# God, the Multiverse, and Everything

Rodney D. Holder

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# AND EVERYTHING

*In memory of my father*

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## Modern Cosmology and the Argument from Design

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# Preface

One of the most vibrant fields of scientific research today is undoubtedly that of cosmology. This is also a subject which excites the non-specialist, since it seeks to answer some of the most fundamental questions of human existence. How did the universe begin? What processes were going on in the very earliest moments of the universe's existence? What did the conditions have to be like for the universe to evolve intelligent life forms? Are there likely to be universes other than our own, and if so what are they like?

It is no surprise, with a brief to answer questions like this, that cosmology is also of interest to professional philosophers and theologians. Indeed it would seem that cosmology raises profound metaphysical questions, which cannot necessarily be answered from within its own domain.

The question I treat in this book is whether the universe as we know it from cosmology can be said to exhibit design and so point us to a Designer—one whom followers of the great monotheistic religions would call God. The values taken by the fundamental constants of physics, and the initial conditions obtaining at the beginning of the universe, are at least suggestive that this is so.

I examine the hypothesis, namely theism, that the universe is in fact designed, against what has come to be theism's main explanatory rival, the notion that there do exist many universes and that one like ours, conducive to life, is bound to show up sooner or later. On this latter, multiverse hypothesis we should not be surprised to discover the very special features required for our own existence because these are the only ones we could observe, and they are certain to be among the many and varied properties, albeit mostly inimical to life, occurring in the grand ensemble of universes.

My treatment of these alternatives is intended to be rigorous, and so inevitably involves discussion at a certain level of technical detail. For example, we need to try and understand some of the concepts from cosmology and particle physics. Then we need a rigorous method for comparison of hypotheses, and that takes us into some knotty issues in the philosophy of probability. There are also issues surrounding the mathematics of infinity to grapple with.

I have tried to keep symbols and equations to a minimum in the main text and to provide as full an explanation as possible where these are retained. Most of the mathematics is banished to appendices, and there is a glossary where technical terms and symbols are explained, but a few equations do occur in the main text as being central to my argument. My hope is that I have provided sufficient information for the non-specialist to be able to follow my reasoning.

The apparent design of the universe presented to us by modern cosmology has interested me for a number of years, and I touched on it in my first book on the relationship between science and faith *Nothing But Atoms and Molecules?* (Monarch 1993). More specialized work on this topic began as an extended essay for the Final

Honour School of Theology in the University of Oxford (Hilary Term 1996). I am grateful to Mr Hugh Rice of Christ Church, Oxford, who supervised that work, and to Dr John Taylor and the Revd Dr Patrick Richmond for helpful conversations about the subject matter, both then and since. Whilst in Oxford I was also able to benefit from the wisdom of Professor Richard Swinburne, the influence of whose writings on the present work will be easily traced, and who has encouraged my further endeavours in this field.

My subsequent research resulted in several published papers, and I am grateful to the publishers of *Noûs* (Blackwell Publishing Ltd), *Religious Studies* (Cambridge University Press), and *Science and Christian Belief* (Paternoster Periodicals) for permission to reproduce material from those papers, now substantially enhanced. I am grateful to the various anonymous referees who commented on my work for these journals, and to Professor Quentin Smith who made his most helpful comments by name.

I am indebted to those who commented on earlier drafts of the book, notably the Revd Dr David Wilkinson, Dr Peter Hodgson, and Professor Roger Trigg, but also anonymous commentators. I am most grateful for the comments and support of the Revd Dr John Polkinghorne, KBE, FRS, another author who has been a great influence on my work, and whom I was privileged to get to know during my time as Chaplain of the English Church in Heidelberg.

I have benefited from correspondence with Professors Timothy and Lydia McGrew, Professor Neil Manson, and Professor Jeffrey Koperski, all working in the USA, and all of whom have been kind enough to send me drafts of their own work.

I have been thankful for opportunities to speak about my work, and to engage with a discerning audience, especially at the Durham Conference of the Science and Religion Forum (1999), with former colleagues at EDS (2001), and at the Ian Ramsey Centre for the Study of Science and Religion in Oxford (2002).

I should also like to record my immense debt to an inspirational teacher of an earlier period of my life, namely my doctoral supervisor, the late Professor Dennis Sciama.

Interaction with all the above has sparked many ideas and especially the honing of the work into its present form. Remaining errors and weaknesses are of course my responsibility entirely.

My thanks go to Sarah Lloyd, commissioning editor at Ashgate, and the rest of the publishing team, for seeing the work through to completion.

Last, but by no means least, as when I wrote my first book, I owe an immense debt of gratitude to my dear wife Shirley. She has taken on many responsibilities, not least in the ministry which we share, so as to enable me to find time for this project within the busyness of parish life. We are both of us grateful for many people's support during a self-initiated 'sabbatical' between full-time stipendiary posts, which included our time in Germany, and provided the welcome breathing space required to make substantial progress towards producing the book.

# Chapter 1

# Scientific Naturalism and the Alternative of Design

Of this fair volume which we World do name,
If we the sheets and leaves could turn with care,
Of him who it corrects, and it did frame,
We clear might read the art and wisdom rare;
Find out his power which wildest powers doth tame,
His providence extending everywhere,
His justice which proud rebels doth not spare,
In every page, no, period of the same.

(William Drummond [1585-1649], Sonnet, *The Book of the World.*)

## The Challenge of Scientific Naturalism

Many people today believe that science has removed the need for God as an explanation for the existence of the universe or the arrival of ourselves in it. They are encouraged by some notable present-day scientists who propagate such a view, often with a vehemence which transcends the sober and rational atmosphere of debate normally obtaining within their own scientific disciplines. Thus Professor Richard Dawkins believes that, in the light of the theory of biological evolution, 'we don't need to postulate a designer in order to understand life, or anything else in the universe'.[1] Peter Atkins argues that 'the universe can come into existence without intervention, and that there is no *need* to invoke the idea of a Supreme Being in one of its numerous manifestations'.[2] Professor Stephen Hawking, whilst less militant, sees God as purely a First Cause, the need for which is obviated if we can explain how the universe has no boundary in space-time.[3]

It might seem that in the light of modern science there is no room for God. On being asked by Napoleon why the Creator was nowhere mentioned in his system of the world, the French mathematician Pierre Simon Laplace (later the Marquis de Laplace) is famously said to have replied, 'Sire, I have no need of that hypothesis.' Was Laplace right to exclude God as an explanation, or was his colleague Lagrange more to be commended in commenting, when the Emperor told him of this incident, 'Ah, but that is a fine hypothesis. It explains so many things.'?[4]

In fact, matters are not so simple. After all, Laplace was himself a practising Roman Catholic, so his remark can hardly have been made with atheistic intent.

Furthermore, Leibniz had already criticized Newton for invoking God as intervening in the creation to prevent the decay and instability of the solar system, since, as Leibniz put it, it was demeaning for the Creator to have to remedy the defects in his craftsmanship. Laplace's nebular hypothesis, an important precursor of modern theories of the origin of the solar system, did away with the need for such interventions, which Newton had seen as evidence of design, but which could equally well be ascribed to faulty workmanship. I agree with Lagrange's comment on the power of the theistic hypothesis, but we must be careful to invoke it only where it is needed.

Dawkins, Atkins and Hawking are exemplars of what I shall call 'scientific naturalism'. I define scientific naturalism to be the position that all physical events can be explained solely, and exclusively, in terms of other physical events. As Dawkins puts it: 'The kind of explanation we come up with ... will make use of the laws of physics, and nothing more than the laws of physics'.[5] Similarly Peter Atkins writes: '... there is nothing that cannot be explained',[6] and he means 'explained by science alone'.

The view I wish to defend against scientific naturalism I shall call 'theism', by which I mean that the universe was designed by a supernatural being akin to the God of the great monotheistic religions. Indeed I shall for convenience call this being 'God' from now on. However, I recognize that theism is not the only possible non-naturalistic hypothesis. An alternative would be the 'extreme axiarchism' of John Leslie, a Neoplatonist position according to which the universe is brought about by its own 'ethical requiredness'.[7] It is not my intention here to make the case for theism as the most probable non-naturalistic hypothesis, though I believe it is so, and that arguments of the kind adduced by Richard Swinburne for the economy and simplicity of theism would show this.[8] I shall also ignore the major argument against theism, i.e. the problem of evil, which should also be taken into account in the more general cumulative building up of the case for theism. Naïvely one might expect this adversely to affect the probability that the universe was created by a good God, but in drawing any conclusion one would need to consider the many reasons theologians have advanced as to precisely why the permitting of evil in the universe would not contradict God's goodness.[9]

The central issue I shall examine is whether the origin and evolution of the universe as understood by modern cosmology, utilizing the laws of physics, are uniquely and adequately explained in terms of scientific naturalism alone. My intention is to show that science cannot do without metaphysical assumptions, and the assumptions it uses ought to lead scientists logically to embrace non-naturalism. In particular, the science of cosmology may be suggesting that science itself provides reasons for doubting scientific naturalism. My main focus will be on the by now well-publicized evidence of the 'fine-tuning' of the universe.

In theological terms, this book constitutes an exercise in 'natural theology'. Natural theology concerns the knowledge of God available to all human beings without recourse to special revelation.[10] I therefore take it as read that this is a legitimate enterprise for Christians (and my own particular perspective is that of a

*Christian* theist) to be engaged in. Roman Catholic theology has certainly always thought so, but there is a strong strand of Protestant theology which totally rejects this whole approach. Thus Karl Barth regards natural theology as presumptuous and apologetics (the defence of the faith, as opposed simply to its proclamation) as illegitimate.

I have engaged with Barth's thought elsewhere,[11] and whilst I agree with him that God's revelation in Christ, as attested in Holy Scripture, is central, I disagree as to the illegitimacy of natural theology, which I see as preparatory to presenting Christ. In this book I am wanting especially to think and argue as a scientist, and I cannot imagine any scientist rejecting an approach which looks at the universally available evidence for belief—indeed, that religion rejects evidence is precisely Richard Dawkins's complaint.

## The Argument from Design

Traditionally, at any rate in Christian theology, a number of arguments or 'proofs' have been advanced for the existence of God. These 'proofs' belong to natural theology as defined above, and include the ontological, cosmological and design (alternatively termed teleological) arguments. In this book I shall primarily be concerned with presenting a version of the argument from design informed by the discoveries of modern cosmology.

The ontological argument proceeded from the concept of God to his existence. St Anselm famously argued that, if we define God as 'That than which nothing greater can exist', and if we agree that something which exists in reality is greater than something which exists only in conception, then it follows that God exists. Some very illustrious philosophers have believed in the argument in one form or another (e.g. Descartes and Leibniz), even if many have regarded it with suspicion (e.g. Kant). It is in fact notoriously difficult to refute. Indeed, contrariwise, Alvin Plantinga has shown how the argument can be formulated so as to be valid. Plantinga's version has the interesting consequence that, if God be possible, then he exists.[12]

The cosmological argument (or, rather, one version of it) began from the observation that there *is* a universe, and asked for the explanation of its existence. At its simplest, the question is, 'Why is there something rather than nothing?'. Famously, Leibniz argued from the Principle of Sufficient Reason that there must be an explanation, namely God. Many philosophers would dispute the Principle of Sufficient Reason and affirm that the universe itself could be the stopping point for explanation. But, given that in science we seek for explanations of the phenomena we observe within the universe, it does not seem unreasonable to seek for an explanation of the cosmos itself.[13]

The argument from design points beyond the existence of the universe to certain striking features of it. These are that the universe exhibits a regularity and intricacy in its make-up which are suggestive of its having been designed. This kind of argument goes back at least to St Thomas Aquinas's Five Ways, the fifth of which pointed to the 'guidedness of nature', from which one was to infer the existence of one who directs all things to their goal, 'and this we call "God"'.[14]

Hume criticized the argument in a number of ways, pointing for example to the lack of analogy between mechanical artefacts pointing to a human designer and natural phenomena pointing to God. If the argument points to anything it may not be the unique God of Christian revelation, but to a pantheon of gods. Kant, even more fundamentally, believed we could have no knowledge of transcendent realities, only the phenomena of experience, and that the perceived order in the world is imposed on the phenomena by our human minds rather than given by God.

These criticisms can be answered.[15] However, since this book is not a general treatise on the argument from design, but a detailed examination of one particular version of it, I content myself with just a few remarks, referring the reader to the philosophical literature for the broader discussion. Thus, it does not actually seem at all unreasonable, when answering the global question as to why there is order in the universe for science to uncover, that the answer might be rather different from that to the typical scientific question, 'What is the cause of this particular feature *within* the universe?'. Even so, scientists themselves certainly point to invisible entities with highly counter-intuitive and unfamiliar properties when seeking answers to the latter question. How much more likely, then, that we should need to appeal to a very special being for an answer to the first question. And again, one could certainly appeal to notions of simplicity and economy to infer one designer rather than many.

Kant's position regarding the human imposition of order also does not seem to square with how scientists see the world. For example, quantum theory seems to be forced on us by the reality of the external world, which exhibits such strange and startling phenomena at the micro-level, rather than being a human creation imposed on the world.[16]

Interestingly Max Planck, the great pioneer of quantum theory and a deeply religious man, showed how the constants of nature could be combined to define natural scales of length, time, mass and temperature. The fact that these turned out to be very different from anthropocentrically defined scales demonstrated for Planck that there really is an ultimate reality independent of the human mind.[17] These constants and scales will be important for our discussion later on.

Then consider the tremendous success of science, from eradicating smallpox to putting a man on the moon. The manifest ability of science to manipulate and predict the behaviour of the world surely speaks of an underlying reality, which we do have at least some purchase on. Moreover, as Brian Davies points out, if order is imposed by the human mind, we would be led to the startling conclusion that nature would cease to function in the orderly fashion uncovered by empirical science if there were no humans to observe it![18]

Notwithstanding Hume and Kant, the argument from design was famously revived by Archdeacon William Paley[19] who produced the following memorable analogy. Paley described himself walking across a heath and finding a watch on the ground. On examining the intricate mechanism of the watch he is struck by the idea that the watch was obviously designed by a clever watch-maker, for a purpose—to tell the time of day. How much cleverer, though, the designer of the far more intricate hand holding the watch! Indeed the contrivances of nature far surpass those of the watch.

It is to this form of the argument that Richard Dawkins draws attention. Indeed Dawkins takes the title of his book, *The Blind Watchmaker*, from Paley's example, and his central thesis is precisely that we and all creatures have been produced, not by a supernatural designer, but by the blind forces of evolution. The problem is, as Dawkins points out, that we now know scientifically how nature came to be so delicately balanced and interwoven. Darwinian evolution shows how different species evolve through the mutation of genes and the selective survival of those better adapted to their environment. We have an alternative explanation, for which there is good scientific evidence, to the God-hypothesis.

Now Paley's version of the design argument appeals to a God-of-the-gaps type of explanation, and Dawkins is surely right to argue that Darwinism defeats the argument in this form. Indeed Christian writers have long since pre-empted Dawkins in making just this point. Any argument based on the idea that God fills in the gaps in the scientific account will be vulnerable to the gaps being filled by science, as pointed out long ago by Charles Coulson, an eminent Christian scientist.[20] Indeed we have already come across just such a case when we noted how Laplace's nebular hypothesis removed the need for God's intervention in the working of the solar system as conceived by Newton—though in fact Laplace's system is both scientifically and theologically the more satisfactory. And Roman Catholic priest and historian of science Stanley Jaki has levelled just this God-of-the-gaps charge against Paley. *Inter alia* Jaki further charges that Paley fails to address Kant, who had already alluded to a watch in his attack on design, and, in emphasizing *beneficent* design, Paley ignores the problem of evil, still imbued with a certain freshness less than 50 years after the Lisbon earthquake of 1755.[21]

Of course the fact that Paley's version of the argument is inadequate by no means precludes the validity of a better argument. A viable argument from design must appeal to more general features about the universe, such as the very fact that there is order at all and that the universe exhibits law-like behaviour, rather than particular examples of order which may have a causal explanation from within scientific laws.

Richard Dawkins produces an analogue to evolution in the form of computer-generated shapes he calls 'biomorphs'.[22] These develop, reproduce, mutate and are sifted for survival according to fairly simple rules, which Dawkins experiments with, and once the process is set in motion the most fascinating and unpredictable forms arise after a few generations. Does this mean there is no need for a designer? Of course not. Who made the rules? Who designed and wrote the computer program which implements the rules? These did not spontaneously arise out of nothing. It is not difficult to see how Dawkins's argument, moving away from Paley to make the more sweeping claim that evolution does away with any need for God, is completely fallacious.

An important feature of the kind of argument we require will be that it is inductive rather than deductive. However, this makes it no less persuasive than any argument from within science, which proceeds to abstract laws from observed phenomena by induction. Richard Swinburne has shown how the design argument, and other arguments for the existence of God, including the cosmological, can be made rigorous in providing corroborative evidence, rather than logical proof, for God's existence.[23]

## The Importance of Order, Beauty and Simplicity for Science

That there is order in the universe which it is open to rational enquiry to discover is in fact a key assumption of science. Without it science cannot even get off the ground. Scientists like Dawkins therefore ought to be interested in the source of this order.

