# UNIVERSE OR MULTIVERSE?

*Edited by*

BERNARD CARR

CAMBRIDGE
UNIVERSITY PRESS

# Contents

# 1

# Introduction and overview

Bernard Carr
*Astronomy Unit, Queen Mary, University of London*

## 1.1 Introducing the multiverse

Nearly thirty years ago I wrote an article in the journal *nature* with Martin Rees [1], bringing together all of the known constraints on the physical characteristics of the Universe – including the fine-tunings of the physical constants – which seemed to be necessary for the emergence of life. Such constraints had been dubbed 'anthropic' by Brandon Carter [2] – after the Greek word for 'man' – although it is now appreciated that this is a misnomer, since there is no reason to associate the fine-tunings with mankind in particular. We considered both the 'weak' anthropic principle – which accepts the laws of nature and physical constants as given and claims that the existence of observers then imposes a selection effect on where and when we observe the Universe – and the 'strong' anthropic principle – which (in the sense we used the term) suggests that the existence of observers imposes constraints on the physical constants themselves.

Anthropic claims – at least in their strong form – were regarded with a certain amount of disdain by physicists at the time, and in some quarters they still are. Although we took the view that any sort of explanation for the observed fine-tunings was better than none, many regarded anthropic arguments as going beyond legitimate science. The fact that some people of a theological disposition interpreted the claims as evidence for a Creator – attributing teleological significance to the strong anthropic principle – perhaps enhanced that reaction. However, attitudes have changed considerably since then. This is not so much because the status of the anthropic arguments themselves have changed – as we will see in a later chapter, some of them have become firmer and others weaker. Rather, it is because there has been a fundamental shift in the epistemological status of the anthropic principle. This arises because cosmologists have come to realize that there are many

*Universe or Multiverse?*, ed. Bernard Carr. Published by Cambridge University Press.

contexts in which our universe could be just one of a (possibly infinite) ensemble of 'parallel' universes in which the physical constants vary. This ensemble is sometimes described as a 'multiverse', and this term is used pervasively in this volume (including the title). However, it must be stressed that many other terms are used – sometimes even in the same context.

These multiverse proposals have not generally been motivated by an attempt to explain the anthropic fine-tunings; most of them have arisen independently out of developments in cosmology and particle physics. Nevertheless, it now seems clear that the two concepts are inherently interlinked. For if there *are* many universes, this begs the question of why we inhabit this particular one, and – at the very least – one would have to concede that our own existence is a relevant selection effect. Indeed, since we necessarily reside in one of the life-conducive universes, the multiverse picture reduces the strong anthropic principle to an aspect of the weak one. For this reason, many physicists would regard the multiverse proposal as providing the most natural explanation of the anthropic fine-tunings.

One reason that the multiverse proposal is now popular is that it seems to be necessary in order to understand the origin of the Universe. Admittedly, cosmologists have widely differing views on how the different worlds might arise. Some invoke models in which our universe undergoes cycles of expansion and recollapse, with the constants being changed at each bounce [3]. In this case, the different universes are strung out in *time.* Others invoke the 'inflationary' scenario [4], in which our observable domain is part of a single 'bubble' which underwent an extra-fast expansion phase at some early time. There are many other bubbles, each with different laws of low-energy physics, so in this case the different universes are spread out in *space.* As a variant of this idea, Andrei Linde [5] and Alex Vilenkin [6] have invoked 'eternal' inflation, in which each universe is continually self-reproducing, since this predicts that there may be an infinite number of domains – all with different coupling constants. The different universes then extend in *both* space and time.

On the other hand, Stephen Hawking prefers a quantum cosmological explanation for the Universe and has objected to eternal inflation on the grounds that it extends to the infinite past and is thus incompatible with the Hartle–Hawking 'no boundary' proposal for the origin of the Universe [7]. This requires that the Universe started at a finite time but the initial singularity of the classical model is regularized by requiring time to become imaginary there. If one uses the path integral approach to calculate the probability of a particular history, this appears to favour very few expansion $e$-folds, so the Universe would recollapse too quickly for life to arise.

However, anthropic selection can salvage this, since one only considers histories containing observers [8].

This sort of approach to quantum cosmology only makes sense within the context of the 'many worlds' interpretation of quantum mechanics. This interpretation was suggested by Hugh Everett [9] in the 1950s in order to avoid having to invoke collapse of the quantum mechanical wave-function, an essential feature of the standard Copenhagen interpretation. Instead, our universe is supposed to split every time an observation is made, so one rapidly generates a huge number of parallel worlds [10]. This could be regarded as the earliest multiverse theory. Although one might want to distinguish between classical and quantum multiverses, Max Tegmark [11] has emphasized that there is no fundamental distinction between them.

Quantum theory, of course, originated out of attempts to explain the behaviour of matter on small scales. Recent developments in particle physics have led to the popularity of yet another type of multiverse. The holy grail of particle physics is to find a 'Theory of Everything' (TOE) which unifies all the known forces of physics. Models which unify the weak, strong and electomagnetic interactions are commonly described as 'Grand Unified Theories' (GUTs) and – although still unverified experimentally – have been around for nearly 30 years. Incorporating gravity into this unification has proved more difficult, but recently there have been exciting strides, with superstring theory being the currently favoured model.[1] There are various versions of superstring theory but they are amalgamated in what is termed 'M-theory'.

Unlike the 'Standard Model', which excludes gravity and contains several dozen free parameters, M-theory might conceivably predict all the fundamental constants uniquely [12]. That at least has been the hope. However, recent developments suggest that this may not be the case and that the number of theories (i.e. vacuum states) could be enormous (for example $10^{500}$ [13]). This is sometimes described as the 'string landscape' scenario [14]. In this case, the dream that all the constants are uniquely determined would be dashed. There would be a huge number of possible universes (corresponding to different minima of the vacuum energy) and the values of the physical constants would be *contingent* (i.e. dependent on which universe we happen to occupy). Trying to predict the values of the constants would then be

---

[1] String theory posits that the fundamental constituents of matter are string-like rather than point-like, with the various types of elementary particle corresponding to different excitation states of these strings. This was originally proposed as a model of strong interactions but in the 1980s it was realized that it could be extended to a version called 'superstring' theory, which also includes gravity.

as forlorn as Kepler's attempts to predict the spacing of the planets in our solar system based on the properties of Platonic solids.

A crucial feature of the string landscape proposal is that the vacuum energy would be manifested as what is termed a 'cosmological constant'. This is a term in the field equations of General Relativity (denoted by $\Lambda$) originally introduced by Einstein to allow a static cosmological model but then rejected after the Universe was found to be expanding. For many subsequent decades cosmologists assumed $\Lambda$ was zero, without understanding why, but a remarkable recent development has been the discovery that the expansion of the Universe is accelerating under the influence of (what at least masquerades as) a cosmological constant. One possibility is that $\Lambda$ arises through quantum vacuum effects. We do not know how to calculate these, but the most natural value would be the Planck density (which is 120 orders of magnitude larger than the observed value). Indeed in the string landscape proposal, one might expect the value of $\Lambda$ across the different universes to have a uniform distribution, ranging from minus to plus the Planck value. The observed value therefore seems implausibly small.

