1 A Conversation on Fine-Tuning

You don't have to be a scientist to appreciate the beauty of the night sky, but there is much more to the Universe[1] than its good looks. For scientists, the goal is to unveil the inner workings of nature, the rules and properties that dictate how the bits and pieces of the cosmos move and interact.

After several centuries of scientific progress, centuries that have revealed so much about our cosmos's fundamental forces and building blocks, science is facing a seemingly simple question whose answer could completely change what we think about the physical world. And that question is 'Why is the Universe just right for the formation of complex, intelligent beings?' This might seem to be a strange question: of course our Universe (or at least, this part of it) is hospitable to human life … we're here, aren't we? But, could it have been different? And how different could it have been? Could the Universe have been completely sterile and devoid of life?

You may be asking yourself 'how could the Universe have been different?' and the answer is the fundamental laws of its matter and energy could have been different. Our best, deepest theories of physics, which describe how the Universe behaves, have a few loose ends. For all the predictive power of these laws, there are basic quantities that theorists cannot calculate; we have to cheat by getting the answer from experiments. These loose ends cry out for a deeper understanding.

Like writers of alternative history novels, we can ask hypothetical questions about the Universe. Specifically, how different would

[1] Throughout this book, our Universe, the one we actually inhabit, will appear capitalized, while hypothetical universes will appear in lower-case.

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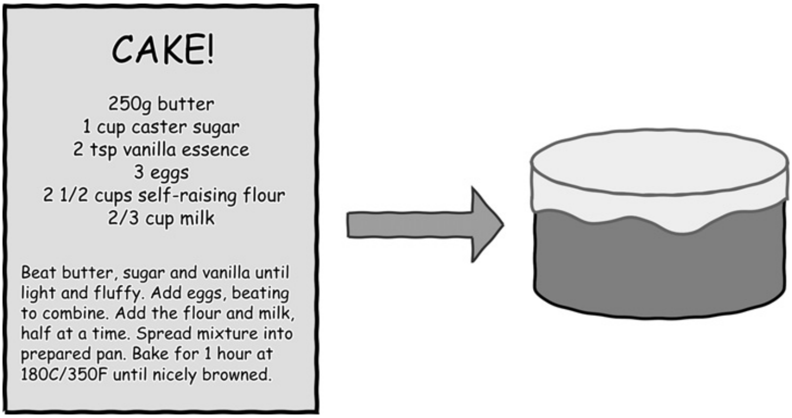

FIGURE 1 A cake recipe illustrates fine-tuning. You can slightly vary the amounts of the ingredients and still make a tasty cake. But deviate too far, add too many extra ingredients, or leave too many ingredients out, and an inedible mess results.

the Universe have been if it were born with a different set of fundamental properties?

These hypothetical universes may not be significantly different from our own, and so we could guess that they too would be hospitable to human life. Or they could be radically different, but still allow an alternative form of life.

But what if almost all of the possible universes are sterile, with conditions too simple or extreme for life of any conceivable type to arise? Then we are faced with a conundrum. Why, in the almost infinite sea of possibilities, was our Universe born with the conditions that allow life to arise?

That is the subject of this book.

AN INTRODUCTION TO FINE-TUNING

What do we mean by fine-tuning? Let's start simply by thinking about baking a cake (Figure 1). The first step might be to get your favourite cookbook and find a recipe – a list of instructions to go from raw ingredients to tasty cake. You combine the ingredients in order, stir and mix, bake for an hour, and finally turn out onto a cooling rack. You know that while the recipe says add two cups of flour, with a little bit more or a little bit less the cake should still turn out alright.

However, doubling the amount of flour, while keeping all the other ingredients the same, could end in baking disaster. And anything more than a pinch of salt would be very unpleasant. You could, of course, double all of the ingredients, cook for slightly longer, and end up with double the cake!

So, the cake recipe is somewhat fine-tuned. You can slightly vary the amount of each of the ingredients and end up with tasty cake. You can also scale the amounts of *all* of the ingredients up or down, and if you adjust the cooking time appropriately, you'll be fine. But deviate too far and you'll probably make an inedible mess. Certainly, if you throw ingredients in at random, and scramble the order of mixing and baking, the chances of something edible emerging are rather small.

So, are the conditions for life fine-tuned?

Let's consider a simple example that we'll come back to later. Everything that you can see is composed of atoms, tiny balls of positive charge surrounded by orbiting electrons. And each electron has exactly the same mass. Just how different would the Universe be if it had been born with electrons with twice the mass? In this hypothetical universe, the electron orbits would be different, changing the size of the atoms, and hence the molecules from which they are built. Perhaps this new mass makes little difference, allowing beings like us to exist. But what if the electron mass had been a million or a billion times larger? With such different atomic and molecular physics, could complex life forms exist? Clearly, we can consider an infinite variety of universes, each with a differing electron mass, and the core question of fine-tuning is what fraction of these could support complex life.

Before continuing, there is a potential confusion with the term *fine-tuning* that we should address. To a physicist, 'fine-tuning' implies

FIGURE 2 A radio set can receive a wide range of frequencies, but only a precisely positioned dial will allow you to enjoy the Norfolk Nights on Radio Norwich[2]. 'Fine-tuning' is a term borrowed from physics, and refers to the contrast between a wide range of possibilities and a narrow range of a particular outcome or phenomenon.

that there is a sensitivity of an outcome to some input parameters or assumptions. Just like baking a cake, if an experiment produces some spectacular result only for a particular, precise set-up, the experiment is said to be *fine-tuned* with respect to the result. 'Fine-tuning for life' is a type of physics fine-tuning, where the outcome is life.

'Fine-tuning' is a metaphor, one that brings to mind an old radio set with dials that must be delicately set in order to listen to Norfolk Nights on Radio Norwich (Figure 2). This metaphor unfortunately involves a guiding hand that sets the dials, giving the impression that 'fine-tuned' means cleverly arranged or made for a purpose by a *fine-tuner*. Whether such a fine-tuner of our Universe exists or not, this is not the sense in which we use the term. 'Fine-tuning' is a technical term borrowed from physics, and refers to the contrast between a wide range of possibilities and a narrow range of a particular outcome or phenomenon. Similes and metaphors are perfectly acceptable in science – space expands like an inflating balloon, for example – as long as we remember what they represent.

