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Introduction

1.1 Multiverse Theories and Why to Consider Them

Multiverse theories are physical theories according to which we have empirical access only to a tiny part of reality that may not at all be representative of the whole. According to such theories, the laws of nature are *environmental* in the sense that other parts of reality to which we may not have any causal and empirical access have very different laws – or that there are at least certain aspects of the laws of nature that are very different in those other parts of reality.

Multiverse theories differ on what those other "parts of reality" are. They can, for example, be distant space-time regions that are so far from us that we cannot causally interact with any objects located there. Or they can be distinct "subuniverses" of an overarching collection of separate universes – a "multiverse" perhaps more in the original sense of the word – which have different laws of nature and may not even stand in any spatiotemporal relations to each other. For the purposes of this book, I refer to all types of physical theories according to which reality is in some sense much larger and more diverse than what we have access to as "multiverse theories."

This characterization of multiverse theories is clearly rough and imprecise. But it suffices to make it plausible that theories qualifying as "multiverse theories" in my sense are likely to be interesting from a philosophical point of view. Indeed, they give rise to intriguing epistemological challenges.

To begin with, it seems hard to deny the possibility in principle that a multiverse theory might hold and that the laws of nature in our "universe" (whatever exactly qualifies as such) are environmental in that they may not be representative of the laws across all the many constituent "universes" of the overall multiverse. But since those hypothetical other universes are, by assumption, causally inaccessible to us, we cannot convince ourselves of their existence directly through observations and cannot check this key aspect of those theories empirically. The best we can hope for is to identify aspects of those theories that make them testable by means of observations confined to our own universe and – if those tests are successful – to indirectly infer the existence and properties of the other universes entailed by them with more or less confidence. In this book, I investigate to what degree that hope to make multiverse theories susceptible to such indirect testing is actually realistic.

Why would we possibly want to consider multiverse theories at all if their very testability raises so complicated questions? One influential motivation to consider them is that several aspects of the laws of nature in our universe seem *fine-tuned for life*. Notably, this seems to hold for various features of the form of those laws themselves, for several constants that appear in those laws, and for the global boundary conditions of our universe that characterize its early stages. According to many physicists, had those features of the laws, constants, and boundary conditions been slightly different, life could probably not have existed in our universe, and so we could not have existed in it. In the eyes of many, the fact that we exist despite the fine-tuning of all those parameters cries out for an explanation. The truth of some multiverse theory may provide one.

The core idea of the suggested multiverse explanation of life's existence despite the required fine-tuning is that, if there is a sufficiently diverse multiverse where the parameters (describing the forms of the laws, the constants, and the boundary conditions) differ between universes, it is only to be expected that there are at least some universes where the parameters are right for life. As living organisms, we could not possibly have found ourselves in a universe that fails to be life friendly. This suggests that, under the assumption that there is a sufficiently diverse multiverse, it is neither surprising that there is at least one universe that is hospitable to life nor – since we could not have found ourselves in a life-hostile universe – that we find ourselves in a life-friendly one. Thus, our existence as forms of life, which seems baffling in view of the fine-tuned parameters that are needed for it, no longer seems surprising if we assume that our universe is actually part of a much larger multiverse with diverse environmental parameters.

This suggested inference to the existence of a multiverse as providing the best account of why there is life despite the required fine-tuning will be called the "standard fine-tuning argument for the multiverse" in what follows. I discuss it in detail in later chapters of this book.

But what concrete type of physical multiverse theory might provide us with a multiverse in the sense of the standard fine-tuning argument for a multiverse?

1.2 Types of Multiverse Theories

The simplest type of multiverse theory that could function in the standard fine-tuning argument for the multiverse is one that hypothesizes only a single, connected space-time manifold where certain constants – e.g., Newton's constant – vary over large temporal and/or spatial length scales. If the variation of the constants occurs on time or length scales that are astronomical but that can still be probed by us, this type of theory may not qualify, strictly speaking, as a "multiverse theory" in the present sense. But if the constants that vary across space or time according to it require fine-tuning to be compatible with life, it may nevertheless effectively play the role of a multiverse theory in the standard fine-tuning argument for the multiverse. Inasmuch as such theories are indeed empirically testable, the available evidence does not seem to provide significant support for them [Uzan, 2003].

Another type of multiverse theory that is straightforward to characterize is one according to which there is an ensemble of (real) spatiotemporally unconnected universes, all with laws of the same form as those in our universe but with different values of certain constants. Since the most established theories of modern fundamental[1] physics are the Standard Model of elementary particle physics (combining the electroweak theory and quantum chromodynamics) and general relativity, in such a multiverse, the universes would all be described by those theories, but with masses of elementary particles and interaction constants different in the different universes.