Let me explain what is at stake here. By the term 'order' I mean a pattern of regularity in the behaviour of the matter of the universe. A further assumption generally made, and especially in cosmology, is that this order, and the laws of nature which describe it, persist in all parts of the universe at all times both past and future. Here I regard this assumption of order to be a methodological starting point for science, one which any scientist, not least a scientific naturalist, would embrace in the course of his work—or certainly endorse if he thought about it. To a practising scientist, unlike to Kant, this order is really there waiting to be discovered.

A closely related example of this evidence for design, without which science could not function, is the utility of the principle of Ockham's razor, named after the great fourteenth century philosopher and theologian William of Ockham. The principle is generally formulated as 'Entities are not to be multiplied beyond necessity', though these precise words are not found in Ockham's extant works. We shall see in chapter 5 that the principle should not be construed solely in terms of numbers of entities, but is essentially a principle of simplicity.

Here we note the importance of the principle for the psychology of scientific research. Whilst it may arguably only have a pragmatic usefulness, the inclination of scientists is to see it as having epistemic value—they believe that simpler theories are more likely to be *true* than complex ones explaining the same phenomena. This point will be of vital significance when in due course we come to examine alternative explanations for the anthropic coincidences uncovered by cosmology.

Scientists are motivated by the general observation that the laws of nature are elegant and aesthetic—this is what makes science an exciting and fulfilling endeavour. The laws uncovered by scientists are often expressed with beautiful and concise mathematical symmetry (in a well-known paper physicist Eugene Wigner has spoken of the 'unreasonable effectiveness of mathematics in the natural sciences'[24]). Hence scientists will choose the simplest and most elegant explanation from competing alternative explanations of any phenomenon.

As an example, it is perfectly possible to view the earth as the centre of the solar system as did Ptolemy. The problem, however, is that, in order to account for the observed retrograde motions of the planets, their orbits round the earth have to be highly complicated epicycles. The revolution begun by Copernicus and completed by Kepler, who placed the sun at one focus of an elliptical planetary orbit, gave a much simpler picture and has been much more fruitful subsequently.

Although the principle does not always offer a clear and unequivocal guide, in general scientists regard it as a rational way of proceeding, and there is a match between what we find to be rational and the way the world is. As with order in the universe and its homogeneity in obedience to the laws of nature found on earth, there is no *a priori* reason why the principle of Ockham's razor should work. Elegance and simplicity seem to be criteria that work in science but science cannot explain why.

Of course agreement with experiment is vital for a theory to be accepted in science. It is also therefore an interesting fact that the method of induction, of drawing general inferences from particular instances, actually works in practice. Moreover it works with *our* concepts. Nelson Goodman posed a famous 'new riddle of induction' with his insistence that observations of emeralds which turn out to be green support both the hypothesis 'All emeralds are green' and 'All emeralds are grue', where 'grue' means 'green up until 31 December 2010 and blue thereafter'.[25] This is logically true but scientists work with arguably simpler concepts like green and find them to work.

As we have seen, however, agreement with experiment is far from being the only criterion. In a well-known article, Paul Dirac, the great Cambridge physicist who unified special relativity and quantum theory and predicted the existence of anti-matter, took an extreme view of the importance of elegance in a theory:

> It is more important to have beauty in one's equations than to have them fit experiment ... because the discrepancy may be due to minor features that are not properly taken into account and that will get cleared up with further developments of the theory ... It seems that if one is working from the point of view of getting beauty in one's equations, and if one has a really sound insight, one is on a sure line of progress.[26]

The search for simplicity and beauty in his scientific work was just as central for Einstein. As Banesh Hoffmann notes, 'The essence of Einstein's profundity lay in his simplicity; and the essence of his science lay in his artistry—his phenomenal sense of beauty.'[27] And again:

> When judging a scientific theory, his own or another's, he asked himself whether he would have made the universe in that way had he been God. This criterion may at first seem closer to mysticism than to what is usually thought of as science, yet it reveals Einstein's faith in an ultimate simplicity and beauty in the universe. Only a man with a profound religious and artistic conviction that beauty was there, waiting to be discovered, could have constructed theories whose most striking attribute, quite overtopping their spectacular successes, was their beauty.[28]

The search for beauty is equally important for Nobel prizewinner Steven Weinberg. Indeed his book *Dreams of a Final Theory* is replete with allusions to the need for beauty in scientific theories, even including a whole chapter on the topic. One quotation must suffice:

> Yet in this century, as we have seen in the cases of general relativity and the electroweak theory, the consensus in favor of physical theories has often been reached on the basis of aesthetic judgments before the experimental evidence for these theories became really compelling. I see in this the remarkable power of the physicist's sense of beauty acting in conjunction with and sometimes even in opposition to the weight of experimental evidence.[29]

Despite this Weinberg is an atheist. I find it strange that he can write of 'aesthetic judgments' and beauty, yet a few pages later write of the 'chilling impersonality of the laws of nature'.[30] Indeed, at the end of an earlier book Weinberg made his now famous remark, 'The more the universe seems comprehensible, the more it seems pointless.'[31] But where does all this comprehensibility and beauty come from? Why on earth should we expect it?

Michael Polanyi exposes the contradictory thinking of many scientists who, like Weinberg, appeal to beauty in judging candidate scientific theories, yet at the same time claim that science is 'impersonal'. He describes the classic case of the discovery by Einstein of the special theory of relativity.[32] Textbooks generally ascribe Einstein's achievement to an almost mechanical application of 'positivist' scientific methodology: the Michelson-Morley experiment showed no movement of the earth through the ether, Einstein deduced the constancy of the speed of light, and hence the new space-time conception of special relativity. In reality Einstein derived special relativity largely from a consideration of anomalies in the electrodynamics of moving media deriving from the traditional framework of absolute space and time. Relativity displayed a beauty and rationality, betokening a corresponding beauty and rationality implicit in nature, which then sustained belief in the theory despite the fact that the Michelson-Morley experiment, and later experiments by D. C. Miller, *didn't* show a null result for ether drag (though of course the theory's predictions have now been verified experimentally countless times over). Polanyi writes: 'We cannot truly account for our acceptance of such theories without endorsing our acknowledgement of a beauty that exhilarates and a profundity that entrances us.'[33] The application of human intellectual capacities for recognizing beauty and rationality results in what Polanyi calls 'personal knowledge'.

This is all in stark contrast to the positivist position, according to which scientific theory is merely a convenient codification of observations. As we shall see in due course, a notable adherent of positivism is Stephen Hawking, who nonetheless, and to my mind contradictorily, seems very happy to be speculating about superstrings, branes and the like, whose only motivation is their beauty and rationality, since they are utterly divorced from observation!

**Possible Responses from Scientific Naturalism**

The magnitude of this assumption of order, and its correlates in elegance, simplicity and the validity of the principle of induction, should not be underestimated, for it is truly remarkable that the universe should exhibit such supreme rationality and intelligibility. As Einstein put it, 'The eternal mystery of the world is its comprehensibility',[34] and again, 'The fact that it is comprehensible is a miracle'.[35] The validity of the same laws of nature in all parts of the universe at all times, and the openness of these laws to human enquiry, are indeed quite remarkable. An evolutionary account is inadequate to explain how we understand cosmology and quantum theory, since understanding them has no survival value.

Of course, from the point of view of science it is simplest to suppose this universal pattern of order and reliability (we shall return to the important topic of simplicity in chapter 5), but it does cry out for explanation on its own account. It is not adequate to say that it is not surprising that there is order because only so could we be here to observe it, i.e. we would not observe any of the vastly more numerous orderless universes.

Nobel prize-winning physicist Richard Feynman once gave a public lecture, during which he described how, on the way in to the lecture, he had observed a car in the car park with Tennessee number plate ARW 357.[36] 'Can you imagine? Of all the millions of license plates in the state, what was the chance I would see that particular one tonight? Amazing!', remarks Feynman. Of course, the *a priori* probability is very small, but this causes Feynman no problem, because any other car would be just as unlikely and just as insignificant. It just so happens that the car with number plate ARW 357 was the one which showed up. Similarly, according to some physicists, we do indeed live in a universe in which the laws of physics are ordered in a particular way, but if they were different in any number of equally improbable ways, we would not be here. Some cosmologists and philosophers believe that life is insignificant, a bit of froth on the surface of a meaningless universe, in which case alternative universes are just like alternative cars showing up in the car park.

This argument is vulnerable at two points. First, surely most of us would regard life, and in particular our own existence, not as mere froth but as of real significance and value. For this reason, the universe which actually exists is in a different category from the vast majority of universes which do not possess this value. And secondly, we can provide an explanation, namely the theistic hypothesis, for why, of the vastly many universes which could exist, one of meaning and value actually does so.

Swinburne[37] gives an example which tells against the 'car park argument'. A madman operates a machine that shuffles 10 packs of cards simultaneously. He tells his kidnapped victim that, unless the machine produces, and continues to produce for every draw, 10 aces, the machine will alternatively explode so that the victim will be killed and no longer able to observe any draws. But when the victim does observe successive draws, his conclusion is surely that the machine is rigged, rather than that there is nothing to explain because he wouldn't be around if anything else but 10 aces were drawn. This kind of argument will recur later when we return to the car park argument, and give further consideration to the idea that the universe is simply a brute fact.

Theism offers an explanation for the order found in the universe because, according to Swinburne, it is to be expected within the creation of a good God. If there is no God then we are expected to believe that the orderliness of the universe, manifested in all matter at all times and in all places obeying the same set of laws, is a brute unexplained fact; and this, as we have seen, seems extremely unlikely. Conversely, such order is extremely likely if it derives from a common source, just in the way that all tenpenny pieces are identical because they all come from the same mould. Thus order is very likely if there is a God. Moreover, if God produces a universe at all he is very likely to produce an orderly one rather than a totally disordered one because of his character. Swinburne argues that the properties of omnipotence, perfect goodness, and so on ascribed to God are essential to him and contribute to his simplicity. Creation of an ordered universe is a consequence of his goodness, since order is necessary for beauty and for rational creatures to grow in knowledge and power; and a good God has reason for making things beautiful rather than ugly and for making rational creatures in a learning environment.

Theism thus offers an explanation where the 'brute fact' notion failed to do so. A third possibility, suggested by Hume and given scientific credence by Boltzmann, is that eternal matter is forever arranging itself by chance and that we just happen to be in a phase of high order (we could not be in a phase with no order, as noted above). This interesting idea founders, as we shall see in due course, because the probability of finding the amount of order there actually is in the universe is much lower than the probability of finding the amount needed for us to be here. In fact, we can give numerical estimates of these probabilities, as discussed in chapter 7.

Hume's idea can be read as an example of a more general category of 'many universe' theories, and it seems to me that something like this is the solution to which the scientific naturalist is almost forced. The idea is that there are very many (usually infinitely many) universes, in which the parameters of the laws of physics take on different values. A universe like ours is then bound to show up sometime and we shouldn't be surprised to be in such a one because we couldn't exist in the vast majority of other possible universes. Going back to Swinburne's packs of cards, an alternative to the machine being rigged is that there are vastly many pack-shuffling machines, some of which are bound to draw 10 aces by pure chance. Our victim just happens to be one of the proportionately few lucky survivors.

We shall need to examine the 'many universes' hypothesis in its various guises in considerably more detail. At the outset we need to establish terminology. The word 'universe' is generally understood to mean 'all that exists'. That is clearly in conflict with the notion that there can be 'many universes'. Hence, following Murray Gell-Mann, I use the term 'universe' for an individual space-time region with a particular set of physical laws and parameters, and I use the term 'multiverse' for an ensemble of such universes.[38] We shall see that cosmologists speculate on various ways of conceiving the multiverse. I shall argue that the notion of a multiverse fares badly in explaining the order of our particular universe when compared with the alternative of design.

Meantime, I close this section with a further quotation from Einstein on the scientist's religious feeling of awe before the universe:

> His religious feeling takes the form of a rapturous amazement at the harmony of natural law, which reveals an intelligence of such superiority that, compared with it, all the systematic thinking and acting of human beings is an utterly insignificant reflection. This feeling is the guiding principle of his life and work, in so far as he succeeds in keeping himself from the shackles of selfish desire. It is beyond question closely akin to that which has possessed the religious geniuses of all ages.[39]

## Outline of the Book

My aim is to utilize modern discoveries in cosmology to support an argument from design. With this in mind I begin by presenting the modern scientific account of the origin and evolution of the universe. I show that the broad sweep of the Big Bang theory is well established, whilst at the same time there appear to be fundamental limits on our ability to probe the first tiny fraction of a second from the origin. It is questionable whether cosmologists working on theories of the very early universe are doing physics or metaphysics.

In order for the Big Bang universe to give rise to intelligent life, certain parameters relating to the initial conditions and the constants of nature must be very tightly constrained. This is the evidence of the universe's 'fine-tuning' which is highly suggestive of design. There is in fact a vast amount of this evidence—an endless list of seeming coincidences necessary for life—so I inevitably limit myself to a few important examples. It is the kind of evidence needed for a viable argument from design because it relates to the laws of physics and the initial conditions which are required before physics can actually do its work. Physics can tell us what the laws are but cannot explain why they are what they are. The design argument says they were deliberately chosen by God, who assigned values to the parameters expressly in order that the universe give rise to intelligent creatures at some point in its history.

Whilst the fine-tuning is suggestive of design, we also need to examine critically what alternatives to design cosmologists have come up with (some of which I have already mentioned above). These I lay out, and then go on to propose a method for assessing what amount to alternative metaphysical explanations, for, contra Dawkins *et al.*, a metaphysical explanation of some sort is unavoidable. The method proposed for assessment is Bayesian probability theory, which I take to be the most rigorous procedure for evaluating competing scientific hypotheses. Richard Dawkins describes explanations in terms of God as competing on the same ground with scientific explanations,[40] so it would seem appropriate to take Dawkins at his word and evaluate our metaphysical explanations in the same way as we would scientific ones.

We then come to my evaluation of the three main alternatives, namely: (i) there is a cosmic designer; (ii) there is one universe as a brute fact; and (iii) there is a multiverse. This last seems to be a genuine alternative to design since, unlike the single brute fact universe, it offers an explanation of the fine-tuning, namely that we should not be surprised to be in a universe like ours since there are an infinite number of universes in which all the parameters vary and we could only exist in one like ours.

Whilst on the face of it the multiverse hypothesis thus offers a viable explanation for the fine-tuning of ours, and hence for life, I argue that design is more probable, essentially because, agreeing with Richard Swinburne, God is of higher prior probability than an infinitude of universes.

This initial conclusion is considerably strengthened by a more detailed look at versions of the multiverse hypothesis. The analysis reveals a number of crucial problems. Thus it turns out that the existence of infinitely many universes in the first place depends critically on parameter choice. Then the probability that any universe in an ensemble is fine-tuned for life is not positive, as would be needed for the hypothesis to guarantee a universe like ours, but zero. The physical realisation of any ensemble would in fact exclude an infinity of possibilities. Furthermore, the hypothesis is untestable and unscientific, and, as mentioned earlier, it is not consistent with the amount of order found in this universe, nor with the persistence of order. Moreover, the inflationary universe popular with many cosmologists does not seem to fulfil its early promise of facilitating an escape from design. In the sense that it provides a mechanism for generating many universes it is subject to the same criticisms as other multiverse scenarios. In a further chapter the above point about the limit to the number of physically realizable universes is expanded. All these considerations substantially weaken the case for many universes as an explanation for the fine-tuning of this one.

My final chapter summarizes all these findings, firmly concluding that design by God best explains the fine-tuning of our universe.

## Notes

1 Dawkins (1988), p. 147.
2 Atkins (1981), p. vii.
3 Hawking (1988), pp. 140-141.
4 The story of the Napoleon-Laplace encounter, and Lagrange's later comment, are related in Rouse Ball (1901), p. 427; and the original argument between the Emperor and Laplace may have been that witnessed by the great British astronomer Sir William Herschel—see Lubbock (1933), p. 310.
5 Dawkins (1988), p. 15.
6 Atkins (1981), p. 3.
7 Leslie (1979), p. 6.
8 In Swinburne (1991). Issues of economy and simplicity will be important, however, for my argument later on, mainly when I compare theism with the many universes hypothesis, but also with Hume's polytheistic alternative mentioned later in this chapter.