So there's a difference between asking 'is the Universe fine-tuned for life?' in the physics sense, and 'was the Universe fine-tuned for life by a creator?'

[2] Home of Alan Partridge, superb comic creation of Steve Coogan.

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A Sunny Day and a Conversation

Introducing tricky topics is never easy – if it were, then they wouldn't be tricky. So we look for inspiration from the birth of the scientific revolution, when Galileo faced exactly this problem when trying to promote the radical idea that we should remove the Earth from the centre of the Universe, and suggesting instead that the planets orbit the Sun. Of course, Galileo also faced the problem of conflict with the academic establishment and the Church, which could have hefty consequences in the seventeenth century.

Galileo's solution was not to write a monologue, unambiguously stating his case and publishing in an academic journal, as a scientist would do today. To present the competing 'World Systems', Galileo wrote a dialogue, where three protagonists, Salviati, Sagredo and Simplicio, argue the merits of rearranging the Solar System. Such a dialogue is reminiscent of discussions in academia, or at the pub. Or both.

In the following, we want to introduce the core concept of this book to you, namely the question of whether the Universe is fine-tuned to allow life to flourish. Some may think this is a rather empty question, but once we realize that we don't quite know why the Universe is the way it is, then the question 'what if things had been different?' becomes extremely interesting, and leads to some rather surprising conclusions.

Our dialogue will set the scene for the chapters to come, examining life and liveability by delving into our understanding of the very fundamental nature of the Universe. However, a dialogue can be hard work (reading a play of Shakespeare is a lot harder than seeing it performed) and forthcoming chapters will revert to a more typical writing style.

Of course, modern 'management-speak' has got rid of dialogues, discussions, debates and diatribes, and so to please middle management everywhere, we present an action-oriented brainstorming conversation to identify additionalities[3] pertaining to the fine-tuning of the Universe for life.

Narrator: Our scene is set amongst Sydney's sandy beaches and rocky cliffs. While the parts of Sydney that the tourists don't see, including the arterial highways and apartment blocks, are filled to bursting point, there are many beautiful and serene pockets where one can sit and think about life. Our story starts in one such corner, on a gloriously sunny day, with two cosmologists thinking about the Universe.

Geraint: It's an amazing time in astronomy. For decades, we've known that there are billions of stars in our own galaxy, and billions of galaxies in the Universe. Thanks to the Kepler space mission, we now know that most stars have planets. Lots of planets could mean lots of life!

Luke: Yes, there are lots of planets, but that does not necessarily mean that there is lots of life. And even if life were common, we would expect much of it to be little higher than pond scum. Boba Fetts and Spocks may be very few and far between.

Geraint: But life arose here! And if the laws of physics are the same everywhere in the Universe, then shouldn't we expect the prospects for life to be similar?

Luke: It takes more than the same physics. Obviously, if you're going to make carbon-based, oxygen-breathing, star-powered life, then you'll need some carbon, some oxygen, and the occasional star.

But we don't know how life first arose. We have some clues about how it could happen, but no one knows the chemical reactions that connect the warm little pond of chemicals to a living cell. Still, there are places that look obviously worse than Earth.

Geraint: I guess we only have to look at the distant lumps of rock in our own Solar System. Pluto is frozen, and any life there, deprived of any significant heating by the Sun, would proceed at a snail's pace.

[3] This phrase was repeated many times at a 'scientists should be more entrepreneurial' seminar we attended. We have no idea what it means.

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Luke: Right. Life needs the right kind of environment. But the laws of physics also play a key role.

Geraint: How so?

Luke: Well, in a few ways. The *laws of physics* have several key parts. Firstly, there are the building blocks of the Universe, the stuff. Then there are the ways that these building blocks can interact, which are the fundamental forces. And the laws of physics also presuppose the stage, the space and time in which the building blocks exist and interact.

Geraint: OK. This is physics for beginners: particles, atoms, molecules, gravity, magnetism, light and radioactivity. The rulebook for how the Universe behaves.

Luke: Exactly. We are the result of the action of the laws of physics over the history of the Universe. It is these laws that power the Sun, forge the elements, build the planets, form the molecules, and drive the chemistry of life.

So now we can ask: What if? What if the laws of physics were different? What if the building blocks, atoms and molecules, had different masses? What if electricity and magnetism were stronger, or gravity repulsive? What if elements were more radioactive? Or there was no radioactivity at all? What if we messed about with the stage, playing around with the very space and time underlying the cosmos? What would change in the Universe? And what would it mean for life?

Geraint: But isn't that a rather silly question to ask? What's the point of playing 'what if' games?

Luke: Human curiosity, for a start. Life seems so contingent, so full of possibility. There are so many ways that things could have turned out: if only I'd caught that bus, that falling vase, that ball or that big break in Hollywood. The twists and turns of history have inspired academic essays with titles such as 'If Louis XVI Had Had an Atom of Firmness' and 'Socrates Dies at Delium, 424 BC', several shelves of novels that explore the coulds, woulds and mights of

Hitler winning WWII, and a hundred thousand (or so) forum posts at alternatehistory.com and counter-factual.net.

In science, we play 'what if' games for a few reasons. We want to know which of our competing theories is the best. We compare Albert Einstein's theory of gravity with Isaac Newton's theory, calculating which gives the most accurate description of the Universe we see around us. Part of that comparison is asking: what would the Universe be like if Newton's theory was true? What would we observe if Einstein got it right?

Also, even our best and deepest physical theories have loose ends. There are numbers in the equations that the theory cannot predict. We just have to measure them. They are called the *constants of nature*. Why do they have the value that we measure? If that question has an answer, it must go beyond our current theories. Perhaps we can get a clue from asking 'what if these constants were different?'

Geraint: Why think that they could be different? In other words, why think that these other universes are possible?

Luke: We don't know whether they're possible – that's what we want to learn from a deeper, simpler, more unified law of nature. Perhaps they are mathematical constants, and cannot be changed without replacing the entire theory. Perhaps they aren't constants at all, but vary from place to place.

Geraint: Even if we did play with the laws of physics, how different could the Universe possibly be?

Luke: Well, you might suppose that because life is so versatile, any old universe would manage to make *something* living. Life has pulled itself together from the hodgepodge of chemical reactions in this Universe. Perhaps any old chemical rulebook will do.