There is also another fine-tuning problem, in that the observed vacuum density is currently very similar to the matter density, a coincidence which would only apply at a particular cosmological epoch. However, as first pointed out by Steven Weinberg [15, 16], the value of $\Lambda$ is constrained anthropically because galaxies could not form if it were much larger than observed. This is not the only possible explanation for the smallness of $\Lambda$, but there is a reluctant acceptance that it may be the most plausible one, which is why both string landscape and anthropic ideas are rather popular at present. The crucial issue of whether the number of vacuum states is sufficiently large and their spacing sufficiently small to satisfy the anthropic constraints is still unresolved.

It should be noted that M-theory requires there to be extra dimensions beyond the four familiar ones of space and time. Some of these may be compactified, but others may be extended, in which case, the Universe would correspond to a 4-dimensional 'brane' in a higher-dimensional 'bulk' [17, 18]. In the first versions of this theory, the cosmological constant was negative, which was incompatible with the observed acceleration of the Universe. A few years ago, however, it was realized that M-theory solutions with a positive cosmological constant are also possible [19], and this has revitalized the collaboration between cosmologists and string theorists. The notion that our universe is a brane in a higher-dimensional bulk also suggests another multiverse scenario, since there might be many other branes in the bulk. Collisions between these branes might even generate big bangs of the kind which initiated the expansion of our own universe [20]. Indeed, some people have envisaged successive collisions producing cyclic models, and it has been claimed that this could provide another (non-anthropic) explanation for why $\Lambda$ naturally tends to a value comparable to the matter density [21].

## 1.2 Historical perspective

We have seen how a confluence of developments in cosmology and particle physics has led to a dramatic improvement in the credibility of the multiverse proposal. In this section, we will put these developments into a historical perspective, by showing how the notion of the multiverse is just the culmination of attempts to understand the physics of the largest and smallest scales. For what we regard as the 'Universe' has constantly changed as scientific progress has extended observations outwards to ever larger scales and inwards to ever smaller ones. In the process, it has constantly revealed new levels of structure in the world, as well as interesting connections between the laws operating at these different levels. This section will also provide an opportunity to review some of the basic ideas of modern cosmology and particle physics, which may be useful for non-specialists.

### *1.2.1 The outward journey*

#### *Geocentric view*

Early humans assumed that the Earth was the centre of the Universe. Astronomical events were interpreted as being much closer than they actually are, because the heavens were assumed to be the domain of the divine and therefore perfect and unchanging. The Greeks, for example, believed the Earth was at the centre of a series of 'crystal spheres', these becoming progressively more perfect as one moves outwards. The last one was associated with the immovable stars, so transient phenomena (like meteors and comets) were assumed to be of terrestrial origin. Even the laws of nature (such as the regularity of the seasons) seemed to be human-centred, in the sense that they could be exploited for our own purposes, so it was natural to regard them as a direct testimony to our central role in the world.

#### *Heliocentric view*

In 1542 Nicolaus Copernicus argued in *De Revolutionis Orbis* that the heliocentric picture provides a simpler explanation of planetary motions than the geocentric one, thereby removing the Earth from the centre of the Universe. The heliocentric picture had earlier been suggested by Artistarchus, although this was regarded as blasphemous by most of his fellow Greeks, and Nicholas de Cusa, who in 1444 argued that the Universe had no centre and looks the same everywhere. Today this notion is called the Copernican or Cosmological Principle. Then in 1572 Tycho Brahe spotted a supernova in the constellation of Cassiopeia; it brightened suddenly and then dimmed over the course of a year, but the fact that its apparent position did not change as the Earth moved around the Sun implied that it was well beyond the Moon. Because this destroyed the Aristotelian view that the heavens never change, the claim was at first received sceptically. Frustrated by those who had eyes but would not see, Brahe wrote in the preface of *De Nova Stella*: 'O crassa ingenia. O coecos coeli spectators.' (Oh thick wits. Oh blind watchers of the sky.)

### *Galactocentric view*

The next step occurred when Galileo Galilei used the newly invented telescope to show that not even the Sun is special. His observations of sunspots showed that it changes, and in 1610 he speculated in *The Sidereal Message* that the Milky Way – then known as a band of light in the sky but now known to be the Galaxy – consists of stars like the Sun but at such a great distance that they cannot be resolved. This not only cast doubt on the heliocentric view, but also vastly increased the size of the Universe. An equally profound shift in our view of the Universe came a few decades later with Isaac Newton's discovery of universal gravity. By linking astronomical phenomena to those on Earth, Newton removed the special status of the heavens, and the publication of his *Principia* in 1687 led to the 'mechanistic' view in which the Universe is regarded as a giant machine. In the following century, the development of more powerful telescopes – coupled with Newton's laws – enabled astronomers to understand the structure of the Milky Way. In 1750 Thomas Wright proposed that this is a disc of stars, and in 1755 Immanuel Kant speculated that some nebulae are 'island universes' similar to the Milky Way, raising the possibility that even the Galaxy is not so special. However, the galactocentric view persisted for several more centuries, with most astronomers still assuming that the Milky Way comprised the whole Universe. Indeed this was Einstein's belief when he published his theory of General Relativity in 1915 and started to study its cosmological implications.

### *Cosmocentric view*

Then in the 1920s the idea anticipated by Kant – that some of the nebulae are outside the Milky Way – began to take hold. For a while this was a matter of intense controversy. In 1920 Heber Curtis vigorously defended the island universe theory in a famous debate with Harlow Shapley. The controversy was finally resolved in 1924 when Edwin Hubble announced that he had measured the distance to M31 using Cepheid stars. An even more dramatic revelation came in 1929, when Hubble obtained radial velocities and distance estimates for several dozen nearby galaxies, thereby discovering that all galaxies are moving away from us with a speed proportional to their distance. This is now called 'Hubble's law' and it has been shown to apply out to a distance of 10 billion light-years, a region containing 100 billion galaxies. The most natural interpretation of Hubble's law is that space itself is expanding, as indeed had been predicted by Alexander Friedmann in 1920 on the basis of general relativity. Friedmann's model suggested that the Universe began in a state of great compression at a time in the past of order the inverse of the Hubble constant, now known to be about 14 billion years. This is the 'Big Bang' picture, and it received decisive support in 1965 with the discovery that the Universe is bathed in a sea of background radiation. This radiation is found to have the same temperature in every direction and to have a black-body spectrum, implying that the Universe must once have been sufficiently compressed for the radiation to have interacted with the matter. Subsequent studies by the COBE satellite confirmed that it has a perfect black-body spectrum, which firmly established the Big Bang theory as a branch of mainstream physics.

### *Multiverse view*

Further studies of the background radiation – most notably by the WMAP satellite – have revealed the tiny temperature fluctuations associated with the density ripples which eventually led to the formation of galaxies and clusters of galaxies. The angular dependence of these ripples is exactly as predicted by the inflationary scenario, which suggests that our observable domain is just a tiny patch of a much larger universe. This was the first evidence for what Tegmark [11] describes as the 'Level I' multiverse. A still more dramatic revelation has been the discovery – from observations of distant supernovae – that the expansion of the Universe is accelerating. We don't know for sure what is causing this, but it is probably related to the vacuum energy density. As described in Section 1.1, the low value of this density may indicate that there exist many other universes with different vacuum states, so this may be evidence for Tegmark's 'Level II' multiverse.