9 An important recent contribution to theodicy, that area of theology which deals with the vindication of God as righteous in the light of the existence of evil in the world, is to be found in Swinburne (1998). I do just briefly allude to this problem again in chapter 5, though, to reiterate, I cannot develop any of the arguments for the purposes of this book.
10 See Macquarrie (1993), p. 402.
11 Holder (2001c).
12 Plantinga (1974), pp. 213-217. Of course one needs to unpack what is meant by God here. For Plantinga God is understood to possess 'unsurpassable greatness', defined in turn as 'maximal excellence', i.e. omniscience, omnipotence and moral perfection, in every possible world. It follows that if unsurpassable greatness is exemplified in some world, it is exemplified in all, i.e., in the terminology of modal logic, if God is possible, then he exists.
13 See, for example, Davies (1993), pp. 74-93, for an assessment of various forms of the cosmological argument.
14 St Thomas Aquinas, *Summa Theologiae*, 1a. 2, 3.
15 Most texts on philosophy of religion give a discussion of the pros and cons of the design argument, as well as the other classic arguments. See, for example, Davies (1993), pp. 94-119.
16 We shall have cause to discuss quantum theory further. Whilst all physicists accept the mathematical formalism, there is still much controversy surrounding its interpretation, as we see in chapter 4. This is essentially because physicists are not happy with the question marks which the traditional 'Copenhagen' interpretation places back on reality, and they wish to recover a more thoroughgoing realism.
17 See Barrow (2002), pp. 23-29. The constants in question were Planck's constant appearing in quantum theory, the gravitational constant, and the speed of light.
18 Davies (1993), pp. 97-98.
19 Paley (1802).
20 Coulson (1971), p. 31. Coulson was Rouse Ball Professor of Mathematics at Oxford, the chair more recently occupied by cosmologist Sir Roger Penrose, whose work we shall later have cause to discuss.
21 See Jaki (1990), pp. 59-74. Of course, I have admitted to ignoring the problem of evil myself in this book, though I do acknowledge its relevance in making the overall case for theism.
22 Dawkins (1988), pp. 53-73.
23 Swinburne (1991).
24 Wigner (1960).
25 Goodman (1946). As time goes by the date appearing in citations of Goodman's paradox tends to move further into the future!
26 Dirac (1963).
27 Hoffmann, cited in French (ed.) (1979), p. 141.
28 *Ibid.*, p. 175.
29 Weinberg (1993), p. 103.
30 *Ibid.*, p. 196.
31 Weinberg (1977), p. 154.
32 Polanyi (1958), pp. 9-15.
33 *Ibid.*, p. 15.
34 Einstein (1936), p. 61.
35 *Ibid.*

36 Feynman (1995), p. xix.
37 Swinburne (1991), p. 138.
38 Gell-Mann (1994), pp. 210-212.
39 Einstein (1935), p. 28.
40 E.g. in Dawkins (1994) he says: 'Religion does not confine itself to ethics and other non-scientific preserves: it strays massively and obtrusively into the territory of science. It has pretensions to explain life and the universe. A religion is therefore a rival scientific theory and must be judged by the rigorous standards of science.'

# Chapter 2

# The Origin and Evolution of the Universe

There was a Door to which I found no Key:
There was a Veil past which I could not see:

(Edward Fitzgerald, *Rubaiyát of Omar Khayyám of Naishápúr*, ed. 1, xxxii.)

## A Brief Introduction to Big Bang Cosmology

It is now accepted by the vast majority of cosmologists that the universe began in a hot, dense state some 15,000 million years ago. From the expansion and cooling of the primordial fireball evolved the galaxies, stars and planets—the universe we observe today. This is the standard Big Bang theory of the origin of the universe.[1]

The key observation giving rise to the Big Bang theory was made by Edwin Hubble in the 1920s. This is that the universe is expanding. The basic building block of the universe is the galaxy cluster, and clusters of galaxies are observed to be receding at a rate proportional to their distance—the further away they are, the faster they are moving. Although the details are somewhat technical, the principle by which this law is obtained is easy to explain. Quite simply, the distance of an object is determined from its brightness—the further away, the fainter it will be. In addition the light from an object moving away from us will be shifted to the red, and this redshift enables us to determine its speed of recession.

Interestingly this velocity-distance proportionality law is the only law which would look the same from whichever galaxy in the universe the observation was made, indicating that we are not in any privileged position ('centre') in the universe. The natural conclusion to draw from the expansion is that the matter of the universe was more compact in the past, indeed that the present universe must have evolved from a very dense, initial state.

The fact that a conclusion seems 'natural' is, however, not sufficient for it to be right scientifically. In 1948 a group of distinguished cosmologists working in Cambridge—Hermann Bondi, Thomas Gold and Fred Hoyle—produced a rival theory, known as the 'steady state theory'. These cosmologists were working with a philosophical principle, the 'perfect cosmological principle', according to which the universe, at least on the large scale, should look the same at all times as well as in all places.[2] A universe obeying this principle would have no temporal origin, and so, at any rate as these atheistically minded scientists thought, no requirement for God to explain the origin.

Of course, the Big Bang theory does not guarantee that the universe had a beginning in time either. For example the universe could be oscillatory, comprising an endless sequence of expansions and recontractions, big bangs and big crunches. Whilst the oscillatory model is problematic (as I explain in chapter 4), it suffices to make the point that science cannot decide the *metaphysical* question of the universe's temporal origin. I shall use terminology such as the 'origin' of the universe, the 'age' of the universe, and so on, with this qualification understood. Even so, the Big Bang theory is certainly compatible with the view of St Augustine, writing *circa* 400 AD, that 'assuredly, the world was made, not in time, but simultaneously with time'.[3] Indeed it is quite instructive to note how much of the modern discussion, e.g. on the cyclic universe and plurality of worlds, has been pre-empted by Augustine and other ancient writers. I explain in chapter 4 why I think it is theologically mistaken to suppose that theism is somehow undermined by models of the universe which have no origin in time.

The steady state theory explained the expansion of the universe by invoking the continuous creation of new matter, and hence over time new galaxies, at just the rate required to fill the spaces left as the existing galaxies recede from one another. Since the rate at which new matter needed to be formed was extremely low, the theory was, apparently, immune from experimental falsification.

In fact, however, there are three main strands of observations which convincingly support the Big Bang theory, and serve to undermine the steady state theory:

(1) In 1948 George Gamow predicted, on the basis of the Big Bang theory, the existence of a uniform, remnant radiation field bathing the universe, radiation which had cooled dramatically from very high temperatures pertaining in the early universe. The calculation put the present temperature of this remnant radiation rather too high, and the idea lay dormant until the 1960s when Robert Dicke of Princeton, New Jersey, independently took up the idea of the hot Big Bang whilst investigating oscillating universe theories.

The most important feature of this predicted radiation is that it exhibits a so-called black-body (or 'thermal') spectrum. That is to say, the radiation is in thermal equilibrium at a uniform temperature. This equilibrium would have been achieved in the early universe when the temperature was high enough for the matter to be ionized and the radiation to have interacted with it, for example by scattering of the photons of radiation by the free electrons. Many such interactions lead to equilibrium. As the universe expands, it cools and the matter recombines, and interactions between matter and radiation cease. The legacy from this early epoch, however, remains, namely the black body spectrum of the radiation.

In 1965 Arno Penzias and Robert Wilson, of Bell Telephone Laboratories, working at the time at Holmdel near Princeton, detected unwanted and unexpectedly large noise in their antenna. This comprised microwave radiation at an effective temperature of about 3.5 K—meaning 3.5 degrees above absolute zero and revised slightly downwards since then to about 2.7 K.

Dicke and colleagues (notably Jim Peebles) seized on these observations as just what had been expected from the Big Bang theory. The observation of the cosmic background radiation has been seen as of clinching importance for the Big Bang theory, which explains it quite naturally, and devastating for the steady state theory, which cannot explain it, except by highly contrived means—and even these contrived explanations have had to be abandoned in the face of measurements from the COBE (Cosmic Background Explorer) satellite showing that the spectrum of the radiation is black body to very high accuracy.

(2) The theory correctly predicts the abundances of the light elements (notably helium and the deuterium isotope of hydrogen, but a few others as well), which it explains as being formed from nuclear reactions in the first minutes of the universe's existence, substantially earlier than the era from which we get the microwave background radiation.

Nuclear fusion, by which the chemical elements are built up, occurs at very high temperatures when atomic nuclei can collide at high enough speeds to overcome the repulsion due to their electric charges. Gamow had originally hoped that all the elements could be built up in the Big Bang, where high temperature conditions would obtain, but his calculations showed that almost nothing but hydrogen and helium could be formed then.

Very high temperatures are also reached in the interiors of stars, and Fred Hoyle and colleagues in the 1950s showed how the abundances of 'heavy' elements, such as carbon, oxygen and iron, could be accounted for by stellar nucleosynthesis, which occurs much later in the history of the cosmos, as we shall see below. Indeed, in their classic paper of 1957, Hoyle, William Fowler, and Geoffrey and Margaret Burbidge, showed that virtually the whole periodic table, the elements from carbon to uranium, could be built up in this way.[4] These calculations constitute a quite remarkable achievement for modern physics, though the astrophysics community was shocked that the Nobel Prize which this work truly merited was awarded to Fowler alone in 1983.[5]

Despite this triumph, it turned out to be quite impossible that the light element helium, the second element in the periodic table, could be produced in anything like its observed abundance of about 25% by mass, in stars. Hoyle and colleagues, in calculations more accurate than Gamow's, showed that just the right amount of helium could be produced in the Big Bang (incidentally putting a nail in the coffin of Hoyle's own favoured steady state theory).[6]

What is more, deuterium, the heavy isotope of hydrogen, is observed to occur in the ratio of about 1 atom for every $10^5$ atoms of hydrogen. But deuterium gets destroyed in stellar interiors rather than produced! Again, however, the abundance of deuterium can be accurately calculated as resulting from nucleosynthesis in the Big Bang. There are a few other light elements, or isotopes thereof, occurring in trace amounts, e.g. lithium, which are also explained as originating in the Big Bang. In a nutshell, light element production in the Big Bang completes a satisfying account of how the elements heavier than hydrogen are manufactured.

(3) If we look at very distant objects in the universe we are looking at the universe as it used to be in the distant past. On the basis of the steady state theory we would of course expect to see no difference in the large-scale features of the universe over time. The Big Bang theory, on the other hand, would lead us to expect signs of cosmic evolution. In the late 1950s Martin Ryle (later Sir Martin Ryle) and colleagues used the radio astronomy facilities in Cambridge to observe distant 'active galaxies'. They discovered that there were too many faint (and presumably distant) sources, compared with intense (and therefore presumably closer) sources. This is inexplicable on the steady state theory, but compatible with the notion that younger galaxies (the more distant ones on the Big Bang theory) exhibit more violent activity than older (and closer ones), and so there has indeed been evolution. Much more recent optical observations of active galactic nuclei (quasars) have confirmed such evolution.

These three sets of observations, and most particularly the first, have established the Big Bang theory as extremely well supported, and effectively refuted its main rival, the steady state theory.

## An Excursus into Particle Physics

In a moment, we shall explore the Big Bang theory a little more closely, examining various stages in the universe's history. But before we can do that, we need to discuss some aspects of particle physics. We begin by briefly considering the four fundamental forces of nature.

The four fundamental forces are: (i) gravity, which is a force of attraction between any two bodies; (ii) electromagnetism, which concerns the electric and magnetic forces between charged particles; (iii) the weak nuclear force, which is responsible for radioactive decay; and (iv) the strong nuclear force, which is responsible for binding the nucleus of an atom together. Particles which experience the strong force are called hadrons; the familiar protons and neutrons belong to a subspecies of hadron called baryons, and comprise three 'quarks'.

We have already begun to see that, according to the Big Bang theory, both temperature and density increase as we go back in time, and as they do so atoms are split into their component, more fundamental particles. First, atoms are ionized (split into negatively charged electrons and positively charged nuclei); then the nuclei themselves split apart into their constituent protons and neutrons; and even these are believed to be split further as the temperature continues to rise. So we can see how cosmology, in seeking to understand the early universe, must engage with particle physics; but there is a fundamental problem, namely that, at the earliest epochs, we do not know what the particle physics is, which we should be applying!

It would appear that as we explore further back in time, ever more closely approaching the point of origin at time zero, we encounter a number of barriers. The physics we know, which applies in the terrestrial laboratory and has been tested in particle accelerators, begins to look inadequate. Remarkably, we do know the physics which applies at very early times indeed—hence the success of element abundance prediction, for example, which occurs in the first minutes of the universe's existence. We can with reasonable confidence go back even further to about $10^{-10}$ seconds from the origin, when the electromagnetic and weak nuclear forces, previously combined (see below), separate. However, as we press back to still earlier times, we find that matter exists in ever more exotic states which we do not (yet, at any rate) have the physics to describe. Thus, before $10^{-32}$ seconds or thereabouts we need a Grand Unified Theory in which the strong nuclear force is combined with the weak and electromagnetic forces, and before $10^{-43}$ seconds a quantum theory of gravity which combines gravity with the other forces too. We now examine how physicists are faring with the search for such theories.

The 'holy grail' which physicists are seeking is what they often describe as a 'Theory of Everything' (TOE). Such a theory would unite all four fundamental forces into a single force. It would describe matter in terms of its basic building blocks. It would explain why there are just the particles there are in nature—it would therefore go back a step from the myriad variety of particles which have been observed in our particle accelerators to see these, not as given brute facts of nature, but as consequences of something much simpler. It would also unite quantum theory, which is required to describe the behaviour of matter on the scale of the very small, with general relativity which is required to describe matter on the scale of the very large, and which describes the structure of space-time.

All these are laudable aims. However, it is a gross misnomer to call such a theory a Theory of Everything, as I and others have argued.[7] Such a theory would not only fail to explain higher level phenomena, such as life or consciousness, but would have nothing whatever to contribute to an understanding of such phenomena. And even at the physical level, in order to make predictions the laws of physics need to be supplemented with initial conditions, and even then will not determine the history of the universe but only give us the probabilities for alternative histories.[8]

Interestingly Stephen Hawking has recently recanted his belief, expressed so forcibly in his inaugural lecture as Lucasian Professor of Mathematics at Cambridge entitled 'Is the End in Sight for Theoretical Physics?', and in *A Brief History of Time*, that physicists are on the threshold of discovering the ultimate TOE. He does so on the grounds that mathematics, which would be used to express the TOE, has been shown by mathematician Kurt Gödel to be either inconsistent or incomplete.[9] That Gödel's famous theorem of 1931 has a knock-on effect on physics is a point which some of Hawking's colleagues have been making for some time.[10]

But putting such anti-reductionist arguments aside, to seek a unifying theory such as I have described is at the heart of what physics is all about. As Paul Davies notes (and as we discussed in chapter 1), the search is motivated by a deep belief among physicists that nature ought to be simple—a belief which Davies rightly calls 'an act of faith'.[11] How far have physicists got with finding such a theory, and how will this impact on the design argument as motivated by the fine-tuning of the universe as I shall expound it?

In fact, various unifications have already been successfully accomplished. The electric and magnetic forces were united in a brilliant synthesis by James Clerk Maxwell in the nineteenth century. It was the great insight of Einstein to propose that Maxwell's equations (which implied the constancy of the speed of light), like Newton's equations of dynamics, obeyed the 'special principle of relativity', according to which observers moving in inertial frames of reference (those in uniform motion relative to the fixed stars) would observe the same physical laws. The resultant 'special theory of relativity' has been abundantly vindicated from its observed, often bizarre, consequences. In 1927 Dirac united special relativity and quantum theory in deriving his equation for the electron, and hence predicted the existence of a similar but positively charged particle, the positron (the first anti-matter particle, observed by Carl Anderson in 1932).

Unification has proceeded apace since World War II. First, a relativistic quantum field theory, i.e. a theory of the electromagnetic field consistent with both quantum mechanics and special relativity, was developed in 1948 by Richard Feynman and Julian Schwinger in the USA, and Sin-Itiro Tomonaga in Japan. This theory is known as quantum electrodynamics (QED) and earned its originators the 1965 Nobel prize.

The electromagnetic and weak nuclear forces were united between 1967 and 1970, in a theory of 'electroweak' interactions, by Sheldon Glashow, Abdus Salam and Steven Weinberg (for which these men received the Nobel prize in 1979).

The atomic nucleus consists of a number of protons and neutrons bound tightly together. Protons and neutrons in their turn are believed to be comprised of quarks. The theory which describes the binding of quarks to form the nuclear particles was developed in about 1974 and is called quantum chromodynamics (QCD).

The so-called 'standard model' of particle physics, which had evolved by the early seventies, consists of two parts: the unified electroweak force and QCD. This model would seem to be well established. In particular it has received substantial experimental verification, for example the triumphant observation at CERN in Geneva of the W and Z particles predicted by the electroweak theory. Nevertheless, importantly from the point of view of anthropic fine-tuning to be considered later in this book, the model does not explain the particle masses—these are among the 19 free parameters within the model.[12]

Physicists are of course not content to leave things in this rather messy state. They want a Grand Unified Theory (GUT) to replace the standard model; and beyond this there is the Holy Grail of a Theory of Everything uniting gravity with the electroweak and strong forces.