A drawback of this type of multiverse theory is that it has little to no independent motivation over and above the fine-tuning considerations. In contrast, the so-called *landscape multiverse* [Susskind, 2005], which results from combining string theory with certain models of inflationary cosmology, is an independently motivated cosmological scenario. As we will see in what follows, it can make a good claim to count as a multiverse theory in the sense of the standard fine-tuning argument for the multiverse.

1.2.1 Inflationary Cosmology

Inflationary cosmology, originally developed by Guth [2000], is currently the dominant theoretical framework of early-universe cosmology. It states that the very early universe expands (near-) exponentially fast, cooling down by many orders of magnitude, before transitioning to a period of much slower expansion and "reheating." The original motivation for inflationary cosmology was that it promised an explanation of otherwise puzzling cosmic coincidences – namely, the so-called flatness, horizon, and magnetic monopole problems of cosmology [Guth, 1981; Linde, 1982]; see [Guth, 2000] for a review. To appreciate the appeal

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[1] Almost always, when I use the adjective "fundamental" in this book, it is meant in a loose sense, signifying something like "concerning the most basic entities and interactions that we have knowledge of." Except in the book's last chapter, I never use "fundamental" in the more ambitious sense in which one can reasonably ask whether there is an ultimate, fundamental, physical level where the edifice of physical theories "bottoms out."

of inflationary cosmology, it is worth briefly reviewing these problems. (Readers familiar with inflationary cosmology can skip this subsection.)

The flatness problem arises from the observation that the universe today is completely flat (it has zero curvature within the precision of our measurements) on large length scales. This is puzzling because, according to the well-understood dynamics governing the expansion of our universe in the past billions of years, any slight deviation from perfect flatness would have dramatically increased over time. This means that our universe must have been very flat indeed in its very early stages; i.e., it must have started out in some highly nongeneric, “fine-tuned” state of near-perfect flatness.

Inflationary cosmology supposedly solves this problem by resulting in a state with (very near-) zero curvature at its end, independently of how curvature was at its start. The inflationary expansion period, in other words, produces a universe that is so flat that the slower expansion process since inflation, which tended to increase any remaining curvature, has so far not resulted in any measurable deviation from it on large length scales.

The claim that inflation thereby solves the flatness problem is controversial. For example, Hollands and Wald [2002] criticize it by arguing that the universe must occupy a very specific kind of state in order to be at the onset of curvature-erasing inflation. According to this criticism, inflation merely substitutes one “fine-tuning” problem for another and, thus, does not really mean progress with respect to the flatness problem. (The general structure of fine-tuning problems will be discussed in Chapter 2.)

The horizon problem, in turn, arises from the fact that, again on very large length scales, the universe today seems almost completely homogeneous and isotropic. This is puzzling because distant regions that we now observe as having identical large-scale properties have never been in causal contact with each other – at least not if we extrapolate the known (noninflationary) dynamics of the expansion of our universe into the past. But if certain regions of the universe have never been in causal contact with each other, their homogeneity cannot be the result of a joint equilibration process. This makes their homogeneity and isotropy on large length scales at least prima facie very surprising.

Inflationary cosmology supposedly solves this problem by providing a mechanism of how distant regions with identical large-scale properties have been in causal contact after all: if there has been a very early inflationary period, the distant regions were once in causal contact after all, and their observed homogeneity and isotropy raise no great puzzles.

This suggested solution is not without its critics either. Hollands and Wald [2002] raise worries about it that parallel those that they have about inflation’s suggested solution to the flatness problem.

Finally, the magnetic-monopole problem, arises if one assumes that a so-called *grand unified theory* (GUT) obtains, which entails the existence of stable magnetic monopoles. The motivation for such a theory is that it can, in principle, provide an elegant unification of the electroweak theory and quantum chromodynamics similarly to how the electroweak theory itself provids a unified account of electromagnetism and the weak nuclear interaction.

If magnetic monopoles are permitted by the laws of nature, one would expect them to be produced in abundance in the hot very early universe, and their absence from observation is thus puzzling. Inflationary cosmology would, in that case, provide an explanation of that absence because inflation could easily have diluted magnetic monopoles to the point of making them undetectable. The power of this argument for inflationary cosmology depends on how strong one takes the theoretical case for magnetic monopoles based on GUTs to be. In the contemporary theoretical environment, where considerations in favor of GUTs may seem less compelling than in the early 1980s, the argument for inflation based on magnetic monopole abundance may not be regarded as very strong.

As already indicated, it is somewhat controversial whether inflationary cosmology really solves the problems just outlined, which it was originally designed to solve. The question of whether it does so is related to the question of whether conditions that give rise to inflation are rather generic or, in fact, so specific that the challenge to account for why they might have been met seems as large as the explanatory challenge that inflation purportedly helps to address.