This brief historical review of developments on the outer front illustrates that the longer we have studied the Universe, the larger it has become. Indeed, the multiverse might be regarded as just one more step in the sequence of expanding vistas opened up by cosmological progress (from geocentric to heliocentric to galactocentric to cosmocentric). More conservative cosmologists might prefer to maintain the cosmocentric view that ours is the only Universe, but perhaps the tide of history is against them.

### *1.2.2 The inward journey*

Equally dramatic changes of perspective have come from revelations on the inward front, with the advent of atomic theory in the eighteenth century, the discovery of subatomic particles at the start of the twentieth century and the advent of quantum theory shortly thereafter. The crucial achievement of the inward journey is that it has revealed that everything in the Universe is made up of a few fundamental particles and that these interact through four forces: gravity, electromagnetism, the weak force and the strong force. These interactions have different strengths and characteristics, and it used to be thought that they operated independently. However, it is now thought that some (and possibly all) of them can be unified as part of a single interaction.

Figure 1.1 illustrates that the history of physics might be regarded as the history of this unification. Electricity and magnetism were combined by Maxwell's theory of electromagnetism in the nineteenth century. The electromagnetic force was then combined with the weak force in the (now experimentally confirmed) electroweak theory in the 1970s. Theorists have subsequently merged the electroweak force with the strong force as part of the Grand Unified Theory (GUT), although this has still not been verified experimentally. As discussed in Section 1.1, the final (and as yet incomplete) step is the unification with gravity, as attempted by string theory or M-theory.

A remarkable feature of these theories is that the Universe may have more than the three dimensions of space that we actually observe, with the extra dimensions being compactified on the Planck scale (the distance of $10^{-33}$ cm at which quantum gravity effects become important), so that we do not notice them. In M-theory itself, the total number of dimensions (including time) is eleven, with 4-dimensional physics emerging from the way in which the extra dimensions are compactified (described by what is called a Calabi–Yau manifold). The discovery of dark dimensions through particle physics shakes our view of the nature of reality just as profoundly as the discovery of dark energy through cosmology. Indeed, we saw in Section 1.1 that there may be an intimate link between these ideas.

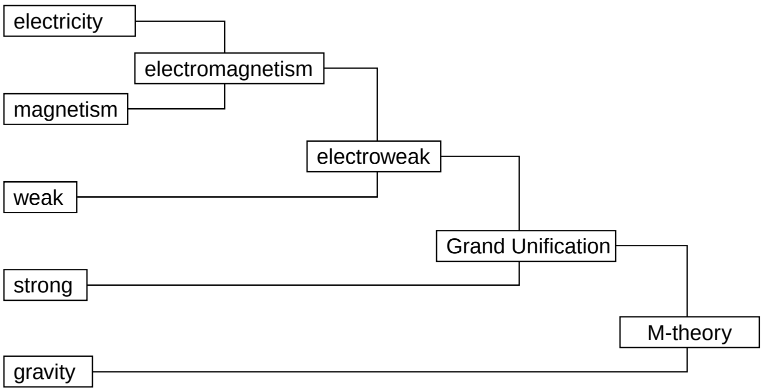

Fig. 1.1. This shows the successive steps by which physics has attempted to unify the four known forces of nature. Time runs to the right.

### *1.2.3 The cosmic uroborus*

Taken together, scientific progress on both the outer and inner fronts can certainly be regarded as a triumph. In particular, physics has revealed a unity about the Universe which makes it clear that everything is connected in a way which would have seemed inconceivable a few decades ago. This unity is succinctly encapsulated in the image of the uroborus (i.e. the snake eating its own tail). This is shown in Fig. 1.2 (adapted from a picture originally presented by Sheldon Glashow) and demonstrates the intimate link between the macroscopic domain (on the left) and the microscopic domain (on the right).

The pictures drawn around the snake represent the different types of structure which exist in the Universe. Near the bottom are human beings. As we move to the left, we encounter successively larger objects: a mountain, a planet, a star, the solar system, a galaxy, a cluster of galaxies and finally the entire observable Universe. As we move to the right, we encounter successively smaller objects: a cell, a DNA molecule, an atom, a nucleus, a quark, the GUT scale and finally the Planck length. The numbers at the edge indicate the scale of these structures in centimetres. As one moves clockwise from the tail to the head, the scale increases through 60 decades: from the smallest meaningful scale allowed by quantum gravity ($10^{-33}$ cm) to the scale of the visible Universe ($10^{27}$ cm). If one expresses these scales in units of the Planck length, they go from 0 to 60, so the uroborus provides a sort of 'clock' in which each 'minute' corresponds to a factor of 10 in scale.

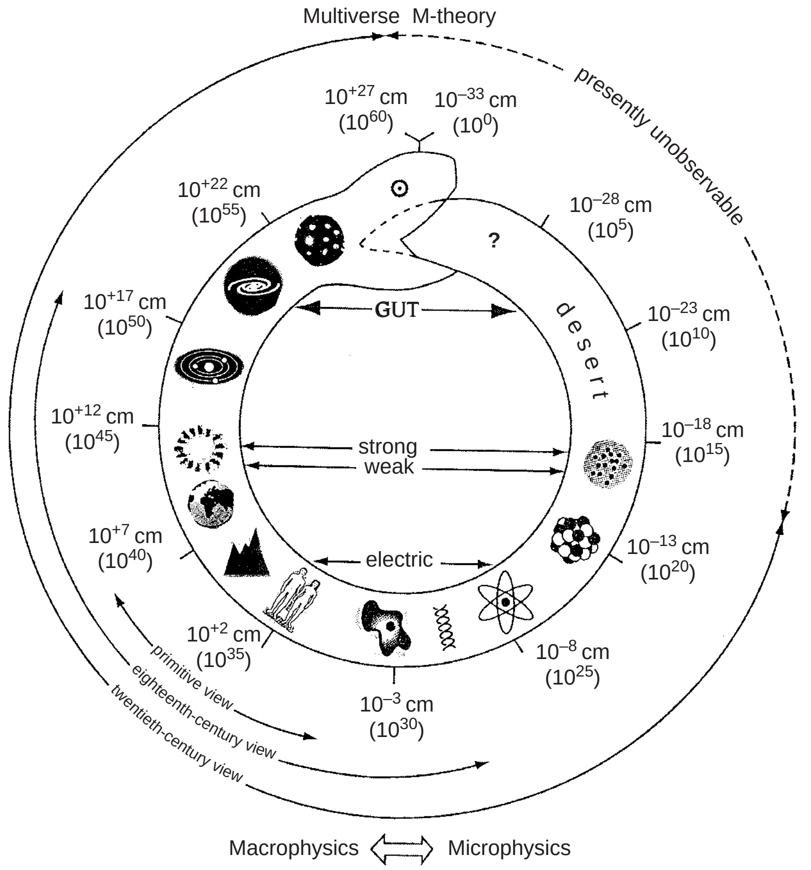

Fig. 1.2. The image of the uroborus summarizes the different levels of structure in the physical world, the intimate link between the microphysical and macroscopic domains and the evolution of our understanding of this structure.