The idea of GUTs is that at low energies we see the separation of forces into those we know about already, but at high energies the forces are united into a single interaction. The trouble is that the unification energy is about $10^{13}$ times that for the electroweak force and way beyond anything achievable in the laboratory. Moreover, other predictions made by GUTs are highly problematic. For example, most GUTs predict proton decay, which has not been observed, and also magnetic monopoles (isolated magnetic charges as opposed to the usual magnetic dipoles)—again which have not been observed. In the Big Bang, GUTs would describe the almost incredibly early epoch $10^{-43}$ sec $\lesssim t \lesssim 10^{-32}$ sec. The theory of inflation has been invoked to solve the magnetic monopole problem, and seems to solve some other problems in cosmology—I shall return to it in chapters 4 and 7, but in more detail in chapter 8.

**Strings—the Ultimate Theory?**

GUTs are speculative enough, but when we come to Theories of Everything, which unite all four forces, the problems are orders of magnitude greater still.

The leading contender for a TOE (or perhaps more accurately a 'superunified' theory) is 'string' theory, or in its later manifestations, 'superstring' theory and M-theory.[13] This is the theory which has made the most running in the physics community, and so the one I shall concentrate on below. However, it is important to note the main rival, namely 'loop quantum gravity'.[14] Both theories suffer from a lack of any anchoring to observation, as we shall see particularly for string theory. Loop quantum gravity's distinctive prediction is that space-time is granular, i.e. not infinitely divisible. The scale of such granulation, however, is the Planck length, about $1.6 \times 10^{-33}$ cm, and way beyond the reach of observation.[15]

The basic idea of string theory is that the ultimate building blocks of matter are not the quarks or other elementary particles known to us, but tiny bits of string. The string-like objects (not the space as in loop quantum gravity) are taken to be about a Planck length long with zero thickness. This is incredibly tiny, comparing as it does with a size of about $10^{-8}$ cm for an atom and $10^{-13}$ cm for an atomic nucleus.

Proponents of string theory claim for it a beautiful mathematical elegance, certainly a feature which has both appealed to physicists in the past and one which successful theories have been found actually to exhibit (see chapter 1). Importantly string theory solves a number of disquieting problems with existing theories such as the occurrence of infinite quantities (infinite mass and charge etc.) which are necessarily unphysical. The elementary particles we observe are simply different modes of vibration of the strings. I say 'simply', but an important complication is that these vibrations occur in more than the familiar 3 spatial dimensions we are used to. These extra dimensions get 'curled up' so as to be far too tiny to be detectable. Why there are precisely three 'extended dimensions' remains unexplained, even with the latest versions of string theory which I now describe.[16]

String theory has evolved from its early phase into, first, 'superstring theory', and, most recently, 'M-theory'. The vibrational patterns of the original string theory described only the force-mediating particles, called bosons, whose quantum mechanical 'spin' (analogous to classical angular momentum) is a whole number. Then supersymmetry was postulated, whereby each matter particle, called a fermion, and possessing spin an odd multiple of ½, is related to a corresponding boson.[17] Since it was found that presently known particles could not be 'superpartners' of one another, this has resulted in the postulated existence of a host of new particles—selectrons, sneutrinos, squarks, etc., where the initial 's' stands for 'supersymmetric-'. Superstring theory incorporates supersymmetry into string theory.[18]

Whilst this might seem anti-Ockhamite, and even though none of the postulated extra particles have been detected, physicists seem happy with this state of affairs because supersymmetry apparently solves several theoretical problems. The reasons for embracing supersymmetry include (i) the simple aesthetic desire for maximal symmetry in a theory; (ii) the removal of inconsistencies from the original string theory due to the predicted existence of tachyons, particles which move faster than light; (iii) the removal of the need for some fine-tuning in the standard model; and (iv) the fact that the force strengths of the weak, strong and electromagnetic forces are driven to exact, rather than only approximate, equality at the GUT temperature, $T \sim 10^{28}$ K.[19]

It turns out, however, that supersymmetry can be incorporated into string theory in 5 different ways, which is hardly satisfactory if one is looking for a unique TOE. M-theory is a generalization of string theory which incorporates all 5 superstring theories.[20] The name is due to Edward Witten but the meaning of 'M' can be what takes any physicist's fancy—Mystery, Mother (as in 'Mother of all Theories'!), Membrane, ...[21]

In M-theory the basic unit of matter is no longer the one-dimensional string, but a multi-dimensional generalization thereof, dubbed the 'brane'. Then a 1-brane is a string, a 2-brane is a membrane, and so on to higher dimensions, the general case being the $p$-brane. Many physicists (including, apparently, Stephen Hawking[22]) now think that M-theory may be the final TOE, precisely because it is a general framework which produces the 5 string theories as special cases. For example, a membrane will squash down into a string given certain approximations, and indeed it is argued that it is because physicists had to use approximations that they missed this generalization in the first place. Even so, Brian Greene, a leading string theorist, admits that as yet we have a scant understanding of M-theory, and cannot explain which if any of the sub-models describes our actual universe!

String theory in all its manifestations is indeed highly problematic, both scientifically and philosophically. Naturally the strings, membranes and so on are so small as to be quite unobservable. In itself that would not be an insuperable problem, except for a logical positivist: the existence of the fundamental particles of nature has always been inferred indirectly from their effects, tracks in a bubble chamber etc., rather than directly; and it certainly seems rational to believe in their reality. And in chapter 1 I noted the importance of beauty and rationality in a theory, even if experimental evidence was, at least initially, lacking. It seems to me that the problems for string theory run deeper than that.

Currently experiments in particle physics can be done at energies of the order of 100 GeV.[23] The Planck energy, at which quantum gravity effects become apparent, is $10^{19}$ GeV. To do experiments at this energy would require accelerators at least 10 light years in length! The estimated current technological limit to achievable energies is about $10^7$ GeV.[24] Indeed, the situation may be much worse even than this: as reported by Greene, Shmuel Nussinov of Tel Aviv University, in more careful calculations, has estimated that one would need an accelerator the size of the universe to see individual strings!

Because the natural mass scale built into string theory is the Planck mass, so enormous compared with the masses of the particles we can presently observe, string theory cannot predict the ratios of the masses of the latter—they are all essentially massless in the theory. So the problem is that there do not seem to be any experiments we can do to verify string theory, because it makes no predictions in measurable régimes.

The question seriously arises as to what physicists involved in string theory are actually doing. Are they doing science at all? Or are they doing metaphysics? This kind of question has certainly been posed by some particle physicists. Sheldon Glashow writes: 'I think that the old tradition of learning about the world by looking at the world will survive, and we will not succeed in solving the problems of elementary particle physics by the power of pure thought itself.'[25]

Glashow is appealing here to experiment which has been the basis of science at least since Francis Bacon. The universe is contingent (it might have been other than it is and might not have been at all), and to find out about the way it is, you simply have to look at it. Abstract thought, which Plato might have deemed adequate for understanding the world, is not so. Even beautiful and rational theories need to make testable predictions.[26]

Richard Feynman is also highly critical of string theory because the link with experiment has been broken. 'They are not calculating anything', he says of string theorists, and worse, 'for anything that disagrees with experiment they cook up an explanation'.[27] In particular, they are not predicting the spectrum of particle masses, or the values of the coupling constants (constants which describe the strengths of the fundamental forces, and which are important in anthropic arguments).

It would appear that nature is presenting us with barriers which it may be impossible to traverse. A quantum theory of gravity is needed in order to understand the first fraction of a second of the Big Bang. If string theory, or M-theory (or alternatively loop quantum gravity), is the right theory, that is what is needed. But if the theory is untestable, the question arises as to whether we shall ever be able to understand that first fraction of a second. On the other hand, it is certainly very interesting that cosmology, the study of the universe as a whole, and particle physics, the study of the basic building blocks of matter, are so interlinked. Michael Green, one of the foremost string theorists, wrote in 1988 that the theory is in its early days, and needs a good deal of development and further understanding before predictions can be made.[28] Clearly some progress has been made since then, most especially with M-theory. But we are still way short of tangible predictions. Perhaps they will come and then maybe M-theory will have something to say about the early evolution of the universe which may have observational consequences. Who knows?[29]

**Back to the Beginning**

It will be helpful to divide the evolution of the universe into distinct phases, characterized by the form which matter takes, the stage of force unification which is operative, and the physical processes occurring, in each. We thus trace the universe's history forwards from the earliest epoch, giving an indication of the time $t$ from the initial singularity and the temperature $T$ pertaining. I include for completeness the first two eras, when, as indicated above, the physics is most speculative:

(1) The Planck era: $t \lesssim 10^{-43}$ sec, $T \gtrsim 10^{32}$ K. This is the era when the universe is so dense and small that a theory combining general relativity (the modern theory of gravity) and quantum mechanics is required to describe it. We have seen that string theory, perhaps as generalized into M-theory, is a major candidate for such a theory, and have noted some of the philosophical problems associated with an attempt to describe such an early epoch. String theory would imply that, at about the Planck time, $t \approx t_P \approx 10^{-43}$ sec, three spatial dimensions were separated out for expansion whilst the others retained their Planck-scale size.

(2) The Grand Unified Theory (GUT) era: $10^{-43}$ sec $\lesssim t \lesssim 10^{-32}$ sec, $10^{32}$ K $\gtrsim T \gtrsim 10^{27}$ K. This is the era when the forces of nature apart from gravity are assumed to be united. We have seen that the physics of this era is also highly speculative.

At the end of the GUT era, when the temperature had fallen to about $10^{29}$ K, a phase transition (change of state) is assumed to occur in which the strong force and the electroweak force separate through 'spontaneous symmetry breaking'. The process is analogous to the way in which a crystal forms as atoms start to arrange themselves along randomly chosen axes, when previously there was no preferred direction (in this case the rotational symmetry is broken; in the particle physics case it is rather more complex kinds of symmetry).

It is now widely believed that this force separation occurred during a very brief period, from $t \approx 10^{-35}$ sec to $t \approx 10^{-32}$ sec, when the expansion of the universe accelerated and the universe increased in size from a mere $10^{-25}$ cm to 10 metres. This is the so-called 'inflationary' expansion of the universe, to which we shall have cause to return in later chapters (especially chapter 8). Following inflation, if it occurred, we enter the realm of the standard hot Big Bang model, though our knowledge is still sketchy for at least the early part of the next phase.

(3) The hadron era: $10^{-32}$ sec $\lesssim t \lesssim 10^{-4}$ sec, $10^{27}$ K $\gtrsim T \gtrsim 10^{12}$ K. During this era the quarks which interact via the strong force are too energetic to bind together to form the protons and neutrons with which we are more familiar. Also the heavy W and Z particles which mediate the weak force are essentially indistinguishable from photons whilst electromagnetism and weak forces remain united. However, at $t \approx 10^{-10}$ sec, when $T \approx 10^{15}$ K, a further phase transition occurs whereby the electroweak force splits into electromagnetic and weak forces, which affect the particles differently. The W and Z particles rapidly decay at this point.

At $t \approx 10^{-4}$ sec, the temperature falls sufficiently for the quarks to be bound to form protons and neutrons.

This era leaves us with a mix of particles we are fairly familiar with—such as protons, neutrons, electrons and their anti-particles—and radiation. Because of the rapid collisions between the particles, and interactions between the matter and radiation, this mix is in thermal equilibrium. In the steady state of thermal equilibrium particles enter and leave any range of velocity, spin, etc., at the same rate, and the production and annihilation rates of particle species are in balance. Thus at this stage of the universe's evolution the number of proton anti-proton pairs, and other pairs, will be roughly the same as the number of photons. There will also be almost exactly equal numbers of baryons and anti-baryons, in fact an excess of 1 part in $10^9$ of particles over antiparticles, an important quantity bequeathed for the future of the universe, from its earliest moments, to which we shall return in chapter 3.

(4) The lepton era: $10^{-4}$ sec $\lesssim t \lesssim 100$ sec, $10^{12}$ K $\gtrsim T \gtrsim 10^9$ K. When the temperature has fallen below that corresponding to the rest energy of a proton, the proton anti-proton pairs annihilate, and cannot now be replaced by free creation from thermal radiation.[30] All the antiprotons disappear so that only the small primordial excess of protons remains, and these are dynamically and thermally negligible. Hence we arrive in the lepton era where energy is shared by radiation and the lighter particles called leptons, which do not participate in the strong interaction. Leptons include electrons and positrons, muons (particles with mass about 200 times that of the electron), and neutrinos (massless or at any rate very low mass particles resulting from the radioactive decay of a nucleus). As the temperature drops further, first the muon-antimuon pairs, and then most electron-positron pairs, annihilate.

During the lepton era protons and neutrons transmute into each other via weak interactions. The overall ratio of numbers of protons to neutrons for equilibrium is determined from the Boltzmann distribution of statistical mechanics and depends on the ratio of the mass difference between these particles to the temperature.[31] For $T \gg 10^{10}$ K this ensures that protons and neutrons occur in approximately equal numbers. For $T$ below $10^{10}$ K the number of protons starts to predominate. However, since the expansion time-scale also becomes shorter than the equilibrium time-scale at these temperatures, the ratio of number of protons to number of neutrons is rapidly 'frozen out'. The value it takes is important for the helium production in the Big Bang, which takes place in the following era.

(5) The plasma era: 100 sec $\lesssim t \lesssim$ 300,000 years, $10^9$ K $\gtrsim T \gtrsim$ 4000 K. The lepton era bequeaths us an electron excess equal to the proton excess, for total charge neutrality. Photons repeatedly scatter off the electrons (this process is known as Compton scattering) so that matter and radiation essentially comprise a single fluid, with radiation providing all the pressure, and the matter and radiation being at almost the same temperature. When the temperature drops to 4000 K the protons and electrons combine to form atomic hydrogen. By $T \approx$ 1000 K only 1 in $10^4$ electrons remains free.

At the beginning of the plasma era, with the universe barely minutes old, neutrons and protons combine to form deuterium ($^2$H) and then helium ($^4$He). We have seen that detailed calculations give a helium abundance from these reactions of 25% by mass, in agreement with observation. Interestingly, as noted above, these calculations came from Fred Hoyle and colleagues, Hoyle having been a proponent of the steady state theory which his own calculations contributed to overthrow. Similar arguments apply to the surviving deuterium abundance, plus the abundance of some other lighter elements and isotopes such as $^3$He and $^7$Li. I shall have occasion in chapter 8 to refer to how the observed abundances of the light elements constrain the important cosmological parameter $\Omega_0$, the ratio of the mean density of energy (or at any rate the baryonic matter component thereof) in the universe today to the so-called critical density (as defined in the next chapter). For now, we note that these light element abundance predictions are generally considered to be a triumph of the Big Bang model of the universe.

(6) The post-recombination era: $t \gtrsim$ 300,000 years, $T \lesssim$ 4000 K, and $T \to$ 3 K as $t \to t_{now}$, the present time. Following recombination, the matter and radiation are uncoupled, and the universe becomes transparent to radiation. It is from this epoch, therefore, that we now receive the remnant, microwave background radiation, which has cooled from 4000 K to 3 K since this era began at $t \approx$ 300,000 years. Since these photons have not scattered off matter since that time, the microwave background radiation provides a direct link with physical processes occurring just a few hundred thousand years after the Big Bang, when the temperature was a few thousand degrees. In particular, minute variations in the spectrum of the microwave background give us vital information about the inhomogeneities (also known as perturbations) in matter density, at this early epoch, which seeded galaxy formation.

In preceding eras radiation pressure had inhibited the condensation of matter, but now matter and radiation are uncoupled these density perturbations can grow to form galaxies, a process beginning at round about $t \approx 10^9$ years. Within galaxies, stars form. The most massive stars evolve most quickly, and manufacture the chemical elements necessary for life through nuclear reactions in their cores, as described in the seminal work of Burbidge, Burbidge, Fowler and Hoyle referred to earlier, with the light elements made in the Big Bang to start from. After several billion years these stars run out of the nuclear fuel which has powered them and explode as supernovae, whereby the surrounding interstellar medium is enriched with the chemical elements which they have made. Thus the building blocks for planets round subsequent generations of stars, and, on at least one planet, the raw material for life, become available. This well-authenticated story has made it virtually a cliché now in astrophysics to say that 'we are made of the ashes of dead stars'.

And so we have the modern, Big Bang account of the evolution of the universe. The canonical picture painted from epochs (4) to (6) above is remarkably assured. We even understand the physics of the electroweak phase transition happening at $t \approx 10^{-10}$ sec in phase (3), since this is predicted by the Glashow-Salam-Weinberg model, as explained above. Whilst the physics of phases (1) and (2) remains speculative, it is nevertheless a truly astonishing triumph of twentieth century cosmology to have been able to trace the history of the universe back to within a small fraction of a second of its origin.

## Notes

1 There is a massive literature on the Big Bang. Popular level works include Barrow (1994), Hawking (1988, 2001), Lidsey (2000), and Rees (1997, 2000). More technical works include Raine and Thomas (2001), and Peebles (1993). Other works will be cited as we progress.

2 Bondi (1961), p. 12. The 'perfect cosmological principle' is a generalization of the 'cosmological principle' which stipulates only that the universe presents the same aspect from all points in space. Both aim to apply the more familiar Copernican principle, which shifts the earth away from its special place at the centre of the solar system, to our place in the universe as a whole.