As pointed out by Hawking and Page [1988] and elaborated more recently by Shiffrin and Wald [2012], the phase space of general relativity is non-compact. Probabilities over entire space-time histories can only be defined if ambiguities are removed by choosing a regularization procedure. Because of the differences between viable regularization procedures, different accounts of the probability for inflation to happen – e.g., the conflicting ones given in Gibbons et al. [1987] and [Gibbons and Turok, 2008] – come to radically different conclusions regarding how "probable" inflation really is. Correspondingly, they differ on how much postulating an inflationary period can contribute to resolve the horizon and flatness problems.

Nowadays, it is no longer inflationary cosmology's potential to solve the horizon and flatness problems that is widely regarded as its most important attraction. Rather, its ability to make precise and accurate predictions concerning the spectrum of the cosmic microwave background (CMB) fluctuations is now seen as its most important empirical achievement. These fluctuations have recently measured with unprecedented accuracy by the Planck satellite [Planck Collaboration, 2016]. Overall, the observed fluctuation pattern corresponds very well with the predictions derived on the basis of at least some inflationary models [Martin, in press].

As observed by McCoy [2015], it is remarkable that the theory now apparently fares quite well from an empirical point of view even though its original motivation – that it allegedly solves the flatness, horizon, and magnetic monopole problems – is now no longer widely viewed as compelling.

Indeed, there is also some debate on how compelling the support really is that inflationary cosmology derives from its successful prediction of the observed CMB fluctuations pattern. Notably, it has been argued that certain noninflationary models of cyclic cosmology are just as good in predicting that pattern [Lehners and Steinhardt, 2013]. But the majority view seems to be that at least some inflationary models are superior in this respect [Linde, 2014].

If there really was a period of rapid inflation in the very early universe, what might have been the mechanism that drove it? According to most models of inflation, one or more scalar fields, the so-called inflaton(s), are the most likely culprits.

There has been some debate on whether the Higgs boson, which is responsible for the masses of several particles in the Standard Model of elementary particles, might be the inflaton. But in most models of inflation, the inflaton field is distinct from any known particle and only identified by its role in generating an inflationary period. In other words, in most models of inflation, as driven by an inflaton, the inflaton field must be postulated to fulfill precisely that purpose and has no independent motivation.

The predictive and explanatory successes of inflationary cosmology – which, as just outlined, may come with certain caveats – provide one of the main reaons for taking multiverse theories seriously. The reason is that, according to many inflaton models, notably ones in which the potential of the inflaton field depends quadratically on the field strength, island universe formation is globally "eternal." When it comes to an end, it does so only locally, resulting in the formation of a causally isolated space-time region that effectively behaves as an "island universe." This process of continuing island universe formation never stops. As a result of it, a vast (and, according to most models, infinite) "multiverse" of island universes is continually being produced [Guth, 1981].

Inflationary cosmology as a general framework should not be equated with eternal inflation. Notably, there are empirically viable inflaton models according to which the inflationary period globally does come to an end [Mukhanov, 2015], [Martin, in press, Sect. 7C]. As we will soon see, though, the idea of inflation being eternal gets further support and attraction when one adds string theory to the picture. Doing so also brings into play a natural way in which the laws of nature might be effectively different in the different island universes, yielding an actual multiverse scenario.

1.2.2 String Theory

String theory is one of the leading approaches – perhaps still *the* leading approach – to unify our best current theories of particle physics as collected in the Standard Model of elementary particle physics and Einstein's theory of general relativity. The objects that the theory posits are one-dimensional objects called "strings" and various higher-dimensional analogs commonly referred to as "branes." Particles that are familiar from elementary particle physics are recovered as excitation modes of strings as they appear to an observer who lacks an apparatus with the resolution required to resolve the string structure.

In order to have the potential to be empirically viable, string theory must be considered in a version that includes *supersymmetry*. According to the idea of supersymmetry, the two main types of particles, fermions and bosons, are connected by a symmetry operation in the mathematical sense – "supersymmetry" – that can be regarded as a generalization of the familiar space-time symmetries such as invariance of the laws under spatial rotations. If supersymmetry holds, each fermionic particle has a bosonic counterpart with otherwise very similar properties, and vice versa. However, no supersymmetric partners of particles known to exist have been found in any collider experiments yet: there is not a single fermion or boson, for which a candidate partner particle has been detected. It follows that the partner particles, if they exist, must have considerably higher masses than the known particles. This means that supersymmetry must be *broken* by some hitherto unknown mechanism that makes it undectable at so far accessible energy scales.