A further aspect of the uroborus is indicated by the horizontal lines. These correspond to the four interactions and illustrate the subtle connection between microphysics and macrophysics. For example, the ‘electric’ line connects an atom to a planet because the structure of a solid object is determined by atomic and intermolecular forces, both of which are electrical in origin. The ‘strong’ and ‘weak’ lines connect a nucleus to a star because the strong force, which holds nuclei together, also provides the energy released in the nuclear reactions which power a star, and the weak force, which causes nuclei to decay, also prevents stars from burning out too soon. The ‘GUT’ line connects the grand unification scale with galaxies and clusters because the density fluctuations which led to these objects originated when the temperature of the Universe was high enough for GUT interactions to be important. Indeed the Big Bang theory suggests that these features arose when the current observable Universe had the size of a grapefruit!

The significance of the head meeting the tail is that the entire Universe was once compressed to a point of infinite density (or, more strictly, the Planck density). Since light travels at a finite speed, we can never see further than the distance light has travelled since the Big Bang, about $10^{10}$ light-years; more powerful telescopes merely probe to earlier times. Cosmologists now have a fairly complete picture of the history of the Universe: as one goes back in time, galaxy formation occurred at a billion years after the Big Bang, the background radiation last interacted with matter at a million years, the Universe's energy was dominated by its radiation content before about 10 000 years, light elements were generated through cosmological nucleosynthesis at around 3 minutes, antimatter was abundant before about a microsecond (before which there was just a tiny excess of matter over antimatter), electroweak unification occurred at a billionth of a second (the highest energy which can be probed experimentally), grand unification and inflation occurred at $10^{-35}$ s and the quantum gravity era (the smallest meaningful time) was at $10^{-43}$ s.

Perhaps the most striking aspect of the top of the uroborus is its link with higher dimensions. On the microscopic side, this arises because the various versions of superstring theory all suppose that the Universe has more than the three dimensions of space which we actually observe but with the extra dimensions being compactified. On the macroscopic side, the higher-dimensional link arises because we have seen that some versions of M-theory suggest that the Universe could be a 4-dimensional 'brane' in a higher-dimensional 'bulk' [17, 18]. This suggests that there might be many other branes in the bulk, although we have seen there are multiverse proposals which do not involve extra dimensions.

Figure 1.2 also has an historical aspect, since it shows how humans have systematically expanded the outermost and innermost limits of his awareness. Thus primitive humans were aware of scales from about $10^{-2}$ cm (mites) to $10^{7}$ cm (mountains); eighteenth century humans were aware of scales from about $10^{-5}$ cm (bacteria) to $10^{17}$ cm (the solar system); and twentieth-century humans were aware of scales from about $10^{-13}$ cm (atomic nuclei) to $10^{27}$ cm (the most distant galaxies). Indeed it is striking that science has already expanded the macroscopic frontier as far as possible, although experimentally we may never get much below the electroweak scale in the microscopic direction. We might therefore regard the uroborus as representing the blossoming of human consciousness.

## 1.3 But is the multiverse science?

Despite the growing popularity of the multiverse proposal, it must be admitted that many physicists remain deeply uncomfortable with it. The reason is clear: the idea is highly speculative and, from both a cosmological and a particle physics perspective, the reality of a multiverse is currently untestable. Indeed, it may always remain so, in the sense that astronomers may never be able to observe the other universes with telescopes a and particle physicists may never be able to observe the extra dimensions with their accelerators. The only way out would be if the effects of extra dimensions became 'visible' at the TeV scale, in which case they might be detected when the Large Hadron Collider becomes operational in 2007. This would only be possible if the extra dimensions were as large as a millimetre. However, it would be very fortunate (almost anthropically so) if the scale of quantum gravity just happened to coincide with the largest currently accessible energy scale.

For these reasons, some physicists do not regard these ideas as coming under the purvey of science at all. Since our confidence in them is based on faith and aesthetic considerations (for example mathematical beauty) rather than experimental data, they regard them as having more in common with religion than science. This view has been expressed forcefully by commentators such as Sheldon Glashow [22], Martin Gardner [23] and George Ellis [24], with widely differing metaphysical outlooks. Indeed, Paul Davies [25] regards the concept of a multiverse as just as metaphysical as that of a Creator who fine-tuned a single universe for our existence. At the very least the notion of the multiverse requires us to extend our idea of what constitutes legitimate science.

In some people's eyes, of course, cosmology has always bordered on metaphysics. It has constantly had to battle to prove its scientific respectability, fighting not only the religious, but also the scientific orthodoxy. For example, the prevalent view until well into the nineteenth century (long after the demise of the heliocentric picture) was that speculations about things beyond the Solar System was not proper science. This was reflected by Auguste Comte's comments on the study of stars in 1859 [26]:

> Never, by any means, will we be able to study their chemical compositions. The field of positive philosophy lies entirely within the Solar System, the study of the Universe being inaccessible in any possible science.

However, Comte had not foreseen the advent of spectroscopy, triggered by Gustav Kirchhoff's realization in the same year that the dark lines in the solar spectrum were absorption features associated with chemical elements.

For the first time this allowed astronomers to probe the composition of distant stars.

Cosmology attained the status of a proper science in 1915, when the advent of general relativity gave the subject a secure mathematical basis. The discovery of the cosmological expansion in the 1920s then gave it a firm empirical foundation. Nevertheless, it was many decades before it gained full scientific recognition. For example, when Ralph Alpher and Robert Herman were working on cosmological nucleosynthesis in the 1940s, they recall [27]: ‘Cosmology was then a sceptically regarded discipline, not worked in by sensible scientists.’ Only with the detection of the microwave background radiation in 1965 was the hot Big Bang theory established as a branch of mainstream physics, and only with the recent results from the WMAP satellite (postdating the Stanford meeting which led to this book) has it become a *quantitative* science with real predictive power.

Nevertheless, cosmology is still different from most other branches of science; one cannot experiment with the Universe, and speculations about processes at very early and very late times depend upon theories of physics which may never be directly testable. Because of this, more conservative physicists still tend to regard cosmological speculations as going beyond the domain of science. The introduction of anthropic reasoning doubtless enhanced this view. On the other hand, other physicists have always held a more positive opinion, so there has developed a polarization of attitudes towards the anthropic principle. This is illustrated by the following quotes. The first is from the protagonist Freeman Dyson [28]:

> I do not feel like an alien in this Universe. The more I examine the Universe and examine the details of its architecture, the more evidence I find that the Universe in some sense must have known we were coming.

This might be contrasted with the view of the antagonist Heinz Pagels [29]:

> The influence of the anthropic principle on contemporary cosmological models has been sterile. It has explained nothing and it has even had a negative influence. I would opt for rejecting the anthropic principle as needless clutter in the conceptual repertoire of science.

An intermediate stance is taken by Brandon Carter [2], who might be regarded as one of the fathers of the anthropic principle:

> The anthropic principle is a middle ground between the primitive anthropocentrism of the pre-Copernican age and the equally unjustifiable antithesis that no place or time in the Universe can be privileged in any way.

The growing popularity of the multiverse picture has encouraged a drift towards Carter's view, because it suggests that the anthropic fine-tunings can at least have a 'quasi-physical' explanation. To the hard-line physicist, the multiverse may not be entirely respectable, but it is at least preferable to invoking a Creator. Indeed anthropically inclined physicists like Susskind and Weinberg are attracted to the multiverse precisely because it seems to dispense with God as the explanation of cosmic design.[2]

In fact, the dichotomy in attributing anthropic fine-tunings to God or the multiverse is too simplistic. While the fine-tunings certainly do not provide unequivocal evidence for God, nor would the existence of a multiverse preclude God since – as emphasized by Robin Collins [30] – there is no reason why a Creator should not act through the multiverse. Neverethless, the multiverse proposal certainly poses a serious challenge to the theological view, so it is not surprising that it has commended itself to atheists. Indeed, Neil Manson has described the multiverse as 'the last resort for the desperate atheist' [31].