3 Augustine, St (1994), *The City of God*, XI.6.

4 Burbidge, Burbidge, Fowler and Hoyle (1957). This famous paper is often abbreviated as $B^2FH$.

5 This is not to denigrate Fowler, who acknowledged Hoyle as the second great influence in his life after his own doctoral supervisor Charlie Lauritsen.

6 See Hoyle and Tayler (1964), and Wagoner, Fowler and Hoyle (1967).

7 Holder (1993). See also, especially, Peacocke (1986).

8 See, for example, Gell-Mann (1994), pp. 129-133. Gell-Mann would seem to concur with Penrose's point, which we shall have cause to consider in chapters 3, 7 and 8, regarding the fundamental asymmetry between the beginning and end states of the universe (e.g. Penrose (1989a), pp. 302-347).

9 Hawking (2002).

10 E.g. Penrose (1989a); Barrow (1990); Davies (1992), pp. 166-167. I discuss the implications of Gödel's theorem, both for the prospects of a TOE and for an understanding of human consciousness, in Holder (1993).

11 Davies and Brown (eds) (1988), p. 6.
12 See Quinn and Hewett (1999).
13 Good introductions include Davies and Brown (eds) (1988), and Greene (1999). For a more recent review see Susskind (2003).
14 See the recent review by Rovelli (2003).
15 For a review of the observational status of these two theories, see Amelino-Camelia (2003).
16 The number of extended dimensions is important for the life-bearing potential of the universe, as we discuss in chapter 3.
17 Quantum mechanical spin is measured in units of $\hbar$, where $\hbar = h/2\pi$ and $h$ is Planck's constant. Thus, more accurately, the spin of bosons is a multiple of $\hbar$ and that of fermions is an odd multiple of $\frac{1}{2}\hbar$.
18 Greene (1999), pp. 166-183.
19 Greene (1999), especially pp. 174-182.
20 Greene (1999), pp. 283-319.
21 Greene (1999), p. 312.
22 See Hawking (2001), pp. 57, 175.
23 An electron volt (eV) is the energy gained by an electron falling through a potential of 1 volt. The unit commonly used in particle physics is the GeV (giga electron-volt) where 1 GeV = $10^9$ eV. The GeV also translates into an equivalent temperature, 1 GeV $\approx 10^{13}$ K (this will enable the reader to compare the present discussion with our description in the next section of cosmological epochs in terms of temperature).
24 Abdus Salam, in Davies and Brown (eds) (1988), p. 171.
25 Glashow, in Davies and Brown (eds) (1988), p. 184.
26 Interestingly philosopher Erik Curiel holds that the main problem is not that string theory doesn't connect with observation by making predictions, rather the reverse: its origination is not preceded and therefore motivated by observational anomalies with existing theories, but arises from purely theoretical considerations (see Curiel (2001)). For example, as I noted in chapter 1 in arguing against Kant, quantum theory seems forced on us by the bizarre nature of the world. However, as also noted, the interaction between experiment and other factors, such as elegance, is a complex matter. But that there should be some interaction seems hardly to be disputed!
27 Richard Feynman, in Davies and Brown (eds) (1988), p. 194.
28 Michael Green, in Davies and Brown (eds) (1988), pp. 132-133.
29 The overview by Chalmers (2003), plus the review articles by Susskind, Rovelli and Amelino-Camelia (all four in *Physics World*, November 2003), give a helpful summary of the present position.
30 The typical energy of photons is $kT$, where $k$ is Boltzmann's constant. Pairs of particles and anti-particles with rest energy $mc^2$ can be freely created from photon pairs if $kT > mc^2$. Thermal equilibrium with the photons is maintained through the reverse process of particle anti-particle annihilation. When the temperature drops below $mc^2$ these particles effectively disappear through annihilation. This provides a rough explanation for which particle species are present during the different eras. See, for example, Raine and Thomas (2001), p. 131.
31 If $n_n$ denotes the number of neutrons, $n_p$ the number of protons, and $\Delta m$ the difference in mass, then $n_n/n_p = \exp\{-(\Delta m)c^2/kT\} \approx \exp\{-1.5 \times 10^{10}/T\}$. At $T \approx 10^{10}$ K, $n_n/n_p \approx 0.22$. See, for example, Davies (1982), p. 33.

# Chapter 3

# Cosmic Fine-Tuning

> It is indeed awe-inspiring to think that every tiny action has its consequences, and can mark a parting of the ways which lead to vastly separate destinations.
>
> (Iris Murdoch, *The Sea, The Sea.*)

## The Meaning of 'Fine-Tuning'

The Big Bang theory of cosmology informs us of the cosmic expansion from an initial 'singularity'; the formation of stars and galaxies as the expansion proceeds; the nucleosynthesis of the chemical elements inside stars; the enrichment of the interstellar medium with these elements following supernovae explosions; and the formation of new generations of stars, and planets, from this enriched material. Modern chemistry and biology describe the subsequent development and evolution of life on earth, culminating in mankind.

In recent years cosmologists have asked themselves how special the laws of nature, and the initial conditions to which they are applied, must be in order for the above processes to occur. The *Anthropic Principle* states that there have to be constraints both on the laws and the initial conditions in order for them to produce intelligent life at some stage in the universe's evolution, and it prompts one to examine just what these constraints are.

The Anthropic Principle and its ramifications have given rise to a vast literature. In particular, John Barrow and Frank Tipler have written what has become the classic reference work on the subject with their book entitled *The Anthropic Cosmological Principle.*[1] Other writers who have addressed the subject include Paul Davies in *The Accidental Universe*,[2] John Gribbin and Martin Rees in *Cosmic Coincidences*,[3] and Martin Rees (as sole author) in *Before the Beginning*, *Just Six Numbers*, and *Our Cosmic Habitat.*[4] Stephen Hawking discussed the Anthropic Principle in his best seller *A Brief History of Time* and returns to the subject in his more recent *The Universe in a Nutshell.*[5] John Polkinghorne,[6] Richard Swinburne,[7] Willem Drees,[8] Ian Barbour,[9] Hugh Montefiore[10] and John Leslie[11] have all assessed the impact of anthropic reasoning in cosmology on the argument from design.

Richard Dawkins is aware that something is afoot, and acknowledges that here we have an 'interesting argument', one he would like to see 'spelled out'![12] He is apparently unaware of the serious academic work being done in the field, comprising the vast literature I have only touched on above. His response is eagerly awaited.

Now by the laws of nature we denote Newton's laws of motion and gravitation as modified by Einstein's special and general theories of relativity; Maxwell's laws of electromagnetism describing the behaviour of charged particles; and quantum theory describing the behaviour of matter on the smallest scale. We must include in our discussion the four fundamental forces of nature, described in chapter 2, which are subject to the laws—gravitation, electromagnetic forces between charged particles (and which hold atoms together), the weak nuclear force giving rise to nuclear processes such as the decay of neutrons into protons, and the strong nuclear force binding the nuclei of atoms together. Of particular interest are the coupling constants which govern the relative magnitudes of these forces, and parameters such as the masses of the various fundamental particles.

The constants of nature (such as the gravitational constant, Planck's constant, the velocity of light and so on), and the masses of the various particles (electrons, protons, etc.), are necessary as inputs into the equations describing how matter behaves. The actual values they take are unexplained by science, and may be inexplicable in principle. Yet it turns out that they must take very precise values in order for the universe to be interesting and fruitful, and to produce intelligent life.

The laws of nature are expressed as differential equations which determine how matter behaves over time. Hence, in addition to the constants one needs initial (or 'boundary') conditions as input into the equations. These comprise such factors as the initial expansion rate and the initial density of the universe.

## 'Anthropic' Terminology in Cosmology

It is strictly more accurate to talk of the 'fine-tuning' of the universe than to refer to the 'Anthropic Principle', since the latter term is used in a variety of ways in the literature; thus sometimes an obvious truth is expressed, and at others the expression bears an ambiguous or obviously false meaning.[13] Nevertheless the term has become entrenched in the literature and I shall continue to use it as occasion arises.

The word 'anthropic' is clearly derived from the Greek ἄνθρωπος (anthrōpos) meaning 'man', and I shall sometimes refer loosely to conditions for 'our' existence or 'human' existence, or to the 'anthropic potentiality' of the universe. In reality, however, the arrival of humanity in the universe is not especially privileged by these considerations, and we ought more properly to speak of the conditions for the arrival in the universe of intelligent life, or 'carbon-based life', or perhaps any life at all. Indeed for the most part we are concerned with the conditions necessary for any kind of interesting universe at all.

Ernan McMullin[14] observes that the notion of an 'Anthropic Principle' is but the latest manifestation of the penchant of cosmologists for rather grand, general principles. Thus, as noted in chapter 2, 'the' cosmological principle asserted that the large-scale distribution of matter is the same everywhere and the 'perfect cosmological principle' extended this uniformity to all times. A mistaken belief in the latter led my doctoral supervisor Dennis Sciama (as it had Hermann Bondi) to prefer the steady state to the Big Bang theory, though when the evidence of the microwave background radiation came along, Sciama (excellent scientist that he was) became an enthusiastic advocate of the Big Bang. What McMullin himself dubs the 'indifference principle' is the assertion that there is nothing 'accidental' about the universe.[15] A way of applying this to the initial conditions of the Big Bang, for example, would be to say that, whatever they were, the universe would evolve in the same way. In other words, the initial conditions *might* be accidental, but the evolution of the universe is indifferent to them. The perfect cosmological principle is an extreme version of the indifference principle since it removes initial conditions altogether.

An important phase in the recent history of cosmology was the exploration of so-called 'chaotic cosmologies'. The hope was that the evolution of the universe would be independent of the initial conditions, more specifically that viscous processes would smooth out any initial anisotropies (distortions), so that the universe would indeed evolve into something life-producing. In fact this proposal failed dramatically. Indeed, in a very important paper to which we shall have cause to return, Barry Collins and Stephen Hawking[16] showed that the probability that something like our universe would develop from arbitrary initial conditions, as proposed by chaotic cosmologies, is vanishingly small. They gave this explanation of why the universe is so isotropic (i.e. looks the same in every direction): 'The fact that we have observed the universe to be isotropic is therefore only a consequence of our own existence.' This kind of statement is of the confusing sort I mentioned above and is often repeated in the literature. It is, of course, nonsense. As McMullin remarks, 'But surely a necessary condition cannot function as an explanation?',[17] and likewise Swinburne, 'The laws of nature and boundary conditions cause our existence; we do not cause theirs.'[18] The latter statement was in response to the equally false statement of Barrow and Tipler that 'Many observations of the natural world, although remarkable *a priori*, can be seen in this light as inevitable consequences of our own existence.'[19]

Collins and Hawking, following Dicke and Carter, also gave the following statement, which does better serve to function as an explanation, and which we shall need to examine in much more detail later: '... there is not one universe but a whole infinite ensemble of universes with all possible initial conditions.' This brings us back to another version of McMullin's 'indifference principle'.

The term 'Anthropic Principle' itself was coined by Brandon Carter.[20] The two main forms of it are labelled Weak and Strong Anthropic Principles (often abbreviated WAP and SAP respectively). The weak form is stated by Barrow and Tipler as follows:

> The observed values of all physical and cosmological quantities are not equally probable but they take on values restricted by the requirement that there exist sites where carbon-based life can evolve and by the requirement that the Universe be old enough for it to have already done so.[21]

This is an expansion of Carter's version, 'What we can expect to observe must be restricted by the conditions necessary for our presence as observers'.

The strong form (close to Carter's formulation—he had 'the creation of observers' rather than 'life') is given as:

> The Universe must have those properties which allow life to develop within it at some stage in its history.[22]

Both formulations are ambiguously expressed. To distinguish them, let us regard the 'weak principle' as asserting uncontroversially that, because we are here, we shall inevitably find that the physical constants take values consistent with our existence. The 'strong principle' we take as a speculative statement of physical necessity.

The weak form is then trivially true, yet it would seem to have been of some use, especially in resolving a problem thrown up by Dirac—the problem of the large number coincidences. Dirac had noticed that the number $10^{40}$ is both the ratio of the electric and gravitational forces between a proton and an electron and the square root of the number of protons in the universe. Dirac had wanted to solve the problem of this coincidence by making a fundamental alteration to the laws of nature, i.e. to have the gravitational constant change with time. Dicke observed that the coincidence was explicable because we were at a time in the universe's history when intelligent life had had time to evolve. The coincidences and the weak anthropic explanation are an example of a selection effect of a kind well-known to all experimentalists—biases are introduced because of the conditions under which the experiment is carried out. We shall meet another very important application of the WAP below when we discuss Sir Fred Hoyle's discovery of certain seeming coincidences necessary for stars to produce carbon and oxygen.

In fact, Garrett and Coles have shown how the WAP is genuinely explanatory by framing it in Bayesian probability terms, as we shall see in chapter 5.[23]

The strong form of the Anthropic Principle is a highly dubious metaphysical statement. For it is not at all clear that the existence of life (or observers—though see next paragraph) in the universe is necessary, or indeed that the universe itself or the many universes invoked for anthropic explanation had to exist. The generally held philosophical view is that both the universe and ourselves are contingent, as indeed are the physical constants, and even the laws of nature themselves.

Perhaps the only way the strong principle can be retrieved is by moving to the even more speculative 'Participatory Anthropic Principle' (PAP) of John Wheeler, with its appeal to the quantum theoretical notion of observer-created reality. Wheeler sees this version as consequent upon the Copenhagen interpretation of quantum mechanics (see below, but note that some regard this as a weakness of the Copenhagen interpretation). Whilst there is a sense in which, on this interpretation, the act of observation brings about the collapse of wave-functions and hence a particular 'reality', it is a tremendous leap to regard the whole cosmos as similarly selected by ourselves. Wheeler's train of speculative thought can be extrapolated even further to the postulation of an Ultimate

Observer who 'coordinates' all observations so as to make them self-consistent, and is located either at the final singularity of a closed (i.e. ultimately recollapsing) universe or at future time-like infinity in an open (i.e. forever expanding) universe.[24] This exotic scheme might be regarded as an interesting analogy (it would be stretching things to say more!) to the Christian metaphor of God bringing about the existence of the universe from without by means of his spoken word.

From the above discussion it can be seen that the term 'Anthropic Principle' is confusing, though it remains useful in indicating that human existence depends critically on the 'fine-tuning' of the universe. The term 'fine tuning' is more useful as expressing the explanandum to which so-called anthropic explanations are directed.

## Some Examples of Fine-Tuning

The number of examples of fine-tuning is legion. To set the scene we limit ourselves to six examples relating to physical constants and six to initial conditions.

A. *Physical constants*

(1) One of the most important elements necessary for life, certainly life as we know it, is hydrogen—no hydrogen means no water and hence no life. If the weak nuclear force, the force responsible for radioactive decay, were not, apparently accidentally, related to the gravitational force in a rather special way, either all the hydrogen would be converted to helium within a few seconds of the Big Bang or none would.[25] In the former case, with the weak force somewhat weaker, one would end up with no possibility of water or life at any subsequent stage in the universe's history. Moreover, stars which burnt helium through nuclear reactions in their cores would be much shorter-lived than hydrogen-burning stars. Life would not have time to develop on the planets of such stars. Whilst no helium production in the Big Bang would not be so significant, it would appear that the requirement that massive stars explode in supernovae, so that the chemical elements they have manufactured in their cores through nuclear reactions can be made available for planet-building, constrains the relationship between the weak force and gravity in both directions (i.e. relative increase or decrease of the weak force relative to gravity).[26]

(2) Life as we know it is based on the element carbon, and it is unlikely that any other element could give sufficiently stable compounds to produce alternative life forms. Oxygen is also essential. The chemical elements are built up inside stars, and carbon is one step on the way to manufacturing the other elements in the periodic table. We are required both to get as far as carbon in the first place and then, even more delicately, not to burn up all the carbon we have made to manufacture oxygen and the other elements. If the strong nuclear force, which binds nuclei

together, and the electromagnetic force, which operates between charged particles, were not so very finely balanced as they are we would either get no carbon in the first place or have all the carbon burn making oxygen, for the following reason.

When two atomic nuclei collide they will stick together if the combined energy matches a so-called 'resonance' level for the resulting nucleus. Carbon is formed as beryllium and helium nuclei collide and oxygen is formed similarly as carbon and helium nuclei combine. It so happens that the energy from the beryllium-helium collision very closely matches the carbon resonance, so that if the resonance level in the carbon nucleus were 4% lower virtually no carbon would form. On the other hand, the energy from the carbon-helium collision is ½% short of that which would enable the combination to be readily stable, so that if this resonance were ½% greater all the carbon would burn in forming oxygen!

This aspect of the anthropic argument was discovered by Fred Hoyle. Assuming that carbon-12 had to be manufactured inside stars in sufficient quantity for the subsequent development of life, Hoyle actually predicted the existence of a previously undetected energy level (resonance) in the carbon-12 nucleus. His prediction was confirmed by somewhat sceptical experimental nuclear physicists.