There is an independent line of reasoning in favor of supersymmetry, based on the concept of *naturalness*, which is reviewed in Section 2.2.2. Mainly based on the idea that the fundamental physical theories should be "natural" in the somewhat technical sense to be elucidated there, it was widely expected until some years ago that supersymmetric partner particles would soon be found in collider experiments. But this has not happened, and the failure to discover any direct evidence in favor of supersymmetry is now more and more widely seen as pointing to shortcomings of the naturalness criterion and, more specifically, a blow to the attractiveness of string theory, whose viability depends on supersymmetry being realized.

One of the most important arguments in favor of string theory is the *no alternatives argument*, formally developed by Dawid et al. [2015] and spelled out in detail in Dawid [2013]. Beyond motivating string theory as a potential unification of elementary particle physics and gravity, it observes that there are few, if any, serious *alternative* theories that offer the same potential for unification while being empirically adequate, and it concludes that this provides at least some degree of support for string theory. The no alternatives argument remains controversial, however, in particular, because it is doubtful whether we can ever have a sufficient overview of the space of theoretical possibilities, including hypothetical alternatives to string theory, to make such strong conclusions.

Another argument for string theory refers to the unexpected coherence of different theoretical paths to it that were originally regarded as independent of each other. Several ostensibly different and competing string theories were pursued until 1995. At that time, it became clear that these theories are connected by so-called *dualities*, which means that they can be mapped onto each others in a way that reveals their physical equivalence. Another important duality discovery is that of *Anti–de Sitter/conformal field theory* (AdS/CFT) duality. Exploiting this duality helps make the physical consequences of string theory more transparent, and it has found widespread applications in physics far beyond string theory.

String theory has some specific physical consequences, which are, in principle, empirically testable: notably, it entails "stringy" features of reality, which would become empirically manifest at very high energies close to the Planck scale (about 13 orders of magnitude larger than energies accessible at present-day colliders). The familiar phenomenology of "particles" in present-day high-energy physics is only an "effective" low-energy phenomenon from the string theoretic perspective.

Another consequence of string theory is that space-time has to be 10-dimensional for its supersymmetric version to be compatible with massive particles. Since space-time is manifestly *not* 10-dimensional at the level of our experiences, one must assume that six of the nine spatial dimensions are effectively "compactified" at short spatial length scales. From a theoretical point of view, this is entirely conceivable. So-called *Calabi-Yau manifolds* offer a variety of ways in which the spatial extra dimensions entailed by string theory might in principle be compactified.

String theory is now believed to harbor an enormous amount of lowest-energy states, so-called *vacua*. Already in the 1980s, the number of such vacua was found to be very large [Lerche et al., 1987], and it has since been estimated to be of an order of magnitude comparable to 10^{500} [Bousso and Polchinski, 2000]. At the level of human-scale observations and experiments, the specific properties of these different vacua would manifest themselves in terms of different parameters – i.e., different higher level physical laws and different values of the constants. That there are string theory vacua with small positive cosmological constants, as actually observed, was argued by Kachru et al. [2003] and seems now widely accepted.[2]

The plurality of effective low-energy laws to which string theory gives rise makes it very difficult to extract concrete empirical consequences from the theory.

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[2] I would like to thank George Ellis for alerting me of the Kachru et al. [2003] paper and for sharing his critical perspective on the viability of the mechanism it suggests.

This makes string theory hard to test, and this has led some researchers to speak of a methodological crisis in fundamental physics [Smolin, 2006; Woit, 2006]. That string theory is now often considered in a multiverse setting, combined with eternal inflation, does not appease those critics, on the contrary.

1.2.3 The Landscape Multiverse

Eternal inflation and string theory are independent of each other: it may well be the case that one of those two theoretical ideas is realized while the other is not.

However, *if* one assumes that string theory holds in combination with some scenario of inflationary cosmology, then it seems natural to expect that the inflationary period will be eternal. At least somewhere, a metastable inflating state may initially be realized in the inflating cosmos that happens to decay into noninflating states forming island universes at decay rates that are smaller than the inflating state's own expansion rate. If that is the case, the expansion of the metastable inflating state globally never stops despite the ongoing "bubble formation" of island universes, which in turn continues indefinitely.

A cosmological setting in which string theory holds in combination with inflation being eternal may potentially give us a concrete instantiation of the general multiverse idea as outlined earlier. For if there are indeed infinitely many island universes, as entailed by eternal inflation, then all the different string theory vacua – corresponding to different higher-level physical laws and constants – might actually be realized in them. To make this scenario credible, a physical mechanism would be needed, which accounts for why and how different string theory vacua would be realized in the different island universes. If some such mechanism indeed exists and, as is widely believed, this landscape multiverse includes a universe with the same higher-level laws and constants as our own, it is a candidate multiverse scenario in the sense of the argument for a multiverse from fine-tuning for life.

