which case words such as 'fact', 'sure', and 'certain' are never applicable, and might as well be eradicated from the dictionary: "Knowledge is impossible!"

In fact, those who urge scepticism about scientific ideas are usually absolutely clear that they are *not* 'radical' or 'global' sceptics. As Hoefer (2020, p. 24) writes,

> As philosophers of science we are entitled (and, I would say, obliged) to set aside radical skeptical doubts. Or to put it another way: once the scientific realist forces the anti-realist into positing radical skeptical scenarios in order to keep her anti-realist doubts alive, the game is over.

Thus scientific sceptics think it is reasonable to say that we know lots of things, especially everyday things such as that it is raining outside. Of course, we might be mistaken, and the drops on the window have come from the window cleaner. We might even be right, but for the wrong reason: it *is* raining outside, but the drops on the window that we used as evidence for our claim that it is raining outside actually came from the window cleaner – these are the 'Gettier' cases. But it is reasonable to say that we *know* when we have been sufficiently careful with our observations (e.g. we go outside and stand in the rain for five minutes). And this stands, even though it always remains remotely possible that we are asleep or are somehow being manipulated or otherwise deceived. As Van Fraassen (1980, p. 71) notes, "we do in our daily life infer, or at least arrive at, conclusions that go beyond the evidence we have", and he is keen to hold on to such everyday conclusions: "I must at least defend myself against this threatened [global] scepticism" (*ibid*.).

What sceptics wish to deny is that we can have a similar level of confidence in properly *scientific* ideas. Witness, for example, Brad Wray, who (clearly inspired by Van Fraassen) writes in his 2018 book *Resisting Scientific Realism*:

> I will argue that our current best [scientific] theories are quite likely going to be replaced in the future by theories that make significantly different ontological assumptions. (p. 1)
>
> I argue that there is reason to believe that many of our best theories are apt to be rendered obsolete in the future. (p. 2)
>
> We should not get too attached to our theories. (p. 65)
>
> Today's theories are as likely to be replaced in the future as were the successful theories of the past. (p. 65)
>
> [C]ontemporary scientists should expect that their scientific offspring will look back at their theories with the same attitude they have towards the theories of their predecessors. Their offspring [future scientists] will see that many of today's successful theories will have been discarded and replaced by new theories that today's scientists never even entertained accepting, theories that are currently unconceived. (p. 95)

These claims are purely concerned with science, and – just like Van Fraassen before him – Wray is clear (e.g. p. 43f. and p. 64) that he is *not* a 'radical' or 'global' sceptic. He has specific reasons for maintaining his scepticism about science whilst resisting scepticism in many contexts outside of science. Every scientific sceptic, or 'anti-realist', has to deal with this issue: where does their scepticism end? Under what circumstances, exactly, are they *not* sceptical? (See e.g. Stanford 2006, pp. 12-13.)

Naturally there is no absolute dividing line between scientific claims and other types of claim. It is not as if we reach scientific claims in one way – using the 'scientific method', say – and reach other claims in a completely different way. Wray and other scientific sceptics acknowledge that there is no clear dividing line, but this presents no problem for them: there can be a grey area and at the same time still be clear cases on either side. Sceptics argue that (many/most/all) claims on the scientific side are not secure, and we shouldn't make bold assertions about them (e.g. that they will still be in place in 1000 years). Claims on the other side of the divide may well be absolutely fine, and we might make bold assertions about *them*, even though it isn't totally impossible that we are dreaming, or our brain is wired up to a sophisticated alien computer.

By contrast, this book will argue that this is *not* the way to carve up what (not) to be sceptical about. The fact that an idea comes out of science definitely does *not* mean that we can't be just as sure about it as we can about many everyday things. The evidence for scientific claims can sometimes take a form quite unlike the evidence we have for more everyday claims, but that needn't block our ability to know things. Indeed, often scientific evidence can be *better* – for the purposes of making claims concerning what we know – than more 'everyday evidence'. Simply put, the scientific provenance of an idea has no bearing on how certain we can be about the future-proofness of that idea. Instead of looking at the provenance, we should look (directly, or perhaps indirectly) at the quantity and quality of evidence. And there are circumstances in which we can be sure that the evidence has crossed some threshold, such that it is no longer reasonable to remain sceptical about the underlying idea. There is no *exact* threshold, of course, and there will always be a time when the scientific community is split, with some (a significant percentage) willing to state that the evidence is in, and we should start using the word 'fact', and others (a significant percentage) insisting that we need to remain cautious about any such bold claims (see Chapter 7 for a contemporary example). But, sometimes, we get beyond that stage, and reach a time when at least 95% of reasonable/relevant scientists are happy to use the word 'fact'. (The use of '95%' will be justified in due course.)

And, indeed, scientists sometimes want to make this point themselves. A highly respected National Academies Press publication contains the following:

> [M]any scientific explanations have been so thoroughly tested that they are very unlikely to change in substantial ways as new observations are made or new experiments are analyzed.