By emphasizing the scientific legitimacy of anthropic and multiverse reasoning, I do not intend to deny the relevance of these issues to the science–religion debate [32]. The existence of a multiverse would have obvious religious implications [33], so contributions from theologians are important. More generally, cosmology addresses fundamental questions about the origin of matter and mind, which are clearly relevant to religion, so theologians need to be aware of the answers it provides. Of course, the remit of religion goes well beyond the materialistic issues which are the focus of cosmology. Nevertheless, in so much as religious and cosmological truths overlap, they must be compatible. This has been stressed by Ellis [34], who distinguishes between Cosmology (with a big C) – which takes into account 'the magnificent gestures of humanity' – and cosmology (with a small c), which just focuses on physical aspects of the Universe. In his view, morality is embedded in the cosmos in some fundamental way. Similar ideas have been expounded by John Leslie [35].

On the other hand, science itself cannot deal with such issues, and it seems unlikely that – even in the extended form required to accommodate the multiverse – science will ever prove or disprove the existence of God. Some people may see in the physical world some hint of the divine, but this can only provide what John Polkinghorne describes as 'nudge' factors [36].

---

[2] It should be cautioned that the concept of 'cosmic design' being described here has nothing to do with the 'Intelligent Design' movement in the USA. Nevertheless, atheists might hope that the multiverse theory will have the same impact in the context of cosmic design as the theory of evolution did in the context of biological design.

Convictions about God's existence must surely come from 'inside' rather than 'outside' and even those eminent physicists who are mystically inclined do not usually base their faith on scientific revelations [37]. For this reason, theology receives rather short shrift in this volume. The contributors are nearly all physicists, and even those of a theological disposition have generally restricted their remarks to scientific considerations.

## 1.4 Overview of book

Part I contains articles deriving from two talks at the symposium *Expectations of a Final Theory*, which was held in Cambridge in September 2005. These provide appropriate opening chapters for this volume because of their historical perspective and because they illustrate the way in which the subject has been propelled by a combination of developments in cosmology and particle physics. Starting with contributions from two Nobel laureates also serves to emphasize the degree of respectability that the topic has now attained!

In the first contribution, 'Living in the multiverse', based on his opening talk at the Cambridge meeting, Steven Weinberg argues that the idea of the multiverse represents an important change in the nature of science, a radical shift in what we regard as legitimate physics. This shift is prompted by a combination of developments on the theoretical and the observational fronts. In particular, he highlights the anthropic constraint on the value of the vacuum energy or cosmological constant, a constraint which he himself first pointed out in 1987 and might be regarded as one of the few successful anthropic predictions. He also highlights the string landscape scenario, which is perhaps the most plausible theoretical basis for the multiverse proposal and is the focus of several later chapters.

Frank Wilczek's contribution, aptly entitled 'Enlightenment, knowledge, ignorance, temptation', is based on his summary talk at the Cambridge meeting. In this, he discusses the historical and conceptual roots of reasoning about the parameters of fundamental physics and cosmology based on selection effects. He describes the developments which have improved the status of such reasoning, emphasizing that these go back well before string theory. He is well aware of the downside of this development, but accepts it as part of the price that has to be paid. Such reasoning can and should be combined with arguments based on symmetry and dynamics; it supplements them, but does not replace them. This view is cogently encapsulated in Wilzcek's eponymous classification of physical parameters.

### *1.4.1 Cosmology and astrophysics*

Part II contains chapters whose emphasis is primarily on cosmology and astrophysics. The opening chapter, 'Cosmology and the multiverse', is by Martin Rees, one of the foremost champions of the multiverse concept and the host of the two Cambridge meetings represented in this volume. He points out that the parts of space and time that are directly observable (even in principle) may be an infinitesimal part of physical reality. Rejecting the unobservable part as a suitable subject for scientific discourse at the outset is unjustified because there is a blurred transition – what he describes as a 'slippery slope' – between what is observable and unobservable. After briefly addressing some conceptual issues, he discusses what the Universe would be like if some of the key cosmological numbers were different, and how one can in principle test specific hypotheses about the physics underlying the multiverse.

Although the focus of this volume is the multiverse rather than the anthropic principle, it is important to recall the fine-tunings which the multiverse proposal is purporting to explain. Indeed, in the absence of *direct* evidence for other universes, these might be regarded as providing the only *indirect* evidence. This motivates the inclusion of my own chapter, 'The anthropic principle revisited', in which I reconsider the status of some of the arguments presented in my 1979 *nature* paper with Rees [1]. Although I also veer into more philosophical issues, I have included my chapter here because most of the anthropic relationships are associated with cosmology and astrophysics. I emphasize that the key feature of the anthropic fine-tunings is that they seem necessary for the emergence of *complexity* during the evolution of the Universe from the Big Bang. The existence of conscious observers is just one particular manifestation of this and may not be fundamental.

In 'Cosmology from the top down', Stephen Hawking contrasts different approaches to the central questions of cosmology: why is the Universe spatially flat and expanding; why is it 4-dimensional; why did it start off with small density fluctuations; why does the Standard Model of particle physics apply? Some physicists would prefer to believe that string theory, or M-theory, will answer these questions and uniquely predict the features of the Universe. Others adopt the view that the initial state of the Universe is prescribed by an outside agency, code-named God, or that there are many universes, with ours being picked out by the anthropic principle. Hawking argues that string theory is unlikely to predict the distinctive features of the Universe. But neither is he is an advocate of God. He therefore opts for the last approach, favouring the type of multiverse which arises naturally within the context of his own work in quantum cosmology.

Several other contributors regard quantum cosmology as providing the most plausible conceptual framework for the multiverse, so the book returns to this theme later. However, the multiverse hypothesis comes in many different guises, and these are comprehensively summarized in Max Tegmark's chapter, 'The multiverse hierarchy'. Indeed, Tegmark argues that the key question is not *whether* parallel universes exist but on *how many* levels they exist. He shows that physical theories involving parallel universes form a four-level hierarchy, allowing progressively greater diversity. Level I is associated with inflation and contains Hubble volumes realizing all possible initial conditions. This is relatively uncontroversial, since it is a natural consequence of the cosmological 'concordance' model. Level II assumes that different regions of space can exhibit different effective laws of physics (i.e. different physical constants, different dimensionality and different particle content). For example, inflation models in the string landscape scenario subdivide into four increasingly diverse sublevels: IIa involves the same effective laws but different post-inflationary bubbles; IIb involves different minima in the effective supergravity potential; IIc involves different fluxes (of particular fields) for a given compactification; and IId involves different compactifications. Level III corresponds to the 'many worlds' of quantum theory. Tegmark argues that the other branches of the wave-function add nothing qualitatively new, even though historically this level has been the most controversial. Finally, Level IV invokes other mathematical structures, associated with different fundamental equations of physics. He then raises the question of how multiverse models can be falsified and argues that there is a severe 'measure problem' that must be solved to make testable predictions at levels II–IV. This point is addressed in more detail by later contributors.