With the combination of eternal inflation and string theory in form of the landscape multiverse, we have a concrete multiverse scenario with independently motivated pillars – i.e., a concrete candidate multiverse "theory." This underlines the pressing need to obtain a clearer perspective on the empirical testability of such theories. That need appears even more urgent in view of the fact that it seems doubtful whether the independent empirical motivation of inflationary cosmology through the CMB data and possibly the response to the flatness and horizon problems survive the shift to a multiverse setting. Ijjas et al. [2013] argue that the independent empirical motivation of inflationary cosmology, which they do not regard as compelling in view of the data from the Planck satellite (see Planck Collaboration [2016] for the most recent edition) anyway, breaks down completely when the shift to a multiverse setting is made. In Ijjas et al. [2017], they outline the gist of their worry about inflation being eternal as follows:

> The worrisome implication [of eternal inflation] is that the cosmological properties of each patch [i.e., island universe] differ because of the inherent randomizing effect of quantum fluctuations. In general, most universes will not turn out warp-free or flat; the distribution of matter will not be nearly smooth; and the pattern of hot and cold spots in the CMB light there will not be nearly scale-invariant. The patches span an infinite number of different possible outcomes, with no kind of patch, including one like our visible universe, being more probable than another. The result is what cosmologists call the multiverse. Because every patch can have any physically conceivable properties, the multiverse does not explain why our universe has the very special conditions that we observe – they are purely accidental features of our particular patch. [Ijjas et al., 2013, pp. 38f.]

According to the 33 authors of a letter [Guth et al., 2017] replying to Ijjas, Steinhardt, and Loeb, the prospects for testing – and ultimately confirming – inflationary cosmology are not nearly as bad as portrayed by the three. We do not have to come to a verdict on that debate in the present context. Clearly, to the degree that specific models of inflation portray it as eternal and leading to a proliferation of island universes, the empirical consequences of inflation must be assessed in the light of this feature.

As explained earlier, due to the proliferation of vacua in the string theory “landscape,” the prospects for obtaining any empirical evidence for or against string theory seem independently rather bleak. It would be excellent if that situation could be improved by determining a workable strategy for extracting concrete empirical predictions from multiverse theories such as the landscape multiverse.

1.2.4 Multiverses beyond the Landscape Multiverse

The landscape multiverse scenario is not the only concrete multiverse theory that is seriously considered by at least some physicists. There is a long tradition of cyclic cosmological models that can be seen as proposing multiverse scenarios. These models portray the universe as undergoing many – according to some models, infinitely many – consecutive expansion and contraction cycles, and in some of those models, the parameters characterizing the laws of nature change between cycles. Cyclic cosmologies were popular for a while in the early twentieth century, before Tolman [1934] influentially argued that they are incompatible with basic thermodynamics. Cyclic models have more recently experienced a revival in cyclic brane cosmology, which – like the landscape multiverse – is based on string theory and was developed by Steinhardt and Turok [2001] (see Steinhardt and Turok [2008] for a popular exposition), and in the cyclic model by Baum and Frampton [2007]. Greene [2011, chapters 3–5] provides an accessible popular overview of both the landscape and cyclic multiverse scenarios.

Cosmologist Max Tegmark proposes a categorization of multiverse scenarios into various "levels," which go beyond the level of the cosmological multiverse just discussed. In Tegmark's scheme, the level I multiverse is an infinite extension of the space-time region to which we have causal access. It is not really a multiverse scenario in the sense of the characterization given before because the laws and constants are assumed to be uniform in it.

Tegmark's level II multiverse is a collection of (real) level I multiverses – i.e., different infinite universes – now with different constants and different higher-level physical laws. The landscape multiverse and the cyclic multiverse scenarios just mentioned are level II–type multiverses in Tegmark's sense. Another level II–type multiverse would be one where the Standard Model of elementary particle physics holds in all universes.

Tegmark endorses the Everett interpretation of quantum theory, according to which physical reality is completely described by a universal quantum state. This state undergoes perpetual "branching" into contributions that show almost no mutual inference and effectively function as different "worlds." The totality of the different branches in Everettian quantum theory is Tegmark's level III multiverse.

Tegmark's enthusiasm for multiverse scenarios even extends to an additional, level IV, multiverse, which consists of all *mathematical structures*. Tegmark argues that these are not only mathematically real but also physically real and exist as universes that can be seen as together forming an overarching multiverse, which goes far beyond the level II and III multiverses. As I argue in the penultimate chapter of this book, to the extent that more radical multiverse proposals such as Tegmark's level III and IV multiverse and the philosopher David Lewis's multiverse of *possible worlds* are coherent at all, they cannot be reasonably believed by someone who takes them entirely seriously.