> These explanations are accepted by scientists as being true and factual descriptions of the natural world. The atomic structure of matter, the genetic basis of heredity, the circulation of blood, gravitation and planetary motion, and the process of biological evolution by natural selection are just a few examples of a very large number of scientific explanations that have been overwhelmingly substantiated. (Institute of Medicine 2008, p. 12)

In fact, some of the examples in this passage are better than others (as will be discussed in due course), but the basic point is clear: there are definite cases where science has defeated the sceptic. Future-proof science is a reality, not just a pipe dream.

2. Misleading evidence

Can scientific evidence be highly misleading? Can it be the case that the evidence *looks* extremely strong, to the extent that nearly all scientists want to use the word 'fact', but that's only because the evidence has led them up the garden path? Certainly some have claimed this, citing examples from the history of science to support the claim. Alas, to my embarrassment, I have also said something far too close to this. In 2018 Stephen Harris at *The Conversation* got in touch with the philosophy of science group at Durham, looking for somebody to write an article on "the biggest failed science projects". This ultimately led to my article 'The Misleading Evidence that Fooled Scientists for Decades', published in June 2018 (Vickers 2018b), where I wrote "history shows us that even very strong evidence can be misleading".

This book will argue that, in the contemporary scientific world, evidence can never be all *that* misleading. At least, not if one is careful about it, as the scientific community always is in the fullness of time (so this book will argue). One of the primary examples in my 2018 article was something of a mistake, and I'll correct that mistake in Chapter 3 of this book. What I said in that article was not *totally* wrong(!) – it can be the case that one or two pieces of evidence can be very misleading, taken on their own, although even then the words 'fooled scientists for decades' are not warranted. Better would be 'fooled scientists temporarily', or 'fooled a few scientists, but not the whole scientific community'. The most obvious cases are those where an individual piece of evidence was very surprising, and perhaps had the *potential* to mislead the scientific community, but didn't. Crucially, scientists consider a whole body of evidence over a period of time; they are (usually) in no rush to make a knee-jerk reaction to an individual result. And it is vanishingly rare for a whole body of evidence to be misleading over a substantial period of time, at least in the contemporary scientific world, where there are so many scientists and so many different scientific teams ready to correct the mistakes, fallacies, unwarranted inferences, and exaggerations of one individual scientist or team of scientists. Thank goodness I did at least say, in the final paragraph of my 'Misleading Evidence' article, "It's rare for evidence to be very misleading". But this wasn't strong enough: a *whole body* of evidence is *never* 'very misleading' for a substantial period of time, and for a large enough, diverse enough, scientific community.

I have been talking about evidence as if it is one thing, but in fact 'evidence' is something of an umbrella term: evidence takes many different forms, in different contexts, and its quality and quantity can sometimes be very difficult to assess. I agree with Kyle Stanford (2011) when he writes that, "Scientific confirmation is a heterogeneous and many-splendored thing; let us count ourselves lucky to find it – in all its genuine diversity – wherever and whenever we can." (p. 898). Evidential reasoning – in all its forms – cannot be represented by a single, simple equation, as the Bayesian model of confirmation would suggest. Much energy has been spent debating *empirical* evidence, most obviously evidence taking the form of accommodations and predictions of phenomena. But it is sensible, I submit, to use the word 'evidence' in a broader sense: we can have (good!) reasons for believing claims that are not straight-forwardly empirical reasons. Evidence can sometimes take the form of an argument, for example. And evidence can sometimes come under headings such as 'consistency', 'coherence', and 'explanatory power': these are the so-called *non-empirical theoretical virtues* (see Schindler 2018 for a recent treatment). The intense focus (within academic literature) on successful *predictions* in recent decades is justified to a certain extent, since successful predictions can sometimes be very important individual pieces of evidence. But even several successful predictions can be overwhelmed by other considerations. How we weigh up all these different sources of evidence is far from obvious. Scientists on the ground often use their intuitions, and these intuitions are often quite reliable, though not always. My claim is not that we can come up with a formula for 'the weight of evidence' in a given case; far from it. My claim is merely that sometimes we are sure that the weight of evidence has crossed a threshold, and it is time to drop the word 'theory', and start using the word 'fact'.

When it comes to misleading evidence, it undoubtedly exists. But it exists just as much for everyday claims as scientific claims. Sherlock Holmes can be misled for a while, as all of the evidence seems to point to one guilty party, when in the end the culprit is somebody else. In fact, a huge number of books and films play on this kind of possibility. Very occasionally, evidence can be *highly* misleading in everyday life, as the world seems to conspire against us somehow. Rarely, somebody is out to deceive us, as Iago deceives Othello: Othello has good evidence that Desdemona is having an affair with Cassio, even though she is not. We can also imagine still greater deceptions which have nothing to do with science: e.g. how the producers deceive Truman Burbank in *The Truman Show*. In this case, Truman has extremely strong evidence for all kinds of things that are not actual – what he sees on the news is fictional, and all those around him know that it is, but act as if it isn't.

The senses can be thoroughly misled, too, even if they are incredibly reliable most of the time. I'm not talking about the way we seem to 'see' or 'feel' things in a dream – if that is misleading at all, it is an ephemeral deception, since we know it wasn't real as soon as we wake up. The senses can be misled more dramatically, for example when we fail to see the left-to-right lines in Figure (1a) as parallel, horizontal lines. Or more dramatically still, we see the world very vividly as coloured, when it (almost certainly) isn't (Figure 1b).