Or we could actually investigate these other universes. It's fun to think about what conditions would be like if we changed the laws of nature.[4]

[4] Note that a cosmologist's view of 'fun' may be quite different from your own.

Geraint: Hmmm, OK.

Luke: The surprising thing, discovered by the scientists who did the necessary calculations, is that messing about with the laws of physics radically alters the workings of the Universe. Many universes are inhospitable for life, even completely sterile. Ruining a universe is easy.

Geraint: Well, that would seem to make our Universe a rather happy coincidence. How did all the right pieces come to exist in our Universe?

Luke: Exactly! That is the fine-tuning problem. Why does our Universe have a mix of fundamental particles and laws that allows us to be here to ask questions at all? The fine-tuning of the Universe for life is the realization that if the laws of physics were different, even just by a little bit, life would not exist.

Geraint: So, what's the solution?

Luke: Well, what do we do when we face something seemingly unlikely? Maybe it's just something unlikely – end of story. Maybe it isn't as unlikely as we think. Maybe it's like the lottery – a winning ticket isn't too unlikely because lots of people buy different tickets.

That last idea, applied to the fine-tuning of the Universe for life, is rather ambitious. It supposes that a universe that is right for life exists because there are untold multitudes of universes with different properties. In the cosmic lottery, we got lucky.

Geraint: Sounds like science fiction.

Luke: Some think so. Others, seeing the lack of plausible ideas for explaining the values of the constants of nature, take the idea seriously.

Geraint: And us?

Luke: We're writing a book about it.

REVISING THE BASICS

Before we can start the journey of this book, we need to prepare by asking a few seemingly simple questions.

Question 1: What Is Life?

We're going to be talking a lot about life. We'd like to start with a definition, but this immediately lands us in trouble. Life has proven to be a very difficult concept to define precisely. We can all see the difference between the kind of thing a rabbit is and the kind of thing a rock is. A rabbit can see a fox approaching and run into its burrow; a rock might be pushed into a hole by the wind, but that's a very different kind of reaction. Is life defined by its ability to respond to the outside world? Rocks respond to the wind. But the rabbit reacts to the information that 'a fox is coming', even if it doesn't consciously think that thought. Is that what defines life?

Or is it the ability to reproduce? Rabbits famously make more rabbits; rocks can be crushed into a multitude of smaller rocks, but again that's a very different kind of thing. Rabbits make more rabbits via an internal rabbit-making recipe. The instructions for rabbit production are inside the rabbit, coded as information, and implemented via biological reproduction. Tweaking this biological code is what makes each generation, and each species, different.

And yet, suppose we met an alien race with which we could chat casually about the weather on Mars and what they've learned about the laws of nature. If an alien happened to mention that their species doesn't reproduce – perhaps they are sterile drones, descended from a long dead queen but able to live indefinitely – we wouldn't offend our guests by blurting out: 'Oh, I'm sorry . . . I thought you were alive.'

Living creatures need to draw energy from their environment and put it to use. So is this *metabolism* the defining characteristic of life? More generally, life seems to have the ability to maintain an internal, ordered state against a changing environment. Life forms grow and flourish; they don't simply erode and decay.

One of the problems with crafting a definition for life is the hard cases, the borderlines between living and non-living. Is a virus a life form, even though it doesn't reproduce by cell division? What about *prions*, which are little more than badly formed protein molecules, but are responsible for mad-cow disease? Viruses and prions replicate by hijacking the machinery of a healthy cell, but is this life?

Computers and robots can respond to information about their environment. Are they alive? Crystals can form, grow, and create structure. Are they living, even though they don't do these things in accordance with an internal code, like DNA (deoxyribonucleic acid) in our cells?

Our discussion will touch on even more woolly questions about life. We will be concerned with the conditions under which life *forms*, and how common such conditions are in our Universe and beyond. It would be wonderful if, like our cake mix, we could simply provide a recipe for life:

1 star
1 planet surface (not too hot or too cold)
Sprinkle your planet's surface with
10 parts water
5 parts carbon
3 parts oxygen
A pinch of hydrogen, nitrogen, calcium, phosphorus, potassium, sulphur, five spice, olive oil, a squeeze of lemon (to taste).
Bake using the residual heat of the early stages of the planet's formation. When the crust is firm, grill in starlight for a billion years, continually moistening with the water from colliding comets, until firm to the touch.
Stir with meteorites and volcanos.
Serve at room temperature (with garnish).

Unfortunately, we have only clues as to the sequence of events by which life formed on Earth. This is an extraordinarily difficult scientific problem, for three reasons. Firstly, life – even a single, 'simple' cell – is a miracle of complexity. Every cell in your body, for example, has molecular machines for moving itself, tagging and transporting molecules, processing food, defending against invaders, DNA duplication and repair, producing proteins and receiving and processing outside signals. On top of all that, this entire machine can tear itself in half and produce a complete working copy in about 20 minutes. A modern computer is pretty great, but it can't do that.

Secondly, the study of the origin of life is a *forensic* science. Like a detective gathering clues, scientists are trying to piece together a microscopic event, but are four billion years late to a crime scene that is the size of the Earth, and constantly moulded by water, wind, shifting tectonic plates, volcanos, sunlight and the occasional catastrophic meteorite impact.

Thirdly, and even worse, the origin of life could be an extremely rare event, even given the 'right' conditions. The process by which life forms could be so unlikely that it has only happened once in the galaxy, or worse. This makes the scientists' job much harder, as they may be looking for a singular set of circumstances. Which statistical fluke was responsible for life as we know it?[5]

Should we just stop here? If we don't know the conditions for life, how do we know how those conditions change with the physics of the universe?

Let's dive into an example, previewing later chapters. Our Universe appears to contain a form of energy that has *anti-gravity*. We know this from its effect on the expansion of the Universe, but we don't know what it is. To reflect this ignorance, we have given it the name *dark energy*: a nicely mysterious name that ensures that cosmologists pique the media's interest.