1.3 Overview of This Book

The structure of the remaining chapters of this book is as follows: Chapter 2 reviews the considerations in the physics literature according to which many aspects of the laws, constants, and boundary conditions seem fine-tuned for life as well as criticisms of those considerations. There have been debates about which notion of probability might be best suited to underwrite the claim that fine-tuned parameters are somehow "improbable." Ultimately, the most promising candidate notion of probability to underwrite the claim that life-friendly parameters are "improbable" turns out to be subjective probability, assigned from the perspective of an agent who temporarily abstracts from her knowledge that the parameters have the values that they happen to have.

Chapter 3 discusses a popular alternative response to the finding that many parameters require fine-tuning for life – namely, the inference to some divine designer or God. This response is interesting in itself, and investigating it is an ideal training ground for the discussion of the fine-tuning argument for the multiverse in later chapters. The core idea of the fine-tuning argument for a designer is that a cosmic designer, assuming she/he exists, might for some reason welcome the existence of life and would therefore *set* the parameters as life friendly (something, a further assumption goes, that she is capable of). I discuss how to best formulate this suggested inference from fine-tuning to a designer and consider some objections.

The chief difficulty for the fine-tuning argument for a divine designer, as I argue, is that there are various mutually incompatible versions of the designer hypothesis – some featuring an anthropomorphic designer, others a more abstract one who bears little resemblance to the living organisms we are familiar with. When we consider the latter versions, it seems difficult to see why – and in which sense in the first place – a designer who is so radically unlike any being we are familiar with would favor the existence of life at all and how we could possibly predict his/her "behavior" with some confidence. On a version of the designer hypothesis that features a more anthropomorphic designer, in contrast – here, one might think of a designer along the lines of those encountered in traditional religions – the preferences and actions of the designer may be easy to understand and predict. Unfortunately, such versions of the designer hypothesis are arguably discredited in our post-Darwinian scientific environment and do not deserve serious consideration in the first place. I conclude that inference to a divine designer is probably not an attractive response to the considerations according to which life requires fine-tuning.

Chapter 4 turns to the standard argument from fine-tuning for life to a multiverse as outlined in Section 1.1. This argument, as remarked, centers around the statement that if there is a sufficiently diverse multiverse where the parameters differ between universes, it is no longer surprising that we, as living organisms, exist despite the fine-tuning of the parameters that this requires.

There is a much-discussed objection against the inference from fine-tuning to a multiverse suggested by this argument, namely, that it commits the so-called *inverse gambler's fallacy*: inferring from the existence of one remarkable outcome – in this case, a life-friendly universe – that there are likely many other events – in this case, other universes – most of them with much less remarkable outcomes. To determine whether the inference from fine-tuning to a multiverse really commits this fallacy, I discuss a variety of examples that are structurally similar to the fine-tuned universe and in which it is uncontroversial whether the inverse gambler's fallacy is committed by reasoning that mirrors the fine-tuning argument for the multiverse. In the end, it turns out to be impossible to either affirm or reject the inverse gambler's fallacy charge against the fine-tuning argument for the multiverse. The analogies are either too imperfect or beset by the same ambiguities as the fine-tuned universe. I conclude the chapter by putting forward the suspicion that established standards of rationality may just not determine at all whether the inference from fine-tuning to a multiverse commits the inverse gambler's fallacy or not.

Chapter 5 reformulates the standard fine-tuning argument for the multiverse using the Bayesian language of subjective probabilities. Use of this language allows us to state and address a worry put forward by Juhl [2007]: that belief in some multiverse theory based on the standard fine-tuning argument for the multiverse would inevitably be based on fallacious *double counting* of the fine-tuning evidence. The Bayesian formalism also allows us a fresh look at why it is so difficult to determine whether the standard fine-tuning argument for the multiverse is fallacious or not. As it turns out, that difficulty turns on an ambiguity that relates to the fact that it has been left unclear against which kind of background knowledge the evidence that the parameters are right for life is assessed.

Chapter 6 proposes an alternative, *new* fine-tuning argument for the multiverse, which is by construction structurally immune to the inverse gambler's fallacy charge. The new argument takes a leaf from classic instances of so-called *anthropic* reasoning, as influentially championed by astrophysicists Robert Dicke and Brandon Carter in their accounts of certain *large number coincidences* in cosmology. Since one of Carter's "anthropic principles" is often invoked in expositions of the standard argument from fine-tuning for the multiverse, Dicke/Carter-type anthropic reasoning and the fine-tuning argument for the multiverse are sometimes viewed as instances of the same type of reasoning. But, as it turns out, there is a profound difference between the two in that the fact that we exist (as forms of life) is used as background knowledge in Dicke/Carter-style reasoning, whereas it is used as the evidence whose significance is assessed in the standard fine-tuning argument for the multiverse.