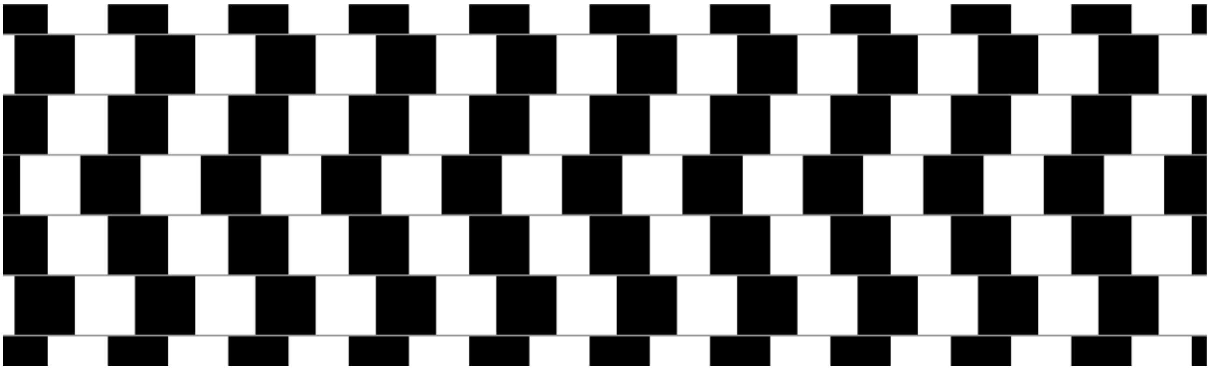

Fig. 1(a) The left-to-right lines are actually parallel, and horizontal (check them!). Credit: Sylverarts Vectors, Shutterstock.

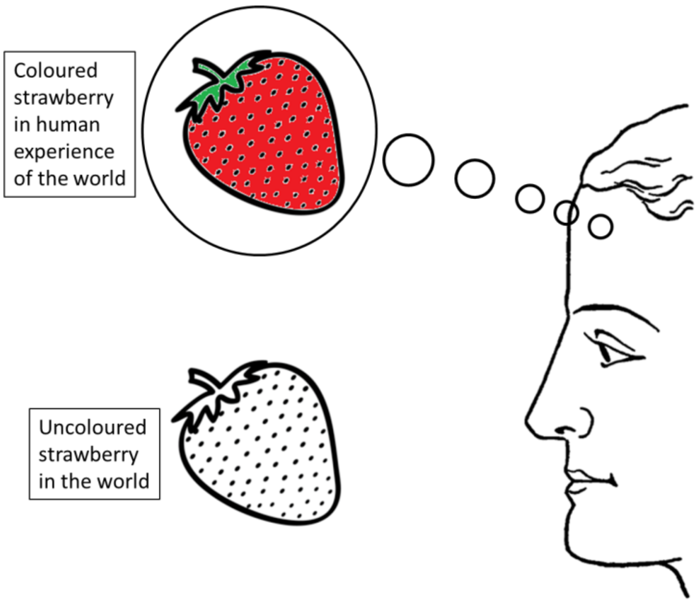

Fig. 1(b): Strawberries are (almost certainly) not coloured in the way they straight-forwardly appear. (Public domain)

The colour illusion is particularly dramatic, because we can't reveal the illusion to ourselves as we can with the horizontal lines in (1a). Indeed, for thousands of years the human race was certain that the world is genuinely coloured, with only rare voices of (speculative) dissent. It was only with the rise of modern philosophy (the primary/secondary quality distinction), developments in physics (What are surfaces made of? What properties do they have?), and developments in psychology and neuroscience, that evidence gradually mounted that when it comes to colour, the world is not how it appears. So in fact, if one is looking for real cases of highly misleading evidence, for a whole community, over a long period of time, the best examples may come from *outside* science, and belong instead to the context where the scientific sceptics are not sceptical: everyday claims such as 'snow is white'.

As the book progresses we will look at various candidates for misleading evidence in the history of science. Numerous examples have now been put forward in the literature, cases where scientists were apparently fooled, and later had to change their minds. I will argue that such cases are *not* grounds for a strong form of scepticism, and leave open the possibility that we can identify many scientific ideas that are future-proof. Many contemporary scientific ideas will be excluded from this, of course, precisely because we have not crossed the evidence threshold yet (and we may never cross it). For one thing, even if the initial evidence looks good, it is prudent to reserve judgement until an idea has been rigorously tested. This has never been more obvious than with the recent 'replication crisis', where many results in psychology/medicine/social sciences, apparently based on statistically significant data, cannot be reliably replicated. The crisis shows clearly that sometimes judgements of the weight of evidence can initially be exaggerated, even by honest, professional scientists. But this is hardly evidence for the kind of scepticism this book is concerned with: it didn't take long for the scientific community to attempt replications of these studies, see those replications fail, and recognise that certain initial claims of 'strong evidence' had been exaggerated. The international scientific community wasn't for a moment tempted to form a consensus, or make an official knowledge claim, regarding these cases. Needless to say, examples of future-proof science identified in this book will be based on much stronger evidence than the cases at issue in the replication crisis.