Dark energy could be a number of things, including something called *vacuum energy*, that is, the energy present in empty space even when there are no particles. Our best theory of the structure of matter

[5] Doesn't this make it unlikely that life formed by natural processes? To calculate the probability that life forms *at all* in the Universe by natural processes, we would need to know the size of the Universe. How many opportunities are there for this unlikely event to happen? We don't know the size of the Universe, so we don't know how to do this calculation. There is no reason to believe that the size of the *observable* Universe (the part of the Universe from which light has had time to reach us here) is any indication of the size of the *whole* Universe.

tells us that each fundamental type of matter will contribute to this vacuum energy, either positively or negatively. Alarmingly, the typical size of these contributions is larger than the amount of dark energy in our Universe by a factor of 1 followed by 120 zeros, or in scientific notation 10^{120}.

What would happen if the amount of dark energy in our Universe were, say, a trillion (10^{12}) times larger? This sounds like a big increase, but it is a pittance compared to 10^{120}. In that universe, the expansion of space would be so rapid that no galaxies, stars or planets would form. The universe would contain a thin soup of hydrogen and helium. At most, these particles might occasionally bounce off each other, and head back out into space for another trillion years of lonely isolation.

We may not know exactly what life is, or exactly how life forms, but we know that life isn't *that*. Such a universe would be fantastically simple, since matter would never get together in large enough numbers to make anything more complicated than a hydrogen molecule. Because gravity won't make matter collapse into galaxies or stars or planets or *anything*, physics is easy. Too easy. Too simple for anything like life.

At this point, people often play the science fiction card, and retort that such a simple universe could contain life not as we know it, life so extraordinary and bizarre that our puny human minds could not even conceive of its existence. But the important word here is *fiction*. Any genesis of life we consider must be based in science, not science fiction. Any universe in which life can arise must provide the conditions for the storage and processing of information; a thin soup of only hydrogen and helium simply does not provide this.

Let's continue thinking about simple vs. complex universes with an illustration. Suppose we're trying to invent a new board game. It will be a bit like chess, but with slightly different rules. As a first attempt, we'll make one small change to the rules: instead of stating that the only piece that can jump over other pieces is the *knight*, our new game says that the only piece that

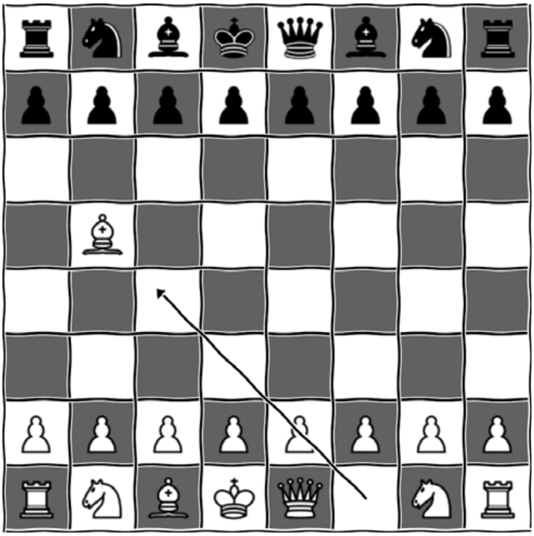

FIGURE 3 How to checkmate in schmess.

can jump over other pieces is the *bishop*. Instead of chess, we've invented *Shmess*.

Is shmess an interesting game? Wait a minute … we haven't defined the term *interesting*. How can we decide whether a game is interesting if we don't know exactly what that term means, or if different people find different things interesting?

In the end, it doesn't much matter. Part of what makes chess interesting to its admirers is the intricacy of its strategy. Chess strategy textbooks can be hundreds of pages long, and Grandmasters spend a lifetime mastering the game. If, on the other hand, we were to write *An Introduction to Strategy in Shmess*, it would need just two sentences: 'White moves her bishop from f1 to b5. Checkmate.[6]' That's it. The game is over before Black has his first move (Figure 3).

We don't need a precise definition of *interesting* to conclude that a game in which one player always wins and the other player always

[6] Technically, it's 'shmeckmate'. But you're just learning so we'll keep it simple.

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does nothing is not an interesting game. The game is too simple. We know what would happen in a game of shmess, and we know that none of those things is interesting.

Let's expand the example. Suppose you've been inventing new board games all afternoon. You've tried a thousand different sets of rules, and all but two are as boring as shmess. Now, we could argue about which definition of interesting is *really* the right one, and whether these two games are *really* interesting. But the big story here is how rare interesting games are in the set of possible games – a conclusion that we can reach without precisely defining *interesting*.

The reason is that, in order to conclude that most games are not interesting, we don't need to decide the borderline cases. We only need to be able to identify obviously non-interesting games.

Similarly, all we need for an investigation of fine-tuning is to be able to identify examples of obviously non-living things. If a universe is simple enough, we can safely conclude that nothing as complex as life could form.

There are hypothetical universes whose laws and constants of nature, while not a definitive death sentence for all life forms, are certainly a dramatic step in the wrong direction. For example, a supervillain with his hand on the cosmic dials could crumble all your atoms into a pile of hydrogen. While it is conceivable that some form of life could exist somewhere in such a universe, a call to your favourite superhero would probably be wise.

As a result, we needn't worry too much about a precise definition of life. A typical dictionary definition will do: life is characterized by the capacity to grow, metabolize, actively resist outside disturbance, and reproduce.

Question 2: What Is the Anthropic Principle?

Scientists and philosophers have debated the extent and implications of the fine-tuning of the Universe for life for several decades. Debates have also raged among interested laypersons. Sooner or later, someone will mention the *Anthropic Principle*.

Discussion of the anthropic principle is clouded by its many, contradictory definitions. We need to clear up this mess, and will do so by tracing the origin of the confusion.

Australian-born cosmologist Brandon Carter introduced the term in a now famous talk in Warsaw in 1973. Here is Carter's *Weak Anthropic Principle (WAP)*:

> We must be prepared to take account of the fact that our location in the universe is necessarily privileged to the extent of being compatible with our existence as observers.

One version of the history of science tells of humankind's gradual realization that they are not the special, unique, all-important centre of the Universe. Medieval mythology arrogantly presumed that the cosmos revolved around us, only to be overthrown by Copernicus and Galileo. We are not at the centre of the Solar System, much less at the centre of the Universe. To such a view, Carter's principle seems obsolete.