The basic idea of the new fine-tuning argument for the multiverse is that the fine-tuning considerations contribute to a partial erosion of the main theoretical advantage that empirically adequate single-universe theories tend to have over empirically adequate multiverse theories: namely, that their empirical consequences are far more specific. If the parameters require fine-tuning to be compatible with the (long-known) existence of life, this means that all living organisms can only observe very specific values, whether there is only a single universe or a multiverse. It is then no longer a very specific achievement of empirically viable single-universe theories that they correctly predict those values. As a consequence, empirically viable single-universe theories become comparatively less attractive when compared with empirically viable multiverse theories, provided that the fine-tuning considerations do not, along other lines, make belief in a multiverse less attractive.

Chapter 7 finally turns to the prospects for empirically testing specific cosmological multiverse theories such as the landscape multiverse scenario or cyclic multiverse models. The most commonly pursued strategy to extract concrete empirical consequences from specific multiverse theories is to regard them as predicting what "typical" multiverse inhabitants observe if the theories are correct, where "typical" is spelled out as "randomly selected from some suitably chosen reference class." Bostrom [2002] influentially dubbed this principle the *self-sampling assumption*. I scrutinize a proposal by Srednicki and Hartle to treat the self-sampling assumption and the reference class to which it is applied as matters of empirical fact that are themselves amenable to empirical tests. Unfortunately, this proposal turns out to be incoherent.

A much better idea, which coheres well with the intuitive motivation for the self-sampling assumption, is that we should make this assumption with respect to some reference class of observers precisely if our background information is consistent with us being any of those observers and neutral between them. I call this principle the *background information constraint* (BIC) and point out that it at least formally solves the problem of selecting the appropriate observer reference class.

As discussed in Chapter 8, however, applying the BIC in practice is far from straightforward and fraught with difficulties because it requires the regularization of space-time infinities by implementing some cosmic "measure." Furthermore, a suitable physical quantity must be chosen as proxy for the number of reference class observers in some given space-time region. Unfortunately, the choices made by the researchers in this procedure are prone to being exploited – often unintentionally – by the researchers as so-called *researcher degrees of freedom* (this is a term from the social science literature) to yield those results that would best conform to the researchers' theoretical preferences. In the light of this difficulty, the prospects for obtaining compelling evidence in favor of any specific multiverse theory by testing whether our observations are those that typical multiverse inhabitants would make do look bad. As it turns out, the multiverse theories that have the best chances of being successfully tested empirically are those that do not behave as typical multiverse theories in important respects – i.e., those according to which all universes are similar or identical in empirically testable ways.

Chapter 9 starts with the observation that the self-sampling assumption can be seen as an *indifference principle of self-locating belief*: it instructs us to treat all the possibilities who we might be in the reference class of observers as equally likely. Indifference principles of self-locating belief are regarded as suspect by some philosophers, however, because they appear to have paradoxical consequences when applied to certain intensely discussed problems of self-locating belief. Notably, an indifference principle of self-locating belief is usually appealed to in the notorious *Doomsday Argument*, and it also plays a role in the derivation of apparent *anomalous causal powers* in Nick Bostrom's *Adam and Eve* thought experiments. The recommendation that we should sometimes act as if there were anomalous causal powers seems very hard to accept. I show that reasoning akin to that used in the

Doomsday Argument and in the Adam and Eve thought experiments leads to a similar recommendation in a version of the famous *Sleeping Beauty* problem.

All these unattractive recommendations can be avoided if, as required by the BIC, one pays careful attention to the background evidence based on which one assigns probabilities to competing hypotheses and chooses the observer reference class in accordance with that background evidence. I also show that, if one adopts this strategy, one can avoid the unattractive view that the Everett interpretation of quantum theory is confirmed by arbitrary empirical data.

The Everett interpretation is discussed in more detail in Chapter 10, which is also devoted to Tegmark's level IV multiverse of mathematical structures and the multiverse of possible worlds in David Lewis's modal realism.

I discuss the motivation of the Everett interpretation as a possible solution to the foundational problems of quantum theory that allows one to preserve the formalism of the theory without making any amendments or adjustments while being a realist about fundamental physics. The Everett interpretation presents quantum theory as a multiverse theory inasmuch as it postulates many "branches" of reality that supposedly are created by the quantum process of decoherence. It is doubtful, however, whether the appeal to decoherence suffices for the Everettian to identify branches as intended in the absence of a compelling solution to the problem of explaining why quantum probabilities function as self-locating credences in the Everettian multiverse as they do according to the Everettian. I address some suggested solutions to this probability problem – in particular, a recent proposal by Sebens and Carroll [2018] that has received significant attention – and find them wanting.