3. Approximate truth

Another important caveat before we really get started: I don't deny that there will be *adjustments* to scientific ideas in the future. Just about any scientific idea one can imagine will be subject to some kind of refinement over the next tens/hundreds of years. What I'm most concerned to resist, however, are claims that our current best scientific theories will be 'discarded' or 'rendered obsolete', as stated in the Wray (2018) quotations given above. Similarly, I'm keen to resist the claim, often made by the sceptic, that future scientists will take 'the same attitude' towards our current theories that *we* take towards past discarded theories, and that "our own scientific theories are held to be as much subject to radical conceptual change as our past theories are seen to be." (Hesse 1976, p. 266).

To illustrate, consider models of our Solar System. One way to think about the history of such models is as follows. Ptolemy got it wrong: the Sun does not orbit the Earth – this idea was eventually discarded. Then Copernicus got it wrong: the Earth does *not* orbit the Sun in circular orbits. Then Kepler got it wrong: The Earth does not orbit the Sun in elliptical orbits. The latter idea is wrong, for example because the Earth's orbit is always perturbed by other bodies, such as Jupiter, but also because it assumes that the Sun's position is fixed, when it is not. Then the 19th-century Newtonians got it wrong, too: The Earth does *not* orbit the centre of gravity of the Earth-Sun system in a near-ellipse according to Newton's laws of motion. Einstein's general theory of relativity changed all that. And now it is widely assumed that Einstein's theory of general relativity needs to be quantized, somehow; this is what theories such as 'loop quantum gravity' are about. So we've been wrong wrong wrong. Each theory has been 'discarded', and along the way we've seen 'radical change' again and again, and we expect more.

Or have we? As I said, this is *one* way to think about the history of scientific thought vis-à-vis the Solar System. But it is contrived. Describing this sequence of theories in terms of repeated 'radical change' is misleading. Consider Newtonians such as Laplace, Poisson, and Le Verrier – specialising in celestial mechanics in the 18th and 19th centuries – faced with a philosopher of science saying,

> [C]ontemporary scientists should expect that their scientific offspring will look back at their theories with the same attitude they have towards the theories of their predecessors. (Wray 2018, p. 95)

Well, is this correct? *Were* those 19th century Newtonian models of the Solar System just as subject to 'radical change' as the epicycle model of Ptolemy, including as it did a static Earth, with all other celestial bodies orbiting around it? Definitely not. Ptolemy's model of the Solar System was indeed radically false, in a large number of different ways – one cannot possibly shoehorn the term 'approximately true' onto this model. By contrast, the model Le Verrier was working with in the 19th century was exceedingly accurate. Contemporary scientists do *not* look back on Le Verrier's model with anything *like* 'the same attitude' that Le Verrier looked back on Ptolemy's model. And this is because – to put it bluntly – Le Verrier's model was approximately true. Absolutely no need for a shoehorn.

It may be objected: Le Verrier could never have dreamed that Einstein's theory of general relativity would come along, and completely transform our conceptions of space, time, and the meaning of 'gravity'. When it comes to space, time, and gravity, Le Verrier's views were indeed 'radically false', and eventually 'discarded' (at least as candidates for truth). But this is to shift the goalposts. We were talking about models of the Solar System, including what the Sun, the Moon, and the planets are, and how they relate to each other and interact[2] with each other over time. When I described Ptolemy's model as 'radically false', I was considering these respects, *not* his views on the nature of space and time. It goes without saying that there are always deeper questions one can ask, including, "Is gravity a force?" But when it comes to modelling the Solar System one can choose to ignore such deeper 'metaphysical' questions, and get on with the modelling job, exactly as Le Verrier and many others did in the 19th century. And when one puts the deeper questions to one side and concentrates on assessing the model of the Solar System Le Verrier believed in, it cannot be denied that his model was approximately correct. In fact, many of the things he believed were *plain true*; for example:

> The Earth orbits the centre of gravity of the Earth-Sun system in a near-ellipse, subject to minor perturbations.

If one similarly looks for (significant, non-trivial) truths within the Ptolemaic account, one will struggle.

If we turn back to the concept of 'future-proof science', then, I do want this to be compatible with adjustments. Some of our current ideas will (of course) turn out not to be 'perfectly' true, but can reasonably be described as approximately true in the straight-forward way that Le Verrier's conception of the Solar System was obviously approximately true. No clever theory of 'approximate truth' is needed to substantiate this: I will use the term in the same way it is used in everyday life. We all handle the concept of *approximate truth* every single day of our lives, whether we realise it or not.[3] Different cases of application of the term 'approximately true' will come up in different contexts, as we progress, and as we tackle the case studies, so I won't say much more here (see e.g. Section 5 of Chapter 7). Suffice it to say, for now, that there are often clear cases of approximate truth in science, just as in everyday life. I submit that we will always look back on Le Verrier's model of the Solar System as an approximately true model. When I say that a scientific idea is future-proof, I do not mean that it won't change at all for the next 1000 years; I agree that there might be minor adjustments, just as there have been minor adjustments to some of Le Verrier's ideas about the Solar System. At the same

[2] How they interact *crudely speaking*, not at some deep metaphysical level. More on this 'depth of description' spectrum in due course.