However, history tells a different story. It was not the medievals who placed the Earth at the centre of the Universe but the ancients. Specifically, Aristotle's cosmology of the fourth century BC consisted of around 50 transparent spheres rotating around the Earth. The stars and planets are made of different stuff – celestial aether – that is perfect and incorruptible. By contrast, Earth is made of, well, earth. While it is the very nature of aether to maintain perfect circular motion, earth's weight and imperfection causes it to sink. Our home planet isn't at the centre; it's at the *bottom*! It's where the crud of the Universe collects.

Aristotle had his reasons for such a system, and they do not involve human arrogance[7]. Rather, they are empirical. When you

[7] We would do well to remember that, while the Hebrew Scriptures place humankind near the pinnacle of creation, the Greek and Babylonian stories do not. The Babylonian Enuma Elish tells of a primordial battle between the chaos monsters

jump, you land in the same place. You don't land 500 metres to the west, which proved to the ancients that it is the heavens that are moving and not the Earth. (Only when one understands Galileo's relativity of motion can this argument be countered.) But motion on Earth doesn't last. If your horse stops pulling its cart, it quickly comes to rest. If you drop anything made of earthly matter, it falls back towards its natural place in the scheme of things, and comes to rest. So the heavens, with their perpetual, perfect, circular motion, must be made of different stuff, and kept in motion by the *Primum Mobile*, the outermost and greatest of the spheres.

It is preposterous, then, for the ancients and medievals to join Copernicus in moving the Earth out into the heavens. This is not because it demotes us from our throne at the centre. Quite the opposite – it puts us in too high and lofty company. We don't belong out there among the perfect spheres. Earthly stuff doesn't move like heavenly stuff. And how could we possibly place the Sun – the perfect source of light and life – at the bottom of the Universe? What had it done to deserve a seat of such dishonour?

New physics, and in particular a new understanding of matter and motion, was needed. The revolution was glimpsed by Galileo and completed by Newton. All objects remain in a state of constant motion unless acted on by a force. The planets move in circular orbits due to the gravitational force of the Sun; otherwise, they move largely unimpeded through practically empty space. Earthly things come to

Marduk and Taimut, the leaders of the competing factions of gods. Marduk triumphs, and rips the corpse of Tiamut into two halves from which he fashions the Earth and skies. Kingu, a rebel god who incited the war, is destroyed so that from his blood Marduk can create:

> . . . a savage, 'Man' shall be his name.
> Verily, savage-man I will create.
> He shall be charged with the service of the gods
> That they might be at ease!

The epic ends with a hall of feasting gods chanting the 50 kingly names of Marduk. Whatever inspired the story that humankind exists to be the slaves of the reigning chaos monsters, it wasn't human self-importance. Greek mythology has a similarly low view of humankind's place in the grand scheme of things.

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rest because of other forces – friction, air resistance, contact forces. In this way, we can explain earthly and planetary motion in terms of the same principles and the same matter.

Modern astronomy shows that we are not even at the centre of our galaxy. (It's probably just as well – the centre of our galaxy hosts a black hole that is a million times heavier than the Sun.) We are the third planet around a typical star in an average-sized galaxy in a universe with planets, stars and galaxies in every direction. Not only are we not at the centre of the Universe, there is no centre.

So just what does Carter mean when he says that our location must be privileged?

Consider a simple example. We usually take air for granted, but the density of the air you are breathing is 10^{27} times the average density of material in the Universe. Places in the Universe with a density at least as large as the air in a room are cosmically rare. Why would you, a human being, find yourself in such a rare location?

The answer is not difficult to discover. Humans are the result of billions of years of evolution, built out of a myriad of complex molecules and structures. This process requires an environment rich in chemicals, and dense enough for efficient chemical reactions. Humans should not be surprised to find themselves in such an environment, even if it is rare.

In fact, any other intelligent beings in our Universe that are questioning their existence will probably find themselves in such *privileged* environments.

We can take this argument further. When Carter says *location*, he means not just in *space* but also in *time*. We expect life to be more likely to arise not just in certain places but also at certain times.

The early Universe consisted of mostly hydrogen and helium, with virtually none of the elements for creating planets, trees and people. The Universe needs to create several generations of stars to produce large quantities of carbon, oxygen and other elements. As an intelligent being, you should not be surprised to find yourself in a Universe that is almost 14 billion years old, that has had sufficient

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time to create the material needed to create you. You exist at a *privileged* time.

WAP says: the Universe is not your experiment, to set up as you please and observe at your leisure. You are not Dr Frankenstein. You are the monster. You have awoken amidst the beakers, electrodes and dials of the machine that created you. *What* we observe may be affected by the fact *that* we observe at all.

Carter took this line of thinking one step further, introducing the *Strong Anthropic Principle* (SAP). It says:

> The Universe (and hence the fundamental parameters on which it depends) must be as to admit the creation of observers within it at some stage.

Simply put, WAP asks: why here? why now? SAP asks: why these physical laws and constants? WAP is about our place in space and time. SAP is about the properties of the Universe, such as the values of the constants of nature.

Carter's SAP is easily misunderstood; the source of most confusion is the word *must*. The sense is not logical or metaphysical, that is, that a universe without observers is impossible. Neither is it causal, as if we made the Universe. Rather, this *must* is consequential, as in 'there is frost on the ground, so it must be cold outside'. *Given that we exist*, the Universe (and its laws) must allow observers.

Carter's WAP and SAP are about what follows from our existence as observers, and so cannot explain why observers exist at all. These principles are mere tautologies, unable to explain anything. However, similar tautologies play a role in scientific explanations of the world. A telescope can see only objects that are bright enough for it to see. Only people who respond to the survey will be surveyed. The organisms best able to survive are more likely to survive. These are not the whole explanation of some phenomenon – natural selection, for example, involves more than survival of the survivors. But they can be important.

Here's where the confusion starts: later writers have not followed Carter. In 1986, two well-known physicists, John Barrow and Frank Tipler, published an influential book titled *The Anthropic Cosmological Principle*. They delved into questions about the existence of intelligent life and its implications for the laws of nature. It is a wonderful book, but it less-than-subtly redefines the weak and strong anthropic principles, causing considerable confusion. According to Barrow and Tipler (p. 16), the Weak Anthropic Principle states:

> The observed values of all physical and cosmological quantities are not equally probable but they take on values restricted by the requirement that there exist sites where carbon-based life can evolve and by the requirement that the Universe be old enough for it to have already done so.