Tegmark's classification emphasizes the central role of inflation, which postulates an era in the very early Universe when the expansion was accelerating. Inflation is invoked to explain two of the most striking features of the Universe – its smoothness and flatness – and to many physicists the theory still provides the most natural basis for the multiverse scenario. One of the prime advocates of the anthropic aspects of inflation is Andrei Linde, so it is most appropriate that he contributes the next chapter, 'The inflationary multiverse'. He first places the anthropic principle in an historical context: although anthropic considerations can help us understand many properties of our world, for a long time many scientists were ashamed to use the principle in their research because it seemed too metaphysical. However, the 'chaotic' inflationary scenario – which Linde pioneered and describes here – provides a simple justification for it. He especially favours 'eternal' inflation and links this to developments in string theory. He then discusses the implications of this idea for dark energy, relic axions and electroweak symmetry-breaking. These implications are explored in more detail in several later chapters, but Linde's article serves as an excellent introduction to these ideas and brings them all together.

One of the issues raised by Linde is the prevalence of dark matter, and this is the focus of the second contribution by Frank Wilczek, 'A model of anthropic reasoning: the dark to ordinary matter ratio'. He focuses on a dark matter candidate called the axion, which is a particle associated with the breaking of Peccei–Quinn (i.e. strong CP) symmetry in the early Universe. Large values of the symmetry-breaking energy scale (associated with large values of the Peccei–Quinn 'misalignment' angle) are forbidden in conventional axion cosmology. However, if inflation occurs after the breaking of Peccei–Quinn symmetry, large values are permitted providing we inhabit a region of the multiverse where the initial misalignment is small. Although such regions may occupy only a small volume of the multiverse, they contain a large fraction of potential observers. This scenario therefore yields a possible anthropic explanation of the approximate equality of the dark matter and baryon densities.

We have seen that another striking feature of the Universe is that its expansion appears to be accelerating under the influence of some form of 'dark energy'. The source of this energy is uncertain, but it may be associated with a cosmological constant. Indeed, we have seen that one of the most impressive successes of anthropic reasoning is that it may be able to explain the present value of the cosmological constant. Several contributions touch on this, but the most comprehensive treatment is provided by Alex Vilenkin, whose chapter, 'Anthropic predictions: the case of the cosmological constant', reviews the history and nature of this prediction. He also discusses the inclusion of other variable parameters (such as the neutrino mass) and the implications for particle physics. In anticipation of a theme which emerges later in the book, he emphasizes that anthropic models give testable predictions, which can be confirmed or falsified at a specified confidence level. However, anthropic predictions always have an intrinsic variance, which cannot be reduced indefinitely as theory and observations progress.

The cosmological constant also plays a central role in James Bjorken's chapter, 'The definition and classification of universes'. If the concept of a multiverse makes sense, one needs a specific, standardized definition for member universes which are similar to our own. Crucial to this description is the definition of the 'size' of the universe and, for the de Sitter model, Bjorken takes this to be the asymptotic value of the inverse Hubble constant. This is directly related to the value of the cosmological constant, so this parameter plays a natural role in his classification. He further proposes that the vacuum parameters and coupling constants of the Standard Model in any universe are dependent upon this size. Anthropic considerations then limit the size of habitable universes (as we understand that concept) to be within a factor of 2 of our own. Implications of this picture for understanding the 'hierarchy problem' in the Standard Model are discussed, as are general issues of falsifiability and verifiability.

Bjorken does not attempt to provide a physical basis for models with different cosmological constants, but a possible motivation comes from string theory, or M-theory. This point is discussed by several contributors, but the most thorough discussion of the cosmological applications of the idea is provided in Renata Kallosh's chapter, 'M/string theory and anthropic reasoning'. Here she outlines some recent cosmological studies of M/string theory and gives a couple of examples where anthropic reasoning – combined with our current incomplete understanding of string theory and supergravity – helps to shed light on the mysterious properties of dark energy. This is a rather technical article, but it is very important because it describes the results of her famous paper with A. Linde, S. Kachru and S. Trivedi, which shows that M/string theory allows models with a positive cosmological constant. This was a crucial development because string theorists used to assume that the constant would have to be *negative*, so this is an example of how cosmology has led to important insights into particle physics.

Closely related to Kallosh's theme is the final chapter in Part II by Savas Dimopoulos and Scott Thomas, 'The anthropic principle, dark energy and the LHC'. Here they argue that – in a broad class of theories – anthropic reasoning leads to a time-dependent vacuum energy with distinctive and potentially observable characteristics. The most exciting aspect of this proposal is that it leads to predictions that might be testable with the Large Hadron Collider, due to start operating in 2007. This illustrates the intimate link between cosmology and particle physics, so this naturally leads into the next part of the volume, which focuses on particle physics aspects of the multiverse hypothesis.

### *1.4.2 Particle physics and quantum theory*

Part III starts with two articles on the values of the constants of particle physics, then moves onto the link with string theory, and concludes with articles concerned with quantum theory. There is a two-fold connection with quantum theory, since the 'many worlds' interpretation of quantum mechanics provided one of the earliest multiverse scenarios (i.e. Tegmark's Level III) and quantum cosmology provides one of the latest.

That the multiverse wave-function can explore a multitude of vacua with different symmetries and parameters is the starting point of Craig Hogan's chapter, 'Quarks, electrons and atoms in closely related universes'. In the context of such models, he points out that properties of universes closely related to ours can be understood by examining the consequences of small departures of physical parameters from their observed values. The masses of the light fermions that make up the stable matter of which we comprise – the up and down quarks and the electron – have values in a narrow window that allows the existence of a variety of nuclei other than protons and also atoms with stable shells of electrons that are not devoured by their nuclei. Since a living world with molecules needs stable nuclei other than protons and neutrons, these fundamental parameters of the Standard Model are good candidates for quantities whose values are determined through selection effects within a multiverse. Hogan also emphasizes another possible link with observation. If the fermion masses are fixed by brane condensation or compactification of extra dimensions, there may be an observable fossil of this 'branching event' in the form of a gravitational-wave background.

In the second chapter, 'The fine-tuning problems of particle physics and anthropic mechanisms', John Donoghue emphasizes that many of the classic problems of particle physics appear in a very different light when viewed from the perspective of the multiverse. Parameters in particle physics are regarded as fine-tuned if the size of the quantum corrections to their values in perturbation theory is large compared with their 'bare' values. Three parameters in the Standard Model are particularly puzzling because they are unnaturally small. Two of these – the Higgs vacuum expectation value and the cosmological constant – constitute the two great fine-tuning problems that motivate the field. The third is the strong CP violating factor, already highlighted in Wilzcek's second contribution. All of these fine-tunings are alleviated when one accounts for the anthropic constraints which exist in a multiverse. However, the challenge is to construct a realistic physical theory of the multiverse and to test it. Donoghue describes some phenomenology of the quark and lepton masses that may provide a window on the multiverse theory.