[3] To illustrate: If we go out for dinner, and the waiter turns up to take our order and says, "I'm ready to take your order" just as his hand is moving to his waistcoat pocket to retrieve his pad and pen, we will not object, "Actually, you weren't ready when you said that. You're only ready now, some seconds later, when you've actually got your pad and pen in hand."

time, however, some of Le Verrier's ideas are retained intact, and indeed this is always possible when the original ideas are approximately true. When I was looking for a statement from 19th century celestial mechanics that was *plain true* I simply omitted reference to Newtonian mechanics. I also used the term 'near-ellipse', deliberately staying vague on how the orbit of the Earth varies from a true ellipse. Charles S. Peirce famously wrote, "It is easy to be certain ... One has only to be sufficiently vague." What's crucial here is that one can often be just partially vague, still saying something of obvious substance. In this way it is often possible to be practically certain about something highly non-trivial.

4. Future-proof science

Which scientific ideas are future-proof? It is not my intention to use this book to provide a comprehensive list! But at the same time, I must be willing to step up to the plate and name some concrete examples. A good starting point is to provide some *singular facts* that are scientific in the sense that we know them to be facts as a result of scientific labour:

1. The sun is a star.[4]
2. The Milky Way is a spiral galaxy, similar in structure to Messier 83 and NGC 6744.
3. The Earth is a slightly tilted, spinning, oblate spheroid.
4. The Moon causes the tides (with just a bit of help from other factors, such as the pull of the Sun).
5. The collection of propositions summarised as 'The water cycle'.
6. DNA has a double helix structure.
7. Red blood cells carry oxygen around the body.
8. Normal person-to-person speech travels as a longitudinal compression wave through the particles in the air.

In these eight cases there can be no reasonable doubt. Indeed, these are such solid facts that any *bona fide* scientist – with relevant specialist knowledge – would find it absurd to add the word 'theory' to

[4] An anonymous reviewer asked 'What does this mean? How would you flesh it out?' (cf. the discussions in Fuller 2007, p. 10, and also Miller 2013, p. 1302). This same question could be asked of any one of my 30 examples. This issue will be addressed in Chapter 9, Section 2.4. ('Objections and replies'), but the brief answer is that one can use standard textbook definitions of key terms that are not super-detailed, but also far from trivial. It is worth reflecting briefly on the fact that 'Pluto is a planet' turned out *not* to be future-proof. However, Pluto was always an outlier, whereas "our Sun is very much a run-of-the-mill star" (Noyes 1982, p. 7). Kinds and outliers will be further discussed in Section 2 of Chapter 8.

any one of these examples, e.g. to talk of the 'Water Cycle Theory'.[5] It may be objected that it is possible for an astronaut to directly *see* that the Earth is a spinning spheroid, but of course we knew the Earth was spherical long before that was possible (to the extent that it is). And in addition one can't say the same of *all* of these examples; we don't directly see that the sun is a star.

If we think these are all indisputable facts, but direct observation doesn't provide the warrant, then why do we believe them so strongly? One answer is that we are taught that they are facts at school. But if pushed further we may agree that they are *taught* as facts because scientists have established that they *are* facts, over many decades, using a combination of scientific methods including observation, experiment, and theory-development. In short, the evidence for these eight claims has gradually built up until no reasonable doubt can be maintained. Very few of us actually know more than a *very* small fraction of the relevant evidence, and here an element of trust inevitably enters the picture. But – unless we are conspiracy theorists – we feel that this trust in authority is very highly motivated. (See Chapter 5 for a full discussion of the role of trust.)

If the given story is accepted, it is difficult to resist sliding a little further. If we accept what is taught to us at school as scientific fact – using that as a proxy for a huge amount of scientific evidence built up over many decades – then there are many possible examples, including more ambitious examples coming more obviously under the heading of 'scientific theory'. In fact, many such examples were put forward in the philosophical literature in the 60s and 70s by those who wished to resist Kuhn's (1962) story of scientific revolutions, to make the point that his examples – exemplifying the cycle of 'normal science', 'crisis', and 'paradigm change' – were cherry-picked. As Godfrey-Smith (2003, p. 98) writes,

> [Kuhn] was surely *too* focused on the case of theoretical physics. […] [I]f we look at other parts of science – at chemistry and molecular biology, for example – it is much more reasonable to see a continuing growth (with some hiccups) in knowledge about how the world really works. We see a steady growth in knowledge about the structures of sugars, fats, proteins, and other important molecules, for example. There is no evidence that *these* kinds of results will come to be replaced, as opposed to extended, as science moves along. This type of work does not concern the most basic features of the universe, but it is undoubtedly science. (original emphasis)

I couldn't agree more: a large part of our current understanding of sugars, fats, and proteins is surely future-proof, even if there remain many open questions about these molecules. And it is not only the

[5] Cf. Hoefer (2020), p. 21: "The core intuition behind SR [Scientific Realism] is a feeling that it is absolutely *crazy* to not believe in viruses, DNA, atoms, molecules, tectonic plates, etc.; and in the correctness of at least many of the things we say about them." (original emphasis). This book is *not* a defence of 'scientific realism', however; see Chapter 2.

structure of these molecules that we can claim knowledge of; we also understand a great deal about how they behave within the bodies of organisms, including human bodies. This is compatible with the thought that there remains much we do *not* understand.