This seeming anthropic coincidence is discussed by Barrow and Tipler[27] and by Davies.[28] Gribbin and Rees point to it as a genuine scientific prediction of anthropic reasoning.[29] Most anthropic reasoning yields values for parameters which we already know—this example, uniquely, predicted something hitherto unknown. It could clearly be regarded as constituting an impressive instance of the application of the Weak Anthropic Principle.

Hoyle himself (an atheist) was so impressed by this particular coincidence, that he was moved to remark:

> If this were a purely scientific question and not one that touched on the religious problem, I do not believe that any scientist who examined the evidence would fail to draw the inference that the laws of nuclear physics have been deliberately designed with regard to the consequences they produce inside the stars. If this is so, then my apparently random quirks have become part of a deep laid scheme. If not, then we are back again to a monstrous sequence of accidents.[30]

And again:

> If you wanted to produce carbon and oxygen in roughly equal quantities by stellar nucleosynthesis, these are just the two levels you would have to fix, and your fixing would have to be just about where these levels are actually found to be ... A commonsense interpretation of the facts suggests that a superintellect has monkeyed with physics, as well as with chemistry and biology, and that there are no blind forces worth speaking about in nature. The numbers one calculates from the facts seem to me so overwhelming as to put this conclusion almost beyond question.[31]

(3) A change in the ratio of the gravitational force to the electromagnetic force by as little as 1 part in $10^{40}$ would have dramatic consequences for the types of star which occur.[32] If gravity were slightly stronger, or electromagnetism slightly weaker, all stars would be blue giants. If it were the other way round and gravity were slightly weaker, or electromagnetism slightly stronger, all stars would be red dwarfs. As it is, most stars are like our sun, lying between these extremes. It is not clear that red dwarfs could generate enough heat to foster life on their planets, but in any case they would never explode in supernovae as required for the dissemination of the chemical elements which are the building blocks of life. On the other hand, Carter has speculated that blue stars, which radiate rather than convect heat, and which retain strong angular momentum, might not have planets (he believes that a star's surface convection is important for planetary formation). In any case they would be much shorter lived, and so life on any planets would have much less time to get going. As Davies points out, what is clear is that this small change would give rise to a radically different universe.[33]

(4) The values of the physical constants are also relevant to later stages in the universe's drive towards producing life. For example, Barrow and Tipler, quoting Regge, note that only if the electron/proton mass ratio is 1/1836 could there exist the long chain molecules which make biological phenomena possible. In particular, the slightest change in this ratio might so alter the size and length of the rings in the DNA helix as to invalidate the molecule's typical way of replicating itself.[34]

(5) When formulating his general theory of relativity, Einstein included an extra repulsive force in the equations, denoted by the Greek letter $\Lambda$ (lambda) and termed the 'cosmological constant'. He had philosophical reasons for including $\Lambda$, even if it was anti-Ockhamite, since it gave rise to a static universe as a solution to the equations. However, Einstein came to regard $\Lambda$ as his 'greatest blunder', since had he not included it he would have been able to predict the expanding universe, subsequently discovered by Hubble. In recent years a non-zero $\Lambda$ has been revived since there are indications from observations of supernovae explosions in distant galaxies that the expansion of the universe is accelerating. What is more, physicists now think they know what gives rise to positive $\Lambda$, namely 'vacuum energy' (NB in quantum theory the vacuum is not 'nothing' but a seething cauldron of activity). Indeed such vacuum energy is believed to power inflation. The problem is that the calculated value of $\Lambda$ exceeds that compatible with observation by 120 orders of magnitude (i.e. by a factor of $10^{120}$). It also exceeds the value compatible with our own existence by about the same factor since too high a value of this repulsive force would prevent the collapse of matter to form galaxies. So we need an incredibly fine-tuned Einstein component of $\Lambda$ to cancel the vacuum energy component, at least after the inflationary era.[35]

(6) Our final example in this section is perhaps the most fundamental of all. We inhabit a universe with three spatial dimensions, four dimensions altogether including time, and it might seem strange even to question whether the dimensionality of the universe could be different. It might also seem strange to call dimensionality a 'physical' constant, but perhaps this aspect of strangeness can be understood in the light of the incorporation of geometry into physics with Einstein's general theory of relativity.

String theorists maintain that there are in fact more than just our three familiar spatial dimensions. The total number of dimensions, including time, has varied somewhat with the evolution of the theory. Twenty six dimensions were postulated in one very early version, more recently 10 dimensions, and now, in M-theory, the 10 are believed to be embedded in a further dimension, making 11 dimensions in all. The question then arises as to why precisely 6 spatial dimensions get compactified, leaving us with 3 extended spatial dimensions, plus time.

Analogously with other cases of fine-tuning, it turns out that life can only exist in a three-dimensional space. As both Rees and Hawking note, digestion would be rather difficult for a two dimensional creature since its digestive tract would split the animal in two![36] Obviously the possibilities for complex structure would be even more limited in only one dimension. Moreover, only in three dimensions is there an inverse square law of gravitation, and this turns out to be the only law giving stable planetary orbits. For example, in four dimensions the law would have to be inverse cube and this would not permit a stable solar system. Indeed, this fact was noted as evidence of design by the mathematically well-educated William Paley whom we met in chapter 1—a much better example than the more famous watch since it *does* appeal to physical law, rather than contingent features of the universe consequent on physical law.

The same comments apply to the inverse square law of attraction between protons and electrons in atoms, so unless space had three dimensions not even atoms would be stable![37] Evidently three spatial dimensions are an essential requirement if the universe is to be life-bearing.

B. *Initial/boundary conditions*

(1) Standard cosmological theory informs us that the universe is either open, i.e. will expand forever, or closed, i.e. will eventually recollapse. Which alternative is realized depends on the mean density of energy in the universe, usually denoted by the symbol $\rho$. If $\rho$ is less than a certain critical value $\rho_c$ the universe is open; if it is greater than $\rho_c$ the universe is closed. If $\rho = \rho_c$ the universe is just open. Present observations show that $\rho$ is very close to $\rho_c$ so that we cannot decide between these alternatives.

Now it turns out that $\rho$ simply has to be very close to $\rho_c$ in order to have a universe in which life evolves. This is because a universe with greater density would have recollapsed before stars had time to evolve and life had time to form, and one with smaller density would expand so rapidly that matter would never collapse into galaxies and stars.

One can trace the closeness required of $\rho$ to $\rho_c$ in order to yield a life-producing universe right back to the Planck time. This time, when the universe is a mere $10^{-43}$ seconds old, is the earliest about which we can sensibly speak, since an as yet unknown theory of quantum gravity is required to take us further back still (see chapter 2 for speculations about this).

Barrow and Tipler report that, in order for the universe to give rise to life,[38] at the Planck time $\rho$ must be equal to $\rho_c$ to an accuracy of $10^{-56}$ to $10^{-60}$. This represents a very tight constraint indeed on the initial conditions of the Big Bang. As Paul Davies has pointed out, an accuracy of 1 part in $10^{60}$ is equivalent to that required in aiming a bullet to hit a target one-inch in diameter situated at the opposite side of the universe, 20 billion light years away.[39] Why the density should be so tightly constrained has been dubbed the 'flatness problem' by Alan Guth, since a universe with density equal to the critical density has zero spatial curvature.[40]

(2) In the seminal paper to which I referred earlier, Collins and Hawking[41] showed that 'the set of spatially homogeneous cosmological models which approach isotropy at infinite times is of measure zero in the space of all spatially homogeneous models'.[42] Such models are known as asymptotically isotropic, and to say that the set of such models is of measure zero means that such a universe has zero probability of selection. Like Barrow and Tipler's statement about density, this too is a highly significant result, and I briefly examine the background to it, deferring more substantial discussion, as for critical density, to chapter 7.

The microwave background radiation bathing the universe is isotropic to a remarkably high degree. More precisely, the temperature and intensity of this radiation appear independent of direction in the sky to 1 part in a thousand (Barrow and Tipler,[43] but 1 part in 100,000 if the earth's motion is accounted for[44]). This is a deeply puzzling feature of the universe, indicating that widely separated regions of the universe, which, because of the limitation imposed by the speed of light, cannot have been in causal contact with each other, nevertheless seem highly co-ordinated. This is the so-called 'horizon problem'.

Isotropy is not just puzzling *per se*, however: it is apparently necessary for life, and therefore another seeming 'anthropic' coincidence. This is because any anisotropy, i.e. shear and rotational distortions, in the expanding medium of the Big Bang must die away quickly if density perturbations are to develop into galaxies. It is assumed (but see chapter 7) that a universe in which this is the case is asymptotically isotropic. As Collins and Hawking remark, 'The existence of galaxies would seem to be a necessary precondition for the development of any form of intelligent life.'

(3) Contrary to our intuitions, it turns out that the universe needs to be the vast size it is in order for man to exist. This is the size it inevitably reaches in the 15,000 million years or so which it takes to evolve human beings. There is in fact, for the simplest cosmological model (which will do for this purpose), a simple relationship between the size, mass and age of an expanding universe. A universe with the mass of a single galaxy has enough matter to make a hundred billion stars like the sun, but such a universe would have expanded for only about a month.[45] Thus the argument that the vastness of the universe points to man's *insignificance* is turned on its head—only if it is so vast could we be here!

(4) As we saw in the last chapter, the universe at its earliest moments is endowed with a very small excess of baryons, a class of particles, including neutrons and protons, affected by the strong nuclear force, over anti-baryons, the anti-matter particles corresponding to baryons (the excess is 1 particle in $10^9$). Baryons and anti-baryons annihilate to give photons. If the universe were baryon symmetric (i.e. contained an equal number of baryons and anti-baryons) at the relevant time, there would be insufficient matter following annihilation for galaxies to form. The process of cosmic evolution—galaxies, stars, planets, life—would not even get going. Whilst it might be the case that this asymmetry can arise from physical processes occurring in an earlier symmetric state, as Grand Unified Theories predict, this would only push the question back a stage—namely to the parameter values taken by the GUTs. This 'pushing back the question' is a phenomenon I shall have occasion to refer to later.

(5) The universe needs to be homogeneous but not too homogeneous. Galaxy formation relies on there being slight density contrasts in the expanding universe so that gravitational collapse can occur. If these 'density perturbations' are much less than about 1 part in $10^5$ at the time of recombination ($t \approx 300{,}000$ years from chapter 2), then they won't amplify to form galaxies. If they are too large at this time (say 1 part in $10^2$ or more), then they will collapse prematurely into black holes. In fact, the COBE satellite shows the value of the density perturbations to be about 1 in $10^5$, making galaxy formation just viable (thankfully!). The imprinting of inhomogeneities of the right magnitude may be explicable in terms of GUTs and inflation, but this again would be pushing back the specialness of the initial conditions of the universe onto the theory which supposedly applies at ultra-early times.[46]

(6) We close our examples of fine-tuning with a case of surpassing precision in the way the universe seems to have been set up. This relates to the amount of order in the universe.

The second law of thermodynamics tells us that the universe is progressing from a state of order to states of increasing disorder. The amount of order in a system is measured in physics by a quantity called entropy—low entropy

> corresponds to a high degree of order and high entropy to high disorder. Now, the universe started in a state of almost incomprehensibly high order (or low entropy).[47] Roger Penrose shows that, in starting the universe, the creator had of the order of
>
> $$10^{10^{123}}$$
>
> possible universes to choose from, only one of which would resemble ours.[48] The probability that a universe chosen at random would possess the necessary degree of order that ours does (and so possess a second law of thermodynamics) is
>
> $$1 \text{ in } 10^{10^{123}}$$
>
> If the universe were less ordered than this the matter in it would have collapsed through friction into black holes, rather than form stars.[49] Black holes represent extreme states of disorder, or high entropy. The problem of why the universe is so ordered is called the 'smoothness problem' by Leslie,[50] and is closely related to the horizon problem in which context we discuss it again in chapter 8.
>
> As Penrose[51] points out, the number $10^{10^{123}}$ cannot even be written down in full. If we attempted to write 1 followed by $10^{123}$ noughts with each nought being written on a separate proton, with a mere $10^{80}$ protons there would not be nearly enough of them in the entire universe to be able to do this! This is fine-tuning indeed.

In a nutshell, the universes governed by these tiny alterations leave no room for interesting developments, and in particular the evolution of complex creatures like ourselves to observe them. And of course physicists have been struck by these coincidences. As Freeman Dyson puts it: 'The more I examine the universe and study the details of its architecture, the more evidence I find that the universe in some sense must have known that we were coming'.[52]

There is a very natural conclusion to draw from all this, namely that the cosmic coincidences we have been considering are indeed no accident: the theistic hypothesis that God designed the universe with the express intention of producing rational conscious beings is surely preferable. The hypothesis of theism can advance reasons why God might create a universe, and in this particular way, which I cannot develop here. Suffice it to say that a good God is likely to exercise his creative power and to produce beings able to appreciate his work. And we note that invocation of God here is not a God-of-the-gaps argument like that which Richard Dawkins successfully exposes, in which particular aspects of the evolution of the universe or life are the subject of explanation and the laws of nature suffice. Here what is at stake are very remarkable features of the tools which the scientific naturalist uses in his trade, the laws of nature themselves. Can he explain why these are as they are?

## Notes

1 Barrow and Tipler (1986).
2 Davies (1982).
3 Gribbin and Rees (1992).
4 Rees (1997, 1999, 2001).
5 Hawking (1988, 2001).
6 E.g. Polkinghorne (1983, 1986, 1988, 1989, 1991). A good summary of Polkinghorne's thought on the subject is in Polkinghorne (1996), pp. 80-92.
7 Swinburne (1990; 1991, Appendix B; 2003).
8 Drees (1990).
9 Barbour (1990).
10 Montefiore (1985).
11 Leslie (1989).
12 Dawkins (1995).
13 Swinburne (1991), pp. 312-313.
14 McMullin (1993).
15 Note that McMullin's 'indifference principle' is to be distinguished from the much older Principle of Indifference in probability theory which I discuss in chapter 5.
16 Collins and Hawking (1973).
17 McMullin (1993), p. 371.
18 Swinburne (1991), p. 313.
19 Barrow and Tipler (1986), p. 219.
20 Carter (1974).
21 Barrow and Tipler (1986), p. 16. Importantly for our later discussion, the probabilities referred to here are not 'prior probabilities' but 'conditional probabilities', i.e. probabilities that certain values are found given the existence of carbon-based life.
22 *Ibid.*, p. 21.
23 Garrett and Coles (1993). Barrow and Tipler, following Carter, also pointed out that the WAP can be construed in terms of Bayes's Theorem—see Barrow and Tipler (1986), p. 17.
24 See Barrow and Tipler (1986), pp. 470-471. A 'time-like' line in relativity is one which represents the 'world-line' of a particle. In contrast points on a 'space-like' line are causally separate because not even light can pass between them. The Ultimate Observer is deemed to be located outside space-time where the world-lines meet. Barrow and Tipler acknowledge that this scenario is 'admittedly very vague', so I would urge the reader not to be too troubled if experiencing problems understanding the PAP!
25 Barrow and Tipler (1986), p. 399; Davies (1982), pp. 63-65. The actual constraint is that the strength of the weak force is roughly equal to the strength of the gravitational force to the power ¼, i.e. to $10^{-11}$ where these strengths are measured as appropriate dimensionless numbers. Decrease the weak force strength by a couple of orders of magnitude to $10^{-13}$ and the helium abundance increases from 25% to 95% with disastrous consequences for the possibility of life.
26 Carr and Rees (1979).
27 Barrow and Tipler (1986), pp. 252-253.
28 Davies (1982), pp. 117-118.
29 Gribbin and Rees (1992), pp. 244-247.
30 Hoyle (1959), p. 64.
31 Hoyle (1981), p. 12.