The main reason that particle physicists have become interested in the multiverse proposal is the development in string theory. In particular, the possibility that M-theory may lead to a huge number of vacuum states – each associated with a different universe – is a crucial feature of Leonard Susskind's string landscape proposal. In 'The anthropic landscape of string theory', he makes some educated guesses about the landscape of string theory vacua and – based on the recent work of a number of authors – argues that the landscape could be unimaginably large and diverse. Whether we like it or not, this is the kind of behaviour that gives credence to the anthropic principle. He discusses the theoretical and conceptual issues that arise in a cosmology based on the diversity of environments implicit in string theory. Some of the later stages of his exposition are fairly technical, but these ideas are of fundamental importance to this volume. Indeed Susskind's chapter has already been on the archives for several years and is one of the most cited papers in the field.

As already stressed, the 'many worlds' interpretation of quantum theory provided one of the earliest versions of the multiverse scenario, and this is particularly relevant to quantum cosmology, which is most naturally interpreted in terms of this proposal. This view is advocated very cogently in 'Cosmology and the many worlds interpretation of quantum mechanics' by Viatschelav Mukhanov. Indeed, he argues that the wave-function of the Universe and the cosmological perturbations generated by inflation can *only* be understood within Everett's interpretation of quantum mechanics. The main reason it has not been taken seriously by some physicists is that it predicts we each have many copies, which may seem unpalatable. However, Mukhanov argues that these copies are not 'dangerous' because we cannot communicate with them.

The link with quantum cosmology is probed further by James Hartle in 'Anthropic reasoning and quantum cosmology'. He stresses that anthropic reasoning requires a theory of the dynamics and quantum initial condition of the Universe. Any prediction in quantum cosmology requires both of these. But conditioned on this information alone, we expect only a few general features of the Universe to be predicted with probabilities near unity. Most useful predictions are of conditional probabilities that assume additional information beyond the dynamics and quantum state. Anthropic reasoning utilizes probabilities conditioned on our existence. Hartle discusses the utility, limitations and theoretical uncertainty involved in using such probabilities, as well as the predictions resulting from various levels of ignorance of the quantum state.

The link between Everett's picture and the multiverse proposal is explored in depth by Brandon Carter. His chapter, 'Micro-anthropic principle for quantum theory', is somewhat technical but very valuable since it provides an excellent historical perspective and leads to an interpretation of the many worlds picture which goes beyond the original Everett version. Probabilistic models, developed by workers such as Boltzmann on foundations due to pioneers such as Bayes, were commonly regarded as approximations to a deterministic reality before the roles were reversed by the quantum revolution under the leadership of Heisenberg and Dirac. Thereafter, it was the deterministic description that was reduced to the status of an approximation, with the role of the observer becoming particularly prominent. In Carter's view, the lack of objectivity in the original Copenhagen interpretation has not been satisfactorily resolved in newer approaches of the kind pioneered by Everett. The deficiency of such interpretations is attributable to their failure to allow for the anthropic aspect of the problem, in the sense that there is *a priori* uncertainty about the identity of the observer. Carter reconciles subjectivity with objectivity by distinguishing the concept of an *observer* from that of a *perceptor*, whose chances of identification with a particular observer need to be prescribed by a suitable anthropic principle. It is proposed that this should be done by an entropy ansatz, according to which the relevant micro-anthropic weighting is taken to be proportional to the logarithm of the relevant number of Everett-type branches.

### *1.4.3 More general or philosophical aspects*

The final part of the book addresses more philosophical and epistemological aspects of the multiverse proposal – especially the issue of its scientific legitimacy. The chapters in this part are also written from a different standpoint from those in the earlier parts. Whereas the contributors in Parts I–III are mainly positive about the idea of the multiverse (otherwise they would presumably not be exploring it), some of the contributors in Part IV are rather critical – either preferring more theological interpretations of the anthropic coincidences or regarding multiverse speculations as going beyond science altogether.

The most sceptical of the critics is Lee Smolin. His chapter, 'Scientific alternatives to the anthropic principle', is the longest contribution in the volume and plays a crucial role in bringing all the criticisms of the multiverse proposal together. He first argues that the anthropic principle cannot be considered a part of science because it does not yield any falsifiable predictions. Claimed successful predictions are either uncontroversial applications of selection principles in one universe or they depend only on observed facts which are logically independent of any assumption about life or intelligence. The Principle of Mediocrity (first formulated by Vilenkin) is also examined and claimed to be unreliable, as arguments for true conclusions can easily be modified to lead to false conclusions by reasonable changes in the specification of the ensemble in which we are assumed to be typical. However, Smolin shows that it is still possible to make falsifiable predictions from multiverse theories if the ensemble predicted has certain specified properties and he emphasizes his own favoured multiverse proposal – Cosmological Natural Selection – which involves the generation of descendant universes through black hole formation. This proposal remains unfalsified, but it is very vulnerable to falsification, which shows that it is a proper scientific theory. The consequences for recent applications of the anthropic principle in the context of string theory (as described in Part III) are also discussed.

Several other contributions in this part address the question of whether the multiverse proposal is scientifically respectable, although they do not all share Smolin's negative conclusion. In 'Making predictions in a multiverse: conundrums, dangers, coincidences', Anthony Aguirre accepts that the notion of many universes with different properties is one answer to the question of why the Universe is so hospitable to life. He also acknowledges that this notion naturally follows from current ideas in eternal inflation and M/string theory. But how do we test a multiverse theory and which of the many universes do we compare to our own? His chapter enumerates what would seem to be essential ingredients for making testable predictions, outlines different strategies one might take within this framework, and then discusses some of the difficulties and dangers inherent in these approaches. Finally, he addresses the issue of whether the predictions of multiverse theories share any general, qualitative features.

The issue of testing also features in the contribution of George Ellis, 'Multiverses: description, uniqueness and testing', who concludes that the multiverse proposal is not really proper science. He emphasizes that a multiverse is determined by specifying first a possibility space of potentially existing universes and then a distribution function on this space for actually existing universes. Ellis is sceptical because there is a lack of uniqueness at both these stages and we are unable either to determine observationally the specific nature of any multiverse that is claimed to exist or to validate experimentally any claimed causal mechanism that will create one. Multiverses may be useful in explanatory terms, but arguments for their existence are ultimately of a philosophical nature. Ellis is not against metaphysics – indeed he has written extensively on philosophical and theological issues – but he feels it should not be confused with science.

The importance of testing is also explored by Don Page in 'Predictions and tests of multiverse theories'. Page is also of a religious persuasion, but he comes to a somewhat different conclusion from Ellis. A multiverse usually includes parts unobservable to us, but if the theory for it includes suitable measures for observations, what is observable can be explained by the theory even if it contains unobservable elements. Thus good multiverse theories *can* be tested. For Bayesian comparisons of different theories that predict more than one observation, Page introduces the concept of 'typicality' as the likelihood given by a theory that a random result of an observation would be at least as extreme as the result of one's actual observation. He also links this to the interpretations of the quantum theory. Some multiverse theories can be regarded as pertaining to a *single* quantum state. This obeys certain equations, which raises the question of why those equations apply. Other theories can be regarded as pertaining to more than one quantum state, and these raise another question: why is the measure for the set of different universes such as to make our observations not too atypical?

The importance of a good probabilistic basis for assessing multiverse scenarios is also highlighted by Nick Bostrom's chapter, 'Observation selection theory and cosmological fine-tuning'. His title refers to a methodological tool for dealing with observation selection effects. Such a tool is necessary if observational consequences are to be derived from cosmological theory. It also has applications in other domains, such as evolution theory, game theory and the foundations of quantum mechanics. Bostrum shows that observation selection theory needs a probabilistic anthropic principle, which can be formalized in what he terms the 'Observation Equation'. Some implications of this for the problem of cosmological fine-tuning are discussed.