Molecular biology is just the tip of the iceberg. Some scholars have countered the list of examples of rejected theories in the history of science with a list of examples of 'theories' or 'bodies of thought' that are apparently secure, and where no revolutions are even remotely anticipated. The following is a list of my own, building upon the eight examples already given (partly inspired by Fahrbach 2011, p. 152).[6] In each case I include a 'singular fact' that is illustrative of a wider body of claims coming under the relevant heading:

9. Evolution by natural selection.[7]
    - Singular fact: Human beings evolved from apes that lived on Earth several million years ago.[8]
10. Numerous chemical facts about elements and how they relate to each other.[9]
    - Singular fact: A typical oxygen atom is 16 times heavier than a typical hydrogen atom.
11. The germ theory of disease, including numerous things we know about the properties and behaviour of various different bacteria and viruses, and how these sometimes contribute to disease and illness.
    - Singular fact: Syphilis is caused by the bacterium *Treponema pallidum* subspecies *pallidum*.
12. The 'neural net' theory of the brain, including a large body of knowledge vis-à-vis brain behaviour and the nervous system.
    - Singular fact: Visual input coming from the retina is processed at the rear of the brain.
13. Much of cosmology, including the large-scale structure of the universe, the expansion of the universe, and the properties of various entities such as quasars, pulsars, and galaxies.
    - Singular fact: Quasars were more common in the early universe.

[6] Earlier scholars have also sometimes given their own examples of future-proof science (although they don't use that term). For example, McMullin (1984, pp. 27-8) gives examples from evolutionary history, geology, molecular chemistry, and cell biology. He also notes (p. 8) that, "Scientists are likely to treat with incredulity the suggestion that constructs such as these [galaxies, genes, and molecules] are no more than convenient ways of organizing the data obtained from sophisticated instruments." More recently, Hoefer (2020, p. 22) writes, "There is a large swath of established scientific knowledge that we now possess which includes significant parts of microbiology, chemistry, electricity and electronics (understood as not fundamental), geology, natural history (the fact of evolution by natural selection and much coarse-grained knowledge of the history of living things on Earth), and so forth. It seems crazy to think that any of this lore could be *entirely mistaken*, *radically wrong* in the way that phlogiston theories and theories of the solid mechanical aether were wrong." (original emphasis). See also Hoefer (2020, p. 25f.) and Hoefer and Martí (2020).

[7] This will be tackled in Chapter 4. Of course, nobody would claim that natural selection is the *only* active mechanism.

[8] To get a sense of the state of the art, see, e.g., Williams (2018), Böhme et al. (2019), and Almécija et al. (2021).

[9] The periodic table of elements is a tricky example in certain respects, since there are ongoing debates about how best to structure it (or at least, how best to structure *parts* of it); see, e.g., Grochala (2018).

14. A large body of thought concerning the geological history of our Earth, including (for example) knowledge of past ice ages.
    - Singular fact: Big Rock boulder in Alberta, Canada, was carried there from the Rocky Mountains by a glacier during the last ice age.

15. A large body of thought concerning the interior of the Earth, including knowledge of the inner and outer core.
    - Singular fact: The Earth has a liquid-metal outer core.

16. A large body of thought concerning the history of life on earth, including the 'Cambrian explosion', and the P-Tr and K-Pg extinction events.
    - Singular fact: There was an explosion of life on Earth approx. 540 million years ago.

17. Detailed knowledge of the history of human life.
    - Singular fact: There have been several different human-like '*Homo*' species, of which only modern-day *Homo sapiens* remains.

18. Plate tectonics, including the history of past land-masses such as Laurasia and Gondwana.
    - Singular fact: Between 120 and 160 million years ago, South America split from Africa.

19. Knowledge of cells, mitochondria, chromosomes, and DNA.
    - Singular fact: The SRY gene on the Y chromosome is essential for the development of male gonads in humans.

20. Knowledge of the chemical and physical evolution of our Sun over the next six billion years.
    - Singular fact: Our Sun will gradually turn into a red giant over the course of the next six billion years.

21. Knowledge coming under the heading of 'biochemistry', including knowledge of the structure and behaviour (within organisms) of important molecules such as various sugars, fats, proteins, vitamins, caffeine, alcohol, etc.
    - Singular fact: Animal cells use glucose and oxygen to produce adenosine triphosphate, a high-energy molecule that can then provide muscles with energy to contract during exercise.

22. Knowledge of the structure of all kinds of molecules, and chemical reactions between molecules.
    - Singular fact: Vinegar ($C_2H_4O_2$) and baking soda ($NaHCO_3$) react to give sodium acetate ($NaC_2H_3O_2$) + water (H_2O) + carbon dioxide (CO_2).[10]

23. Detailed knowledge of many dinosaurs, including at least some aspects of how they lived and interacted.

[10] As McMullin (1984, p. 28) notes, "To give a realist construal to the molecular models of the chemist is not to imply that the nature of the constituent atoms and of the bonding between them is exhaustively known."

   - Singular fact: Tyrannosaurus rex had a highly developed sense of smell.

24. Detailed knowledge of the properties and behaviour of sound waves.
    - Singular fact: Sounds waves are both longitudinal and transverse through solids, but only longitudinal through liquid and gas.