This is, in fact, a combination of Carter's weak and strong principles. It refers to 'all physical and cosmological quantities', including space and time (Carter's weak principle) and the constants of nature (Carter's strong principle). It is, we contend, reasonable to combine the two, but the result should be simply called the *anthropic principle*.

How, then, do Barrow and Tipler define the Strong Anthropic Principle?

> The Universe must have those properties which allow life to develop within it at some stage in its history (1986, p. 21).

This is where things get interesting. They offer several alternative interpretations of this statement, including:

1. There exists one possible Universe 'designed' with the goal of generating and sustaining 'observers'.
2. Observers are necessary to bring the Universe into being.
3. An ensemble of other different universes is necessary for the existence of our Universe.

We're a long way from Carter's SAP. The 'must' in Barrow and Tipler's Strong Anthropic Principle is taken to imply that intelligent life is somehow central to the very being of the Universe, even suggesting we made it!

With this redefinition, the Strong Anthropic Principle becomes quasi-metaphysical, making philosophers thoughtful and scientists suspicious.

This redefinition is unwise. WAP and SAP are supposed to be stronger and weaker versions of the *same kind* of principle. Carter's principles are: the same idea is applied narrowly to space and time (WAP) and more widely to the constants of nature (SAP). However, Barrow and Tipler's motley company of ideas – from circular to speculative – march under the same 'anthropic' banner. This has tended to give them all an undeservedly controversial air. Even Carter's utterly obvious WAP is viewed with suspicion because of its dubious namesakes.

We will leave the anthropic principle for now; it will pop up here and there throughout the book. If you can't wait, and have plenty of time on your hands, typing 'anthropic principle' into your favourite search engine will provide hours of entertainment, though significantly less enlightenment.

Question 3: What Is Science?

We will be tiptoeing around the fringes of science. We need to know when we've wandered too far, straying into speculation, metaphysics, or worse.

Being scientists, our view of the scientific enterprise will be from the inside. We are most familiar with our field and our colleagues and our projects, and must step back to generalize about science and scientists and the scientific method. In particular, transcending our time and culture to paint an authentic portrait of the history of science is no triviality. Inevitably, our account of *the* scientific method will be coloured by the goings-on in building H90 of the University of Sydney.

In fact, this 'scientific method' is a bit of a myth. It sounds like scientists have a little book with stern rules about asking questions, defining hypotheses, and performing experiments to decide if your ideas are rejected by the ugly facts of nature, or live to fight another day. In reality, the process of science is learned on the job, meaning it is a rather messy process in practice.

Our focus will be the field of physics, as this is the most familiar to us and the most relevant to fine-tuning. Physicists are often lumped into two camps; theorists who try to construct the mathematical rules of the workings of the Universe, and experimenters who investigate how the Universe actually behaves. In reality, the distinction between theorist and experimenter is not perfectly sharp, with many people having a foot in both camps, but we'll stick with the distinction for now. Let's start by looking at the role of the experimenters.

The Experimenters

Well, *someone*'s got to actually look at the Universe.

Experimenters come in various shapes and sizes. In astronomy, for example, we are typically passive observers of the Universe we see around us. We can't test our ideas about stars by making one in the lab.

More typically, we picture an experimenter in a lab, surrounded by instruments, chemicals and brains in vats. These experimenters tinker with nature, sending electrons one way or another, or placing crystals into super-strong magnetic fields just to see what happens. In the physical sciences, however, it is not sufficient to simply describe your observations in words (although this can be important). We need to get *quantitative* – we need numbers. This recording of the properties of things, especially how they change as an experiment is tweaked, is a vital part of science.

Consider a simple question: what colour is the sky? These words are being typed on an airplane flying between Sydney and Melbourne, and outside there is the lovely view of the winter sky over Australia.

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The sky could be described as being light blue in colour (ignoring the scattered clouds below), but it is somewhat darker above, and becomes lighter towards the horizon.

A nice description, but how does this patch of sky compare to that observed somewhere else on the planet? To meaningfully compare, we need to measure physical properties of the sky at each location. We can't just exchange impressions; we need numbers.

Light is a form of energy, and we know that it comes in a range of wavelengths. So we could build a device to measure how much energy is deposited in my eye by the light received from the sky. We can also measure how much energy is deposited as we change the wavelength of the light. Such devices exist and are known as spectrographs, as they split the light they receive into a spectrum of colours. All Pink Floyd fans know that a glass prism can split a beam of white light into a rainbow of colours.

We can measure how the sky looks at different wavelengths, and also as we look further above the horizon. With these measurements, we can compare the sky at different locations on Earth.

Unfortunately, the real world is messy. Equipment and detectors are never perfect, and any data we record will come with an associated uncertainty, something that is often referred to as an error, although it does not mean that something is wrong. A better word is noise[8].

For example, suppose we leave our detector out in the sunshine and it collects 10,784.3 joules of energy with an uncertainty of 0.1 joules. We can say that the actual amount of energy falling on the detector is likely to be in the range 10,784.2 to 10,784.4, very likely to be in the range 10,784.0 to 10,784.6, and that it is extremely unlikely that only 100 joules or 100,000 joules arrived.

[8] Our next project will be to write a book about noise and uncertainty in science. In essence, these are the most important things in all of science, but are poorly understood by those not in the field. We dream of the day when it is routine for the media to report uncertainties on a measurement.

Scientists have had to deal with the uncertainties in their measurements for a long time, and have robust mathematical approaches to deal with them. While these methods, known as Bayesian statistics, are widely known, they are not always applied. Why science operates this way is a topic for another book!

More than just looking, experimenters measure, determining the properties of the world around us. But this cataloguing is just one side of science.

The Theorists

What do we do with a mountain of measurements? We can search for patterns and trends, hoping to look behind the data and see the inner workings of the Universe. In physics, theorists seek the mathematical laws by which the machinery of nature operates.

While mathematics has long been appreciated for its beauty and usefulness, its crucial role in physics is a relatively recent discovery. Students in medieval universities were first taught critical thinking via the *trivium*: grammar, logic and rhetoric. They were then taught the *quadrivium*: arithmetic, geometry, music and astronomy. Music might seem out of place, but students learned not performance or composition, but the mathematical theory of harmonics and proportions.