32 Davies (1984), p. 188; and, in more detail, Davies (1982), pp. 71-73; the original argument is due to Carter and is in Carter (1974), pp. 296-298.
33 Davies (1982), p. 73.
34 Barrow and Tipler (1986), p. 305.
35 For a discussion of the significance of $\Lambda$ see Rees (1999), pp. 95-99. We consider $\Lambda$ briefly in chapter 7 (and its associated Appendix E), and in more detail in chapter 8.
36 Rees (1999), p. 136; Hawking (2001), p. 88.
37 Quantitative expression was given to Paley's insight by physicist Paul Ehrenfest in a famous paper published in 1917 entitled '*In what way does it become manifest in the fundamental laws of physics that space has three dimensions?*' See Barrow and Tipler (1986), pp. 260-262, and Barrow (2002), pp. 218-220. Ehrenfest included the extension to atoms and molecules, and was able to be more rigorous in view of the recent advent of quantum theory.
38 Barrow and Tipler (1986), p. 411.
39 Davies (1984), p. 179.
40 In Einstein's theory of general relativity, space is curved owing to the effects of gravity. Curved three dimensional space is hard to visualize, but its analogues in two dimensions can be imagined. The special case of $\rho = \rho_c$ gives rise to a 'flat', i.e. Euclidean, geometry, corresponding to a plane in 2 dimensions. $\rho > \rho_c$ and $\rho < \rho_c$ give positive and negative spatial curvature respectively, equivalent to the surface of a sphere and a saddle shape in 2 dimensions.
41 Collins and Hawking (1973).
42 Spatial homogeneity denotes the universe looking the same in every place, isotropy its looking the same in every direction. Homogeneity to the right degree has also posed problems for cosmologists (there must be some lumpiness for galaxies to form!), as we discuss briefly in (5) following.
43 Barrow and Tipler (1986), p. 419.
44 Guth (1997), p. 336.
45 Barrow and Tipler (1986), pp. 384-385. The size of the observable universe is measured by the distance $\lambda$ to the 'horizon', that surface beyond which light cannot reach us. Hence $\lambda = ct_u$, where $c$ is the speed of light and $t_u$ the age of the universe. The mass $M_u$ within radius $\lambda$ is given by $M_u = 4\pi\rho\,\lambda^3/3$, and for a flat, pressure-free universe the Friedmann equation of cosmology (which I write explicitly in Appendix E) yields $\rho = (6\pi G t^2)^{-1}$, where $G$ is the gravitational constant. Hence the relationship between $M_u$ and $t_u$: $M_u = 2c^3 t_u/9G$.
46 See, for example, Barrow and Tipler (1986), p. 417; Guth (1997), p. 217.
47 Davies (1984), p. 168.
48 Penrose (1989a), pp. 339-345, and Penrose (1989b). The calculation referred to in the text applies to a closed universe, but, as Penrose explains, matters are worse for an open, and therefore infinite, universe. The probability decreases as universe size increases, and only a vanishingly small fraction of open universes would have the required degree of order—see Penrose (1989b), p. 261.
49 Davies (1980), pp. 168-169.
50 Leslie (1989), p. 28.
51 Penrose (1989a), p. 344.
52 Dyson (1979), p. 250.

## Chapter 4

# Avoiding the Inference of Design

> What I am really interested in is whether God could have made the world in a different way; that is, whether the necessity of logical simplicity leaves in freedom at all.
>
> (Albert Einstein, to Ernst Strauss, in G. Holton (1978), *The Scientific Imagination: Case Studies* (Cambridge: Cambridge University Press)).

**Possible Strategies for Scientific Naturalism**

It would appear from the foregoing that something very contrived is happening for the universe to produce intelligent life, and this would be explicable on the hypothesis that God is responsible. However, there are a number of ways of avoiding this conclusion. As stated in chapter 1, we do not consider alternative non-naturalist hypotheses. However, we certainly need to examine whether scientific naturalism is at an impasse or has anything to offer. Six candidate strategies would appear to be available:

(1) the declaration that there is nothing to explain since we could not be here to observe any other kind of universe;

(2) the proposal that some better physical law will sooner or later be found to explain the cosmic coincidences;

(3) the proposal that the laws of physics are not contingent as we imagine, but necessary;

(4) the argument that there exists a multiverse—an infinity of universes—so that the one in which we live is bound to occur;

(5) the argument that in any case modern cosmology vitiates the need for a designer because it offers *creatio ex nihilo*; and

(6) the somewhat bizarre sounding suggestion that the universe was created, not by God, but by intelligent beings living in another universe, or alternatively by a process of natural, rather than artificial, selection.

Let us examine each of these in turn.

**Is There Really Anything to Explain?**

First, then, it is worth asking whether there really is anything to explain. We inhabit this particular universe with the features described. If these features were not as they are we would not be here to observe them. We *only can* observe a universe which gives rise to our own existence.

In chapter 1 we noted Feynman's analogy that a car with number plate ARW 357 is just as unlikely to appear in the car park as any other and so should cause us no surprise. According to some physicists and philosophers, we are similarly supposed not to believe that, of the many alternative possibilities, a universe with life in it requires any special explanation. Given that some universe is instantiated, and all possibilities are highly improbable, we should be no more surprised that this life-bearing universe exists than that any of the, admittedly far more numerous, lifeless and boring universes exist. The only difference is that we are here to observe this universe.

A number of authors have addressed this objection to the fine-tuning argument. There are numerous counter-examples to the car park illustration which we can give to bring out the fallacy in this reasoning, one of which (Swinburne's exploding/ace-producing machine) we have already seen in chapter 1. To take a slightly modified example, suppose a pack of cards were shuffled and dealt, and the sequence came out Ace, Two, Three, etc., in order up to King, of Clubs, followed by the same ordered sequence for Diamonds, then Hearts, and finally Spades. The probability of this sequence occurring by chance is tiny, about 1 in $10^{68}$. So also is the probability of any other sequence. The sequence which occurred, however, is meaningful. Suppose we learned that the person who dealt the hand was known for performing card tricks, or was a bridge player who was known to cheat. Then we would strongly suspect that the sequence dealt was a 'put up job'. We would not suspect this with the vast majority of possible deals, e.g. one that began 2♦, 8 ♣, Q♠, 10♠, 5♣, A♥, ..., i.e. a sequence with no discernible pattern.

The important point is that we can actually provide a good explanation, other than mere chance, for this particular sequence. Peter van Inwagen gives another illustration, very like the ace-producing machine. He starts from an example which is analogous to the car park, though better because an obvious pattern is exhibited.[1] You should not be surprised by a sequence of twenty heads in twenty tosses of a coin, because you would not be surprised at any sequence that did not exhibit an obvious pattern, yet occurred with the same probability (1 in 1,048,576). But suppose you are required to draw a straw from a set of 1,048,576 straws of different length and unless you draw the shortest you will be instantly annihilated. You reluctantly draw a straw and, lo and behold, it is indeed the shortest. The probability of this is also 1 in 1,048,576 and is the same as the probability that any other straw were drawn, say the 256,057th shortest. Yet surely the only reasonable conclusion to draw is that this is some kind of set-up, not that you should not be surprised because the only difference in the cases is that you are still around to debate the issue.

John Leslie has an example which is isomorphous to the exploding machine and short straw examples, namely the firing squad. If fifty sharpshooters all miss me it is not adequate to shrug my shoulders and reply, 'If they hadn't all missed, then I shouldn't be considering the affair'.[2] My still being alive requires explanation—either the sharpshooters all deliberately missed or, perhaps, 'immensely many firing squads are at work and I'm among the very rare survivors'. We consider the latter possibility, which corresponds to the many universes hypothesis, below.

One author who thinks the car park objection succeeds is M. C. Bradley.[3] This is essentially because Bradley does not see intelligent life as significant, at least in the sense of objective value.[4] He picks out one of the vastly many non-life producing universes and calls this 'Strife' and then argues that, were 'Strife' to be instantiated, we should be duty bound to argue for Strife's fine-tuning. But this is to fail to see that the vast majority of possible universes actually closely resemble Strife and therefore something like Strife is very likely and does not call for explanation. In order to produce life, even if only in one place, the universe had to develop complex structures within an unfolding order of remarkable intricacy, dependent on the laws of physics, and the initial conditions at the beginning of the universe, being very closely specified. Bradley's assertion that it is not open to those who accept Darwinian evolution, which produces the appearance of design by natural processes, to find evidence of design in fine-tuning, seems mistaken. Whilst evolution may be regarded as 'naturalistic' in the sense that it explains how complexity can be built up through the interplay of genetic mutation and environmental selection, the laws of nature must be special for this to occur, just as for the Big Bang ultimately to produce planets suitable for life in the first place. The appeal is to the specialness of the laws of nature in both cases, not to a 'God of the gaps', as I indicated in chapter 1. Moreover, that the universe exhibits objective value is commonly regarded as significant by scientists, e.g. Paul Davies: 'My own inclination is to suppose that qualities such as ingenuity, economy, beauty, and so on have a genuine transcendent reality—they are not merely the product of human experience—and that these qualities are reflected in the structure of the natural world'.[5] This leads Davies to opt for design (in preference, on the basis of Ockham's razor, to many universes).[6]

Philosopher J. J. C. Smart regards the argument that 'some set of numbers must come up so you should not be surprised at any particular set' as fallacious, as I do.[7] He observes that the number of unfortunate sequences is vastly greater than the number of fortunate ones and so it is only the odd fortunate one which requires explanation. Arguing along similar lines, George Schlesinger makes the helpful distinction between surprising and unsurprising improbable events with the following example.[8] X buys one of a billion lottery tickets and wins, but even though the probability of his winning is 1 in $10^9$, we should not be surprised because somebody had to win. On the other hand Y is one among a thousand people who enter 3 lotteries in succession. The probability of Y winning all three lotteries is also 1 in $10^9$, but this time we should be surprised because it is now not true that somebody had to win all three lotteries: the probability of this is not 1, but 1 in $10^6$. In this case it would be quite reasonable to suspect foul play. The well-defined and significant property that an individual wins all three lotteries marks out a small subset of the set of possible outcomes. Analogously, the well-defined and significant property of being at least potentially life-bearing marks out an infinitesimally small subset of possible universes. The existence of a universe belonging to this tiny subset requires explanation.

Van Inwagen regards the car park argument as obtuse and silly, and indeed mistaken, and he crystallizes his reason for thinking so thus:

> Suppose that there is a certain fact that has no known explanation; suppose that one can think of a possible explanation of that fact, an explanation that (if only it were true) would be a very *good* explanation; then it is wrong to say that that event stands in no more need of an explanation than an otherwise similar event for which no such explanation is available.[9]

Van Inwagen calls this the 'Merchant's Thumb' principle after another of Leslie's examples. A silk merchant is always observed to hold his thumb over a hole in a piece of cloth, but given that the merchant's thumb has to be somewhere ...[10] We shall see in due course how the apparatus of Bayesian probability theory makes the Merchant's Thumb principle rigorous, indeed how the fallacy of the car park argument emerges naturally from the formalism. A good explanation for some phenomenon makes that phenomenon much more likely to occur than pure chance would do, and so in turn the probability of the explaining hypothesis is raised above its *a priori* value.

Another response to the fine-tuning is that there might be many possible ways of generating life, but in universes very different from our own—with entirely different laws. The universe does not have to be as special as the above analysis suggests to produce life. But this does not negate the fact that *a universe of our type*, i.e. with the same laws as ours, does have to be special. A universe with laws like ours and force strengths much like ours does have to have the various parameters (both constants and initial conditions) finely tuned and that requires explanation. Leslie illustrates this by envisaging a fly on a wall hit by a bullet[11] (or, more appealingly, a cherry painted on a wall and hit by a dart[12]). The fly represents a universe which gives rise to life; the bullet hitting it implies that that universe exists. The phenomenon is explained either because the bullet is fired by a marksman or because there are many bullets hitting the wall. It is irrelevant that there might be many flies at some distance from the one in question.

One possible objection to Leslie's argument is that the region we are required to hit could be much bigger than the fine-tuning argument as I have presented it might lead us to believe. The way I have construed the argument is by taking there to be a set of parameters which when varied one at a time, leaving the others alone, must satisfy certain constraints in order for the universe so described to be life-producing. The picture emerging is that any particular parameter, $\lambda$ say, must lie between some limits, say $\lambda_0 - \delta \leq \lambda \leq \lambda_0 + \epsilon$. In Leslie's picture, that would give a multi-dimensional 'rectangle' in parameter space in which the parameter set was constrained to lie. But it may be possible to vary parameters simultaneously rather than singly, and so arrive at a larger space of life-producing parameters, more topologically complicated than a hyper-rectangle.

There are a number of things one might say about this proposal. First, it is part of a larger problem about the assigning of probabilities, to which we return in later chapters. Secondly, if any parameter in the original analysis was required to belong to a measure zero set, that would still be the case in the scheme in which parameters are varied together.[13] Thirdly, and in my view decisively, it looks as though the number of constraints is actually much greater than the number of free parameters, though it is difficult to provide an exhaustive list. This would lead one to believe that we are very fortunate indeed that the individual constraints combine together consistently at all.[14] Each constraint defines some region in parameter space and we know in practice that the intersection of all such regions is non-empty because we are here (Weak Anthropic Principle). It would seem to be vastly more likely *a priori*, however, that the parameter set of the universe would fall outside the very narrow bounds compatible with life production.

The calculation of this intersecting space is a complex mathematical programming task which has not as yet been exhaustively completed; naïvely, at any rate from the above argument, I would expect it to be of small, if not zero, measure on the whole space. Max Tegmark, the proponent of an all-embracing multiverse theory, to which we shall return later in this chapter, presents partial calculations of this intersecting space, combining two parameters at a time, and draws the same conclusion.[15] Noting, for example, that all of chemistry depends on two free parameters, the electromagnetic fine-structure constant and the ratio of electron and proton masses, and that 'many seemingly vital processes hinge on a large number of "coincidences"', Tegmark states: '... it might thus appear as though there is a solution to an overdetermined problem with more equations (inequalities) than unknowns.' So, on Tegmark's view, we are indeed extremely fortunate that there exists a combination of parameters consistent with life.

Tegmark goes on to state further that this could be taken as support for a religion-based TOE, with the argument that it would be unlikely in all other TOEs. As if this is a bit too unpalatable, he then offers what seems to me an incredibly weak get-out, namely he denies that the constraints are necessary and proposes that other SASs ['self-aware substructures'—Tegmark's generalization of my 'intelligent life'] in other regions of parameter space would evolve by combining chemical elements in a manner different from ours. Even if that were possible, and it seems to be pure speculation, it would of course not meet Leslie's point, noted above, about flies being hit far distant from the one in question (though in this case we would still presumably be talking about the same laws, only with parameter sets disconnected from our tiny region). Tegmark conducts a similar analysis involving strong force and electromagnetic constants, again finds a tiny region which is life-supporting, notwithstanding many constraints, and offers the same get-out, wilfully bypassing the design option. And even after loosening the constraints, Tegmark concedes that the number of 'islands' in parameter space which would support SASs is likely to be finite, so we are still left with the problem of a measure zero set in the whole parameter space.[16]

It would seem from the above that there is certainly something to explain. However, perhaps physics can solve the problem without any recourse to God as an explanation, e.g. an improved cosmological theory may explain some of the coincidences. This possibility we now consider.

## A Better Physical Theory?

The only viable candidate for a more comprehensive physical theory currently on offer is 'inflation'. It is more fundamental than the canonical Big Bang model because it takes us further back in time than standard physics can cope with, and because in doing so it appeals to Grand Unified Theories (GUTs) of particle physics. As we have seen, although superstring/M-theory ostensibly takes us further back still, and is even more unified, this theory is not yet in a position to make any predictions. Certainly inflation has gained wide acceptance in the astrophysical community, so, to ground our discussion, inflation is the theory I shall concentrate on in this section.

Inflationary cosmologies began life in 1981 with Alan Guth's proposal that the universe underwent an early period of rapid, faster-than-light, accelerating expansion, as opposed to the deceleration of the standard model. On this picture, at about $10^{-35}$ seconds from the initial singularity the size of the universe was about $10^{-25}$ cm. By $10^{-32}$ seconds it had expanded to at least 10 metres across. At that point inflation ended and the much slower classical, decelerating Big Bang expansion took over.[17] The expansion rate following the inflationary phase would settle very close to the critical value for a wide range of initial conditions, hence solving the flatness problem. Moreover, it is also claimed that inflation solves the horizon problem, because regions which might have interacted have been pushed very far apart. The universe visible to us is within a single co-ordinated region because any interactions took place at pre-inflationary times.[18]

Polkinghorne notes that it is still true that the inflationary universe only arises if the laws of physics follow a certain pattern, and that the 'anthropic fruitfulness' of such a universe is still to be explained.[19] Surely he is right. Those who believe that inflation removes the need for design seem to argue as follows:

(1) The initial conditions of the universe are very special, invoking our awe.

(2) Theory X (in this case inflation) predicts the initial conditions.

(3) Therefore, we are supposed to lose the awe which we had at the initial conditions.

Surely the right conclusion is instead

(3)′ The awe which we had at the initial conditions is transferred to theory X.

So, even if attempts to explain the coincidences in terms of some more fundamental theory were successful, that would not vitiate the argument from design which the coincidences support: it would merely put the argument back a stage. For these fundamental laws are not *necessary* (though see next section). They could be different, so it is still equally valid to ask, 'Why are these fundamental laws so special that they have the consequences they do for the parameters we have been talking about?'. In Leslie's words we may have found a 'Totally Unified Theory which provided automatically the results which lead people to talk of fine tuning'.[20]

Although inflation will not therefore obviate the need for design, it remains an important component of modern early universe cosmological theory, because it apparently solves a number of puzzles with the standard Big Bang. Also of importance to us is the fact that it may provide a mechanism for generating 'many universes'. This gives us ample reason for returning to critique inflation in more detail later (chapter 8).