25. Knowledge of the properties and behaviour of various different types of cancer.
    - Singular fact: Smoking causes cancer.

26. Knowledge of numerous illnesses and diseases, including Parkinson's, diabetes, epilepsy, HIV/AIDS, Huntingdon's, spina bifida, etc.
    - Singular fact: Human immunodeficiency viruses (HIV) kill immune system cells (T helper cells).

27. A large body of knowledge within pollen and spore science (palynology).
    - Singular fact: Endospores can stay dormant for millions of years.

28. Thermodynamics.
    - Singular fact: At a constant temperature, the pressure of a gas is inversely proportional to its volume.

29. Numerous facts coming under the broad heading of 'climate science', including human-caused global warming.
    - Singular fact: The concentration of carbon dioxide in the Earth's atmosphere in the year 2020 was the highest it has been in 3 million years.

30. Materials science: our understanding of properties and behaviours of various different metals, alloys, plastics, etc, going far beyond purely empirical knowledge.
    - Singular fact: Polycarbonate molecules absorb UV radiation.

So, I think it is quite easy to give 30 examples[11], even including some very broad examples which actually include within them numerous more-specific scientific facts/theories. Of *his* list of nine examples, Fahrbach writes: "Despite the very strong rise in amount of scientific work, refutations among them ["our best scientific theories"] have basically not occurred" (p. 151). The significance of the 'very strong rise in the amount of scientific work' will be explored in Chapter 2, Chapter 5, and elsewhere.

[11] There is some overlap in my examples; e.g. examples 2 and 13, and examples 8 and 24. It is no struggle to come up with additional examples, however. For example, I haven't included Hoefer's (2020) examples concerning (i) our knowledge of electrical phenomena (at a non-fundamental level of description), and (ii) nuclear physics, including facts about nuclear fusion and fission, and nuclear (in)stability. Throughout this book I will repeatedly refer to 'the 30 examples from Chapter 1', with the thought that any examples that concern the reader could easily be replaced with alternative examples.

Of course, the sceptic will absolutely expect to see a (long) list of 'current best theories' that have not (yet) been refuted. It is hardly evidence for future-proof science that one can produce a long list of current theories concerning which current scientists are confident. Lord Kelvin, at the turn of the 20th century, reportedly stated that, "There is nothing new to be discovered in physics now. All that remains is more and more precise measurement." And Albert A. Michelson (famed for the Michelson-Morley experiment of 1887) wrote in 1903:

> The more important fundamental laws and facts of physical science have all been discovered, and these are so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote. (Michelson 1903, p. 23f.)

Given that Kelvin and Michelson said these things, their own lists of examples of 'future-proof science' would no doubt have included examples of 'classical' 19th-century physics that we have now quite thoroughly rejected (at least as candidates for truth). So, we have to be careful: the fact that some prominent scientists are confident about an idea, or theory, should not *by itself* convince us that the idea is (probably) future-proof. But that's OK: this isn't the reason I am confident about the 30 examples listed above. The reason I am confident has to do with the quantity and the quality of the evidence for these ideas, vetted by thousands of scientists, embedded within a sufficiently diverse scientific community.

That's the (very) short story. The long story is rather more complicated, and will be filled in gradually over the next eight chapters.

5. Outline of the book

It is time to get stuck into the details of the debate. This we turn to next, in Chapter 2. So far I have only sketched the position of the 'scientific sceptic', and there are importantly different sceptical positions. Indeed, some of the scholars who describe themselves as 'sceptics', or 'anti-realists', or 'instrumentalists', actually hold positions extremely close to my own. This sounds backward, but that is only because of a confusing use of labels in the relevant literature. It is also crucial for me to engage with the so-called 'scientific realism debate'. I actually do *not* consider this book a stance in the scientific realism debate, since that is a debate most usually defined by a particular distinction between 'observables' and 'unobservables', which will not matter much here, and which I believe to be unfortunate. At the same time, I do wish to argue against the proclamations of many 'anti-realists' or 'non-realists' (including Wray, Stanford, and Van Fraassen).

Following the philosophical groundwork of Chapter 2 we move on to various case studies from both the history of science and also contemporary science. Chapter 3 is the first of the historical case studies. It concerns J. F. Meckel's 1811-1827 novel predictive success concerning the existence of gill slits in the mammalian (including human) embryo. It is argued that this successful prediction, whilst *prima facie* impressive, only modestly confirmed Meckel's theory of recapitulation. This demonstrates that there is no clear link between novel predictive success and truth, even if novel predictive success can sometimes be extremely influential as a type of first-order evidence.

Chapter 4 continues the story of novel predictive success as a candidate example of highly persuasive first-order evidence. Whilst Chapter 3 shows that novel predictive success cannot always be relied upon as a hallmark of future-proof science, Chapter 4 argues further that novel predictive success can be rather *insignificant* evidentially speaking, even when it appears very significant. It does this via a discussion of a relatively recent novel predictive success of the theory of evolution, one that has been selected by contemporary scientists as a significant piece of evidence for the theory: the 2004 discovery of the 'missing link' fossil *Tiktaalik*. Chapter 4 argues that it is much better to direct attention away from individual successes such as this, and towards the full body of evidence. Whilst the full body of evidence is in-practice inaccessible, even to senior experts in the field, it is argued that the weight of evidence can be judged *in*directly via a consideration of certain features of the relevant scientific community. This marks a turning point in the book, with future-proof science being identified via second-order, not first-order, evidence.

