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Part I

Setting the Stage

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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."

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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.

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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,

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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.

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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