The next two contributions tackle the religious issue explicitly. 'Are anthropic arguments, involving multiverses and beyond, legitimate?' is particularly welcome because it comes from William Stoeger, who is both a working scientist and a Jesuit priest. After reviewing the history of the anthropic principle, he discusses the two main versions of the strong form – a divine creator or a multiverse. The latter strives to confine anthropic arguments within the realms of science and invokes an actually existing ensemble of universes or universe domains. He critically examines the scientific status of this proposal, briefly indicating what is needed for the definition and testability of a multiverse, and then describes some purely scientific applications of anthropic arguments. After discussing the key philosophical presumption on which the strong anthropic principle rests – that the Universe could have been different – and its relationship to a possible final theory, he summarizes his main conclusions concerning the two 'transcendent' explanations of the strong anthropic principle. Even if a multiverse is proved to exist, Stoeger would not regard this as providing an *ultimate* explanation and it would certainly not exclude the existence of God. However, he cautions that such considerations go beyond science itself.

As suggested by its title, the chapter by Robin Collins, ‘The multiverse hypothesis: a theistic perspective’, also takes an explicitly theological stance. Many people have promoted the multiverse hypothesis as the atheistic alternative to a theistic explanation of the fine-tuning of the cosmos for the existence of life. However, Collins argues that the multiverse hypothesis is also compatible with theism – indeed he claims that the generation of many universes by some physical process fits in well with the traditional belief that God is infinitely creative. Since such a process would have to be structured in just the right way to produce even one life-sustaining universe, this version of the multiverse hypothesis does not completely avoid the suggestion of design. Finally, he consider other pointers to a theistic explanation of the Universe, such as the beauty and elegance of the laws of nature, and argues that Tegmark’s multiverse hypothesis – that all possible laws of nature are actualized in some universe or another – does not adequately account for this aspect of the laws of nature.

There are, of course, alternative interpetations of the multiverse hypothesis which are neither anthropic nor theistic. One example of this is Smolin’s Cosmological Natural Selection proposal. Another (more exotic) version – which has been explored by Bostrom (though not in this volume) – is that the Universe is a computer simulation. This is the theme of John Barrow’s chapter, ‘Living in a simulated universe’. He explains why, if we live in a simulated reality, we might expect to see occasional glitches and small drifts in the supposed constants and laws of nature over time. There may even be evidence for this from astronomical observations, although the interpretation of these remains controversial.

Another possible interpetation of the anthropic tunings is provided in the final chapter, ‘Universes galore: where will it all end?’, by Paul Davies, who is also somewhat sceptical of the multiverse proposal. He argues that, although ‘a little bit of multiverse is good for you’, invoking multiverse explanations willy-nilly is a seductive slippery slope. Followed to its logical extreme, it leads to conclusions that are at best bizarre, at worst absurd. After reviewing several shortcomings of indiscriminate multiverse explanations, including the simulated multiverse discussed by Barrow, he challenges the false dichotomy that fine-tuning requires the existence of either a multiverse or some sort of traditional cosmic architect. Instead, he explores the possibility of a ‘third way’, involving a radical reappraisal of the notion of physical law, and presents a toy illustration from the theory of cellular automata.

## References

[1] B. J. Carr and M. J. Rees. *Nature*, **278** (1979), 605.

[2] B. Carter. In *Confrontation of Cosmological Theory with Observational Data*, ed. M. S. Longair (Dordrecht: Reidel, 1974), pp. 291–298.

[3] R. C. Tolman. *Relativity, Thermodynamics and Cosmology* (Oxford: Clarendon Press, 1934).

[4] A. H. Guth. *Phys. Rev.* **D 23** (1981), 347.

[5] A. D. Linde. *Phys. Lett.* **B 175** (1986), 395.

[6] A. Vilenkin. *Phys. Rev.* **D 27** (1983), 2848.

[7] J. B. Hartle and S. W. Hawking. *Phys. Rev.* **D 28** (1983), 2960.

[8] S. W. Hawking and T. Hertog. *Phys. Rev.* **D 73** (2006), 123527.

[9] H. Everett. *Rev. Mod. Phys.* **29** (1957), 454.

[10] D. Deutsch. *The Fabric of Reality* (London: Penguin, 1998).

[11] M. Tegmark, In *Science and Ultimate Reality*: *From Quantum to Cosmos*, eds. J. D. Barrow, P. C. W. Davies & C. L. Harper (Cambridge: Cambridge University Press, 2003), p. 459.

[12] G. L. Kane, M. J. Perry and A. N. Zytkow. *New Astron.* **7** (2002), 45.

[13] R. Bousso and J. Polchinski. *JHEP*, **06** (2000), 006.

[14] L. Susskind. This volume (2007).

[15] S. Weinberg. *Phys. Rev. Lett.* **59** (1987), 2607.

[16] S. Weinberg. *Rev. Mod. Phys.* **61** (1989), 1.

[17] L. Randall and R. Sundrum. *Phys. Rev. Lett.* **83** (1999), 4690.

[18] L. Randall. *Warped Passages: Unravelling the Universe's Hidden Dimensions* (London: Penguin, 2005).

[19] S. Kachru, R. Kallosh, A. Linde and S. R. Trivedi. *Phys. Rev.* **D 68** (2003), 046005.

[20] J. Khoury, B. A. Ovrut, P. J. Steinhardt and N. Turok. *Phys. Rev.* **D 64** (2001), 123522.

[21] A. R. Liddle and L. A. Urena-Lopez. *Phys. Rev. Lett.* **97** (2006), 161301.

[22] G. Brumfiel. *Nature*, **439** (2006), 10.

[23] M. Gardner. *Are Universes Thicker than Blackberries?* (New York: W. W. Norton & Co. Ltd, 2003).

[24] G. F. R. Ellis. This volume (2007).

[25] P. C. W. Davies. This volume (2007).

[26] A. Comte. *Cours de Philosophie Positive* (Paris: Bachelier, 1842).

[27] R. A. Alpher and R. Herman. *Phys. Today*, **41** (1988), 24.

[28] F. Dyson. *Rev. Mod. Phys.* **51** (1979), 447.

[29] H. R. Pagels. *Perfect Symmetry* (New York: Simon & Schuster), p. 359.

[30] R. Collins. This volume (2007).

[31] N. A. Manson. *God and Design* (London: Routledge, 2003).

[32] B. J. Carr. In *The Oxford Handbook of Religion and Science*, eds. P. Clayton and Z. Simpson (Oxford: Oxford University Press, 2006), p. 139.

[33] R. Holder. *God, the Multiverse and Everything*: *Modern Cosmology and the Argument from Design* (Aldershot: Ashgate, 2004).

[34] G. F. R. Ellis. *Before the Beginning: Cosmology Explained* (London: Boyars/Bowerdean, 1993).

[35] J. Leslie. *Universes* (London: Routledge, 1989).

[36] J. Polkinghorne. *The Faith of a Physicist* (Princeton, NJ: Princeton University Press, 1994).

[37] K. Wilbur. *Quantum Questions: Mystical Writings of the Worlds Greatest Physicists* (Boston: Shambhala, 2001).