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.

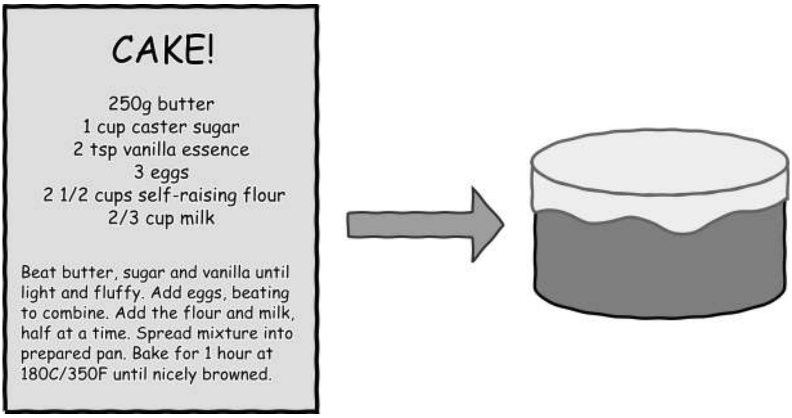

FIGURE 1 A cake recipe illustrates fine-tuning. You can slightly vary the amounts of the ingredients and still make a tasty cake. But deviate too far, add too many extra ingredients, or leave too many ingredients out, and an inedible mess results.

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.

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.

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