Similarly, astronomy was viewed in the tradition of Aristotle as a 'middle science', living between abstract mathematics and empirical (but largely not quantitative) physics. We could theorize in mathematical terms about the geometry of the heavens, but it seemed inconceivable that such symmetry could be found down here.

Rene Descartes, in the early seventeenth century, most clearly envisioned and championed the idea that all of physics could be as mathematical as astronomy. Descartes had a vision of 'unifying all sciences of quantity under mathematics'.[9]

[9] Williams, 1978 (p. 16).

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The first task was to unify celestial and earthly mechanics, astronomy and physics. Descartes' own attempts were unsuccessful, in part because he thought that a vacuum was physically impossible. Building on the important work of a great many scientists, including Kepler and Galileo, it was the towering genius of Isaac Newton who first fulfilled Descartes' vision. Theoretical physicists follow in his footsteps.

The theorist's primary tool is a *model*, built not of Lego® blocks but of mathematics. Returning to the blueness of the sky, our model needs a few components. We need to know about the source of the light we receive from the sky – sunlight – and, in particular, its distribution of energy as a function of wavelength. We need the properties of the atmosphere: its various gases with their molecular structures, and how the atmosphere changes with altitude, being warm and dense near the ground, colder and rarefied up high.

The model would also have to consider how light moves through the sea of molecules that make up the atmosphere. Does light sail through or does it scatter off the molecules? And if it scatters, how does this change with the wavelength of the light?

At all stages, the theorist will call on what is known, such as the molecular make-up of the atmosphere and the pressure and temperature at various heights. They may require new calculations, such as deducing how light scatters differently off nitrogen and oxygen molecules.

Four pieces make up the theorist's model. The physical material is represented by a mathematical *object*, that is, something like a set of numbers or a function or a field or a manifold that captures everything the model says about the system. For example, a collection of classical particles is represented by the position and velocity of each particle in space and time. For the gas in a room, it could be the temperature, pressure and density at each point. A variety of elaborate and sophisticated mathematical objects are available.

The second piece is the mathematical *form* of the equation. This encodes how the stuff moves, acts and reacts. With different equations, our classical particles might attract or repel, our fields might wiggle, or quantum things might … do whatever quantum things do. Physics equations are typically *dynamical* – they tell us how a system changes over time.

The third part is a set of *constants*: plain old numbers. They might tell us how strongly two particles repel each other, or how heavy they are. These constants are – by definition – not able to be calculated by the equation. They must be measured.

The fourth part is the *scenario* to which the equation is applied. Mathematicians call these 'initial conditions'[10] – the equation tells us how the stuff *would* act in a certain situation (move this way, bounce that way, swerve over here), so we need more information to specify how it actually acted. For example, given Newton's theory of gravity, we can investigate the Solar System, a cluster of stars or even the whole galaxy. Given a physical theory describing how electrons flow through a wire, we can investigate all kinds of electrical devices.

Here are the four pieces: the stuff, the dynamics (encoded in an equation), the constants and the scenario. Figure 4 shows how the pieces of a theoretical model come together to predict the orbit of a small particle (m_1) around a larger one (m_2).

The Crunch

Now comes the crunch: compare your theoretical prediction with observation. This is the essence of science. Actually, strictly speaking, this *is* science! Our models are mixtures of well-tested theories, reasonable assumptions and guesses; as Richard Feynman noted, 'it is not unscientific to make a guess.'[11] Science happens when we ask the Universe whether we guessed right. Otherwise, the experimenter is doing little more than stamp collecting, and the theorist is just playing with numbers!

[10] Or, more generally, boundary conditions. [11] Feynman (1965, p. 165).

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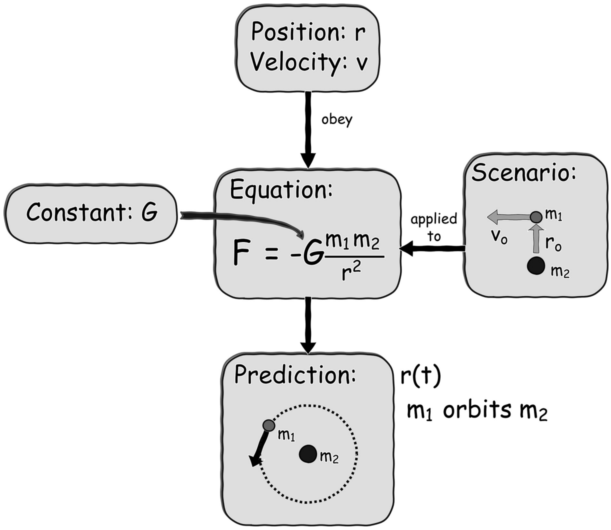

FIGURE 4 We use the example of applying Newton's theory of gravity to predict a planetary orbit. Four pieces must converge. A *mathematical object* represents the state of the system, in this case the position and velocity of the particles. The *equation* relates the state of the system to how it is changing in time. The equation requires a *constant*, G, that controls the strength of gravity. And we apply this general equation to a particular *scenario*, in this case two masses arranged and moving as shown. The result is a prediction: the planet (m_1) will orbit the star (m_2).

Scientists use probability theory to tell them how well a prediction matches the observed universe, and whether the data favour one physical theory over another. The poorly performing are relegated to the minor leagues, while the better ones are reemployed, and continue to be used until they no longer provide an accurate description of the world around us, and new insight is required to construct a better theory.

In this way, science finds increasingly accurate mathematical theories that predict what we observe in the natural world.

BACK TO FINE-TUNING

So, where does fine-tuning fit into science?

We said that science was about comparing your theory with data. However, there's a bit more to it. We prefer theories that aren't ad hoc, jerry-rigged, or too flexible for their own good. In general, if you have 10 data points, and an equation with 10 *free parameters*,[12] then your model can't fail – it will always match the data. Successful, sure, but not impressive. It's like the magician correctly guessing the card you selected from the deck ... on the 43rd attempt. Much more impressive are the theories that explain mountains of data with few moving parts.

Similarly suspicious are theories that need very precise values of free parameters in order to explain the data. To understand why, consider this little tale.

A bank vault is robbed. The armoured door was opened without force; the robbers used the access code. The police arrive on the scene.