If we really turn away from first-order scientific evidence we must ask ourselves afresh: why do we firmly believe various scientific claims, such as the 30 examples listed in the previous section? The answer seems to be that we trust in scientific community opinion. Thus in Chapter 5 we start to ask the question: under what circumstances is scientific community opinion a hallmark of future-proof science? This leads to another historical case study, this time concerning a case where scientific community opinion apparently *got it wrong*: the case of continental drift 1915-1965. It was supposedly proven impossible for the continents to move; many scientists believed this result, and thus continental drift research was ridiculed and otherwise inhibited or suppressed. Does this mean that scientific community opinion can*not* be confidently linked to future-proof science? Chapter 5 analyses the continental drift case and argues that it *can* be so-linked, but we need to carefully identify sufficiently strong cases of scientific consensus. Put briefly, I require a solid scientific consensus amounting to at least 95%, in a scientific community that is large, international, and diverse.

Chapter 6 addresses Hoefer's (2020) concern that, when it comes to fundamental physics, there is a "special vulnerability to underdetermination", demanding significantly greater epistemic caution compared with other scientific contexts. Indeed, Hoefer's argument would suggest that, when it comes to 'future-proof science', one ought to treat fundamental physics as a very special case, completely blocking all pertinent claims, not because they are *not* future-proof, but because one can't be sure. Chapter 6 starts by demonstrating the problem via a discussion of Sommerfeld's 1916 prediction of the hydrogen fine-structure spectral lines, based on a radically false theory of the atom.

It is agreed that there are special epistemic problems in this context, but Hoefer's particular way of drawing the distinction – contrasting 'physics' and 'fundamental physics' – is shown to be problematic: for one thing, the concept *fundamental* can't bear the weight Hoefer wishes to place upon it. Alternative options are considered, including Van Fraassen's (1980) observable/unobservable distinction. But in the end it is argued that any such epistemic distinction will always be too crude, too sweeping. Instead we do better to trust the relevant scientific community – who are already highly cautious in this context – to decide on a case by case basis. Thus it is argued that the criteria for future-proof science introduced in Chapter 5 are also reliable in the context of 'fundamental physics' (broadly construed), and no special caveat is needed.

At this point in the book the link between scientific community opinion and future-proof science has been argued. But there are holes yet to fill in, and these come to the fore when we attempt to apply the proffered theory of future-proof science to contemporary cases. In Chapter 7 we turn to one of the most intriguing hypotheses of recent decades: the asteroid impact theory of the extinction of the dinosaurs. Many scientists have been tempted to state the hypothesis as a fact, and in 2010 a review article was published in *Science* hinting at a scientific consensus. There was a significant community reaction against this piece, however. In addition, there has been plenty of opposition to the claim in both the published literature and activity at (some) major conferences, all the way through from 1980 to 2020. This chapter navigates some of the challenges that can arise when we ask after the strength of feeling in the relevant scientific community vis-à-vis a specific claim. The case carries important lessons for how scientists go about declaring a consensus of opinion, a matter of crucial importance if – as this book argues – we are to identify future-proof science via sufficiently strong scientific consensus.

Chapter 8 applies the proffered theory of future-proof science to another contemporary case, this time of great social importance. During the Covid-19 pandemic, billions of people urgently wanted, and needed, answers to questions concerning scientific knowledge. Were all of the deaths definitely linked via a viral cause? Did it definitely originate in China in December 2019? Were the vast majority of children really safe? Could the vaccines be trusted? One thing lacking was a clear account of how the individual (whether expert or non-expert) could identify the future-proof scientific claims (the 'facts'), distinguishing them from other types of scientific claim, such as 'promising hypotheses', or 'useful speculations'. Looking to the criteria for future-proof science put forward in this book, a worry arises that nothing scientists were saying, in 2020, about the pandemic, could responsibly be called 'future-proof', since in 2020 so little time had passed for relevant scientific claims to be internationally scrutinized. But scientists did in fact have some relevant future-proof knowledge, even only a handful of *weeks* after the onset of the pandemic. This chapter explains how this is possible, given that usually absolute confidence in scientific claims depends upon extensive international scrutiny, often taking many years.

Chapter 9 articulates my final proposal for identifying future-proof science. It draws on the lessons from all the previous chapters to lay out (i) the criteria for future-proof science, (ii) the core argument supporting these criteria, and (iii) a workable strategy for actually *identifying* future-proof science. I build on the 'externalist' suggestion put forward by Oreskes (2019) that the best strategy is to use certain tools to critically assess the status of the scientific consensus, as a proxy for evaluating the entire wealth of first-order evidence from a large number of different perspectives. The shift from 'internal' evidence to 'external' evidence supports calls for adjustments to science education in our schools, with greater emphasis on teaching the 'external', second-order, or 'sociological' evidence for scientific claims. Additionally, this chapter raises some possible, outstanding objections, and provides preliminary responses.