In the discussion of David Lewis's modal realism, I focus on an old objection against it: that serious belief in it would commit one to inductive skepticism. I argue that, in defending his position against this objection, Lewis unfairly shifts the burden of proof to the proponents of the objection. His thesis entails the existence of epistemic agents for whom inductive inferences will often and radically fail, and the onus is on him to demonstrate that, if his theory is true, we could nevertheless be rationally confident to not be among those agents.

Max Tegmark's thesis that there is a level IV multiverse of mathematical structures, which are all physically realized, hinges on the truth of his *mathematical universe thesis*. According to that thesis, our universe is, itself, a mathematical structure. I argue that this mathematical universe thesis is incoherent because it does not allow us to do justice to important distinctions about which quantities in physical theories do have objective physical significance and which are "surplus formal structure" – e.g., the gauge degrees of freedom in the vector potential formulation of electrodynamics. This undermines Tegmark's case for a level IV multiverse.

The book concludes in Chapter 11 with some reflections on the future of physics in the light of the possibility that we may never be able to, on the one hand, discard multiverse theories as pseudoscience nor, on the other hand, obtain compelling evidence in favor of some multiverse theory or against *any* multiverse theory tout court. What does the future of physics hold if we never find out whether there are other universes with different parameters? I argue that this possibility must be seriously considered: our knowledge of physics "at large" – just as our knowledge of physics "at small" – may forever be limited.

1.4 At a Glance: Some Theses Defended in This Book

The problem of obtaining evidence for or against specific multiverse theories is the central theme of this book. Its central thesis is that there are good reasons for taking multiverse theories seriously, but we may never know if any of them are correct and that this may impede further progress in physics. The more specific stepstone theses argued for while circling around the book's central theme and thesis include the following:

- The fine-tuning argument for a divine designer suffers from the dilemma of having to choose between an anthropomorphic or non-anthropomorphic designer hypothesis. For a non-anthropomorphic designer, the argument is not cogent because the actions of superagents that radically differ from agents with whom we are familiar are impossible to predict; for an anthropomorphic designer, the hypothesis lacks basic scientific credibility.
- Established standards of rationality may not suffice to determine whether the standard fine-tuning argument for a multiverse commits the inverse gambler's fallacy or not.
- A new fine-tuning argument for the multiverse can be formulated, which is structurally similar to the Carter/Dicke anthropic accounts of large number coincidences. That argument is not susceptible to the inverse gambler's fallacy charge, but it requires an independently attractive, empirically viable specific multiverse theory in order to result in rational high degree of belief in a multiverse.
- The observer reference class in cosmology should be chosen in such a way that it includes precisely those observers who we could possibly be, given the background knowledge against which we assess the evidential significance of our observations.
- Derivations of concrete empirical consequences from specific multiverse theories are prone to suffer from confirmation bias. In order to extract such predictions, choices have to be made for which there is no determinately right or wrong option, for instance, concerning the cosmic measure to be used or the physical quantity

used as a proxy for observer number in a given space-time region. This results in so-called researcher degrees of freedom, which researchers are likely to exploit, often unintentionally, in order to obtain results that conform to their theoretical preferences. This problem unavoidably leads to opportunities for confirmation bias to manifest itself, which makes any claimed successful predictions from specific multiverse theories untrustworthy.

- Puzzles of self-locating belief can be resolved by paying attention to the background evidence based on which prior probabilities are assigned and the observer reference class is chosen. Notably, that reference class should be chosen in such a way that it includes every observer that the epistemic agent at issue could possibly be inasmuch as she/he has that background evidence.
- Suggested solutions to the probability problem in Everettian quantum theory are unconvincing. A recent proposal by Sebens and Carroll to derive the Born rule in the Everettian framework using considerations about self-locating belief turns out to suffer from a circularity problem because the central principle on which the derivation is based has no independent motivation beside appeal to the Born rule itself.
- It is not possible to coherently, in full seriousness, believe David Lewis's modal realism. Nor is it possible to coherently believe Max Tegmark's thesis that there is a multiverse of all mathematical structures in which they are physically realized. Tegmark's claim that our universe is itself a *mathematical structure* is found to be incoherent.

All the theses are of independent interest over and above the role that they play, if any, in preparing the ground for the central thesis of the book. Certain aspects of their meaning and their significance become clear only in the context of the arguments that I offer for them in the chapters that follow. So, without further ado, let us jump into those chapters.