DREBIN: Maybe they guessed the code.

HOCKEN: No way, Frank. There are a trillion combinations. The system shows that they entered the code correctly on the first attempt. Surely the odds against that are astronomical.

DREBIN: But it's still possible, right?

Here is one way to see the problem with Drebin's theory: it is composed of trillions of sub-theories. There's the sub-theory in which the robbers turn up and punch in 0000-0000-0000. There's the sub-theory in which they punch in 0000-0000-0001. And another with 0000-0000-0002. And so on.

On Drebin's 'they just guessed' hypothesis, each of these sub-theories is intrinsically equally likely. And yet, only one explains the fact that they got into the safe – the one in which they punch in the

[12] A free parameter is a number that can be adjusted to make a model fit the data. When fitting a straight line to some data, we would use the equation $y = mx + c$, the numbers m and c are free parameters; m is the slope, and c is the intercept, and for different values we get different straight lines.

correct code. This makes Drebin's theory suspicious. The 'which code they guessed' part of the theory must be *fine-tuned*. This does not sink the theory, but it does leave the door open for an alternative theory to better explain the data.

This is what the physicist means by 'fine-tuned' – *a suspiciously precise assumption*. (Precision is great in our data, but not in our assumptions.)

Physical theories, like physical systems, can be hierarchical – we build big ones out of small ones. The most fundamental laws we have describe the smallest building blocks of physics: electrons, quarks, photons and a host of other characters we'll meet in the next chapter. This is the domain of *particle physics*.

Similarly, the most all-encompassing scenario we can hope to model is the entire Universe. This is the domain of *cosmology*. Looking for the ultimate initial conditions sends us back to the beginning of time, and more of that in Chapter 5.

So, if the free parameters (constants or initial conditions) of particle physics and cosmology are suspiciously precise, then we have found fine-tuning at the deepest level of our understanding of the Universe.

The fine-tuning of the Universe for *life*, then, is fine-tuning applied specifically to the fact that this universe supports life forms. The claim is that small changes in the free parameters of the laws of nature as we know them have *dramatic, uncompensated* and *detrimental* effects on the ability of the Universe to support the complexity needed for physical life forms.

THE FUNDAMENTAL CONSTANTS OF NATURE

Let's take a closer look at some of these free parameters.

The electron is one of the fundamental particles of the Universe. Electron orbits around the nuclei of atoms dictate the processes of chemistry. With the appropriate experimental equipment, we can measure the mass of an individual electron: $9.109\,382\,15 \times 10^{-31}$ kg (and, with our most accurate equipment, we know this value has an uncertainty of $0.000\,000\,45 \times 10^{-31}$ kg). If you measure the mass of any electron in the Universe, you get the same answer!

When we measure the mass of an object in kilograms, we are implicitly comparing it to a lump of platinum–iridium alloy held in uniform conditions at the International Bureau of Weights and Measures laboratories in the outer reaches of Paris. There is nothing special about this lump, and so nothing special about the kilogram. Nothing changes if we were to express the mass of the electron in pounds, long tons, grains or carats.

However, the mass of the electron relative to other particles in the Universe is important. Each member of the menagerie of fundamental particles comes with a mass, and while some are zero, many are just plain, unexplained numbers.

Here we can play our 'what if?' games. If we change the relative masses of the fundamental particles, what effect does this have on a complex, multi-cellular, balding primate sitting and typing on a planet orbiting a star? We'll see in later chapters that the existence of life depends critically upon particle masses. Universes with different mass ratios are often sterile.

Another fundamental aspect of the Universe is *force*. Pushes and pulls in everyday life come from friction, wind, springs, walls, gravity, motors, muscles and more. At the microscopic level, four forces are enough to model all known interactions between fundamental particles. They are gravity, electromagnetism, and the enigmatically named strong and weak nuclear forces.

Consider gravity. Newton described gravity with his famous 'inverse square' law: any two masses attract each other, with a force that decreases with the square of the distance. Einstein's General Theory of Relativity[13] is a more accurate and more difficult improvement on Newton's theory. In both theories, a quantity

[13] Small bugbear here, but some people talk about Einstein's Theory of General Relativity, not his General Theory of Relativity. The former is incorrect, as it is the theory that is general, not the relativity.

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$$F = -G \frac{M_1 M_2}{r^2}$$

$$R_{\alpha\beta} - \frac{1}{2} R g_{\alpha\beta} = 8\pi G T_{\alpha\beta}$$

FIGURE 5 The gravitational force laws. Newtonian gravity on top and Einstein's version on the bottom. Don't sweat the details; just note that *G* appears in both equations, but cannot be calculated using those equations alone.

known as Newton's gravitational constant appears, which is usually given the symbol G and has a value of 6.67×10^{-11} m^3 kg^{-1} s^{-2} (Figure 5).

If the value of G were different, what would happen? We need to be a bit careful here. Suppose we've transported you to another universe and asked you to measure G. You'll need to calibrate your instruments to measure metres, seconds and kilograms. But wait ... that platinum–iridium lump is back in our Universe! Thankfully, changing G doesn't affect the elements, so we can (in principle!) make what we need. With some caesium 133, you can calibrate your clocks to measure seconds. Measuring the speed of light gives the metre: the distance light travels in 1/299, 792, 458 of a second. We can then construct a replica platinum–iridium lump to give us the kilogram. You can then measure G.

Nothing in Newton's or Einstein's theory tells us the value of G. We have to ask nature, measuring from experiment.[14]

In Newton's theory, if G were twice as large, the gravitational force between masses would be twice as large. In Einstein's deeper understanding of gravity, G measures how strongly mass and energy

[14] If you want to read a tale of dedication and experimental perseverance, you should find an account of how the eighteenth-century scientist Lord Henry Cavendish locked himself away with masses and fine strings to give the first accurate measurement of *G*!

distort the geometry of spacetime (more in Chapter 5). Changing the value of G affects just about everything in astrophysics, from the expansion of the Universe and the formation of galaxies to the size and stability of stars and planets.

Similar constants appear in all of the force laws, where they are called *coupling constants*. The only way we have of knowing the value of these constants is to measure them from nature.

In the next few chapters, we will play the 'what-if' game with particles and forces, revealing just how their properties influence the small and large workings of the Universe.