## The Necessity of the Laws of Physics

Inflation looks useful for the scientific naturalist because it seems to explain some of the contingent parameters in the Big Bang model. A more radical proposal takes this idea much further in saying that the laws of physics are not contingent as we have imagined hitherto, but necessary. In particular, the fundamental constants of physics, which when formulating the fine-tuning argument we took to be contingent, are not so: they must of necessity take the values they do. The ratio of the fundamental forces, the proton-electron mass ratio, etc., simply must take the values experiment and observation show that they do. There is no possible world in which they do not take these values. Our surprise at all the fine-tuning coincidences, which we thought picked out our existent universe as a very special member of a vast ensemble of possible but non-existent universes, is then supposed to be removed because things could not be otherwise.

The first thing to say about this proposal is that it seems inherently implausible. Certainly scientists are nowhere near showing that the set of physical laws instantiated in our universe, with their fundamental constants, are the only logically coherent set of physical laws and constants. As noted in chapter 2, the standard model of particle physics contains 19 free parameters. And M-theory, the most likely candidate for a TOE, which some believe might indeed be the only self-consistent theory, is still in a very primitive state, and in any case makes no predictions about the constants, particle masses, etc., at all. So, in practice, science is not noticeably coming closer to a necessary set of laws.

The second, and perhaps more fundamental, thing to say, is that even if the laws were necessary we would still be floundering for an explanation. As van Inwagen says, our surprise would be increased since now the mystery of necessity is added to it! Van Inwagen gives a helpful analogy which I shall paraphrase.[21]

Suppose a square is divided in the obvious way into a million equal smaller squares. Suppose we assign a number between 0 and 9 to each square using the first million digits in the decimal expansion of $\pi$, beginning with the first square in the top left hand corner, then the next in the row, and so on. Now we assign a different colour to each digit so that a square with digit 0 will be painted yellow, a square with digit 1 blue, and so on. Suppose, contrary to all expectations, that the result is a meaningful pattern, such as a landscape or portrait, of surpassing beauty.

Now of course we cannot say that God designed the number $\pi$ so that such a beautiful pattern would be instantiated. $\pi$ is necessary: it is the same in all possible worlds; it cannot be different from what it is in our world. On the other hand, the resulting pattern is very surprising and, on the face of it would seem to be most improbable. There is simply no reason to expect that $\pi$ should have this property, which has nothing whatever to do with its definition or the way it appears naturally in many mathematical contexts.

Van Inwagen says that this pattern-making could be contrived in a number of ways. Thus one could search the digits of $\pi$ until a sequence of a million digits occurred which had this property, because *some* million-digit sequence will have the property. Or one could search through the uncountable infinity of mathematically fundamental numbers (familiar examples include $\pi$ and $e$ and their multiples) until one found a number which had the property. Or one could change the correspondence rules of colour mapping until one found a match, though one cannot but think that such a rule system would be immensely complex compared with the simple system we began with. But that the *first million* digits of the *particular number* $\pi$, with *this simple* correspondence rule should have the pattern-making property would be utterly amazing. In the same way, van Inwagen argues, it would be utterly amazing if the only possible set of physical laws also happened to provide the 'monstrous sequence of accidents' required for the universe to be life-generating. The choice of $\pi$ from the mathematically fundamental numbers, the choice of the first million digits of the number, and the choice of the simple correspondence rule for the colours are independent. In the same way the many requirements for intelligent life to appear in the universe are independent. Hence, van Inwagen concludes, it would be as amazing for the unique set of physical laws to be life-permitting as for $\pi$ to be picture-generating.

## The Multiverse

Another possibility is to take the opposite tack and assume that our universe is not unique. Indeed, in order to deny design, it is generally postulated that there are infinitely many universes in which such features as the universal constants are randomly selected for each.[22] The idea is that, if there are infinitely many (or vastly many) universes, one like ours is certain to be among them and hence it is no surprise that we are here.

Some philosophers[23] do not believe that many universes provide any advance over a single, brute fact universe, since the probability of *this* universe being fine-tuned is not raised—much as a past history of coin-tossing does not affect the outcome of the next toss. It is also regarded by some as inconsistent with the Bayesian approach to probability which I present in chapter 5, whereby probability is regarded as quantifying 'rational degree of belief' rather than proportions in an ensemble.[24] However, although I have many criticisms which will come out in due course, I do believe that the ensemble—multiverse—is at least potentially explanatory, in the same way that a long string of coin tosses makes a sequence of 10 heads likely eventually, or that one possible inference for Leslie's surviving sharpshooter victim is that many firing squads are at work. This will become clear when we carry out the Bayesian analysis in chapter 6.

Van Inwagen, on the other hand, regards a many universes explanation for the fine-tuning as equally as good as the design hypothesis, on the grounds that both explain the evidence and neither contains any element which is known to be false or improbable. He then assigns equal probabilities to the two hypotheses. I am suspicious of what seems to be use of a principle of indifference (in the sense of probability theory, as we see in chapter 5) in assigning equal probabilities on the grounds of ignorance, and argue later that, although both hypotheses apparently explain the data, there are good reasons for preferring design.

Martin Rees is a cosmologist who supports the multiverse hypothesis, but, rather astonishingly, is not very worried about having reasons to do so. He writes: 'If one does not believe in providential design, but still thinks the fine-tuning needs some explanation, there is another perspective—a highly speculative one, so I should reiterate my health warning at this stage. It is the one I much prefer, however, even though in our present state of knowledge any such preference can be no more than a hunch.'[25] I see no way of taking this statement other than as a simple prejudice in favour of many universes over design, and somewhat in conflict with Rees's profession elsewhere to be a 'cautious empiricist', happiest once we are in the realms of established physics at $t \gtrsim 10^{-3}$ seconds after the Big Bang.[26] But this really won't do: we need to look for reasons for our preference.

How do cosmologists envisage the existence of many universes, i.e. the ensemble which in chapter 1 I labelled the multiverse? In fact there are a number of ways in which a multiverse might be conceived to arise, and George Gale provides a helpful classification of what he terms multi-world theories (MWTs):[27]

(1) 'Spatial MWTs'. Here the multiverse is envisaged as the simultaneous existence of infinitely many regions (sub-universes) in a single, spatially infinite, encompassing space. This is arguably the simplest and most plausible way to achieve many universes, and is conceptually the easiest to grasp. As we noted in chapter 1, to call the regions 'universes' is of course a misnomer, since the term

'universe' is often reserved for 'everything that is'. It is, however, a convenient misnomer and I shall retain it. In explaining the anthropic coincidences, the idea is that we just happen to live in a region with the right parameters for anthropic potentiality. The probability of there being a region like ours is taken to be 1, given each region's parameters being chosen randomly from the infinite range of possibilities. (I shall have cause later to question the assumption of many universe theorists that this probability is 1.)

A hypothesis along these lines, in which the 'embracing' infinite multiverse is of low density and 'open', was suggested by George Ellis in the 1970s and is described by Ellis and Brundrit.[28] Nowadays the hypothesis is given credence by inflationary models (see chapter 8) whose bubble domains correspond to sub-universes in a single space-time, and inflation may then explain the uniformity of our 'neck of the woods'. However, since we could have no causal contact with other regions in which the physical constants and initial conditions were different, this would seem to be a metaphysical rather than scientific hypothesis. It would also appear to break with Ockham's razor, that maxim which, as we saw in chapter 1, inveighs against the multiplication of entities, and which has been of great use historically in deciding between competing scientific hypotheses.

As a further point, it will be of interest to examine just how special our part of the universe is, i.e. is it more or less special than would be expected on this hypothesis? I give some prominence to discussion of this way of achieving many universes in chapters 7, 8 and 9.

(2) 'Temporal MWTs'. The paradigm here is that the multiverse arises as consecutive 'bounces' of a single, oscillating 'closed' space-time, as postulated by John Wheeler.

In this scenario each 'bounce' might be regarded as a distinct universe because we can have no causal contact with it and because 'bounces' might result in radically different régimes from ours. Wheeler has speculated that the various constants of nature and initial conditions could be randomly recycled at each bounce.[29] If there are infinitely many bounces, with each choosing from the infinitely many possibilities for the various parameters, again there is a probability of 1 that some bounce will be a universe like ours, conducive to life (and again, we shall have cause to question the assignment of probability 1 to such an eventual outcome).

There are a number of scientific objections to Wheeler's idea. First, it is not clear how or why a bounce might occur. Infinite compression is assured by the singularity theorems of Hawking and Penrose for a wide range of conditions (although quantum effects might negate this). Then, one would presumably have to do away with the second law of thermodynamics, according to which entropy should increase—otherwise our cycle would be unique, the number of cycles in which life is possible would be (presumably very severely) limited, and this would negate the usefulness of infinitely many bounces. Further, our universe may well not have enough mass to make it recollapse (i.e. it might be 'open'), and it would be odd if ours were the last ever cycle (I agree with Leslie[30] that this seems 'too *ad hoc*'). The whole idea seems fraught with difficulty scientifically, but of course, again it also suffers from precisely the same objection as spatial MWTs, in terms of lack of causal contact and observability. Indeed, temporal MWTs are arguably even worse in this regard. Invocation of many universes in this case is perhaps even more speculative, and again is contrary to Ockham's razor.

(3) 'Other-dimensional MWTs'. This involves adopting a realist approach to universes which do not even belong to our space-time, and, although such universes are deemed to arise through physical processes, they are more akin to the concept of 'possible worlds' in philosophy. One way, as noted by Gale, of achieving many universes in this category is as alternative branches of space-time, all deemed to exist owing to quantum splitting (this scenario is based on Hugh Everett's many universes interpretation of quantum mechanics). Another way, which should perhaps be included in this category, is as 'baby' universes connected by 'worm holes' to 'parent' universes at singularities, since such baby universes create new space. This latter possibility is discussed by Stephen Hawking,[31] and, with slightly more technical detail by Guth,[32] and we return to it briefly below in our discussion of 'creation by aliens'. However, Hawking has recently presented new calculations which, he concedes, invalidate his earlier baby universes proposal.[33]

Everett's many-worlds interpretation of quantum theory is to be contrasted with the older, Copenhagen interpretation of Niels Bohr on which many of us were, often unconsciously, brought up. To summarize the latter very briefly, we start from the idea that the state of a system in quantum theory is described by a 'wave-function'. This wave-function evolves deterministically according to the Schrödinger equation. Then an observation of some property of the system is made which forces 'collapse of the wave function'. What this means is that the outcome of the observation is determined probabilistically from the wave function. Any observation has a number of possible outcomes (which may be finite, as in the measurement of the spin of an electron in some direction, say, or infinite, as for example in the case of the time of occurrence of an atomic decay); the one which occurs does so on the basis of probability. In the Copenhagen interpretation, there is a sense in which the act of observation forces a system into one particular state.

Now the Copenhagen interpretation is undoubtedly problematic, in several ways. The so-called 'measurement problem' stems directly from my description above. Thus we seem to be operating simultaneously with two versions of physics, the quantum and the classical, since the measuring apparatus is taken to be a classical device.[34] For quantum theory to provide a *complete* description of reality we also require the quantum nature of the measuring apparatus to be incorporated. At the very least we need to know how, or at what point, the quantum and classical pictures merge. Then there is the vexed question as to what actually causes the wave function to collapse, and when in the process this occurs. In some interpretations it is the observer who 'creates reality' through the act of observation. Yet it seems absurd to suggest that, if we lock away our photographic plates uninspected and only look at them in a month's time, that is when the wave function collapses.[35] But neither is it satisfactory to claim (as in the Copenhagen interpretation proper) that it is the classical measuring apparatus, when it records a diffraction pattern or whatever, which causes wave function collapse.

The problem is crystallized for us in the famous paradox of Schrödinger's cat. This unfortunate feline is incarcerated in a sealed box along with a phial of poisonous gas. A radioactive atom also in the box has a 50% chance of decaying in the next hour. If it does so a $\gamma$-ray is emitted and recorded by a Geiger counter, which also triggers the breaking of the phial to release the gas, quickly killing the cat. If the atom doesn't decay in the allowed time the cat survives. The experiment ends when we lift the lid from the box to see if the cat is dead or alive.[36]

Now the paradox arises because, according to the Copenhagen interpretation, before I lift the lid the cat is in a 50-50 superposition of the two states 'alive' and 'dead'. The question as put by John Barrow is, 'When and where does the mixed-up, half-dead cat state change from being neither dead nor alive into one or the other? Who collapses the cat's wave function; is it the cat, the geiger counter, or the physicist? Or does quantum theory simply not apply to 'large' complicated objects, even though they are composed of smaller ones to which it does apply?'[37]

In contrast to the Copenhagen interpretation, in the many-worlds interpretation of quantum theory '*all* the "alternatives" are actualized'.[38] Of course, we only observe one pathway through the infinitude of possible pathways arising from 'quantum splitting', namely the pathway constituting our universe. Nevertheless, all the other universes exist, although we cannot have any contact with them. In this bizarre-sounding picture the 'I' of this instant branches off instantaneously into infinitely many 'I's.

How does this interpretation of quantum theory explain the cosmic coincidences? Well, the idea is that early in the Big Bang, in fact earlier than the Planck time of $10^{-43}$ seconds, various important parameters of the universe—its degree of isotropy and homogeneity, and the strengths of the fundamental forces, for example—were chosen by quantum splitting. Since there are infinitely many possible mixes of parameters, a mix is bound to occur through random choice in which the subsequently developing universe gives rise to life.[39] The idea is highly speculative, to say the least.

John Leslie's verdict on this means of reducing the oddity of Life is that it is at the cost of 'severe deOckhamization'[40] (we have noted above that both spatial and temporal MWTs are also deOckhamite, though, as in chapters 2 and 3, I prefer the term 'anti-Ockhamite'). It is grossly uneconomic to multiply universes in this prodigal manner, and goes against the grain of scientific method. Ernan McMullin takes issue with Carter's assertion that 'one is virtually forced by the logic of quantum theory' to the Everett picture, noting that few quantum theorists support it.[41] Barrow, in contrast, notes that its supporters 'include among their ranks some of the world's greatest quantum physicists'[42]—though it transpires that these are mainly involved in quantum cosmology.[43]

Murray Gell-Mann believes the Everett approach is valuable but criticizes the commonly understood implication that the 'many worlds' are 'all equally real'. He prefers the terminology 'many alternative histories', each alternative having its own probability.[44] He mentions one distinguished physicist who inferred that anyone accepting the common interpretation of Everett should be willing 'to play Russian roulette for high stakes because in some of the "equally real" worlds the player would survive and be rich'! But of course, if we deny the reality of the other worlds, we also negate their possible anthropic explanatory value.

McMullin also claims, very importantly, that 'Everett's branching worlds do not provide the range of alternative initial cosmic conditions or alternative physical laws that this version of an anthropic explanation of the initial parameter constraint would require'.[45] Unfortunately this brief statement is left unsubstantiated. On the other hand, surely the burden of proof that the Everett interpretation does provide the required variation lies with the theory's advocates.[46] The answer presumably depends on how much is actually chosen at random—Davies notes that the choosing of fundamental constants is an addition to Everett's original proposal.[47] If all possible combinations are indeed actualized, then it looks as though many-worlds quantum theory will do what is required, though there still remains Leslie's charge of deOckhamization.

Those who advocate the many worlds interpretation (MWI) of quantum mechanics see it as redressing the supposed unsatisfactory view of reality of the Copenhagen interpretation. As we saw above, in the latter an observer brings about the collapse of wave-functions on a random basis, and there is a fundamental dualism. It all sounds very positivistic, in contrast to the realism about the physical world which most scientists adopt—indeed, to understand the real world is a prime motivation of science.

In MWI there is no wave-function collapse, determinism and (albeit extravagant) realism reign, and the observer is demoted from his pedestal. Everything that can happen does happen. All points in the initial data space of Einstein's equations have reality rather than just one seemingly arbitrary point.[48] Although it is argued that this is in fact simpler than the Copenhagen interpretation, I am inclined to side with Leslie in seeing the many worlds as anti-Ockhamite. One has only to start pondering what these worlds are like. This is a problem for all versions of the many worlds hypothesis, and I take up the bizarre nature of what we are being asked to believe in chapter 7. In so far as MWI is able to produce 'more' universes than the other versions, in a sense I shall explain later (see especially chapter 9), this particular problem is the more acute.

Roger Penrose is worried by the lack of economy of MWI, but for him even more objectionable is the fact that MWI does not solve the measurement problem it was designed for![49] Thus, although MWI accommodates wave-function collapse it neither explains how this (or the illusion of it) comes about, why for example a perceiving being should not be aware of superpositions of states rather than particular alternatives, nor the remarkable precision in terms of probabilities with which it does so. Michael Lockwood gives some discussion of this, dismissing the objection rather unsatisfactorily, saying that 'I' do experience the parallel states and comparing the problem with the experience of time—only an instant of one's conscious biography is experienced 'now'. It seems to me that this does not answer Penrose's multiple objection.[50]

It will be interesting to see what progress is made on David Deutsch's suggestion, based on his theory of quantum computation, that the Copenhagen interpretation and MWI can be distinguished observationally.[51] Barrow and Tipler also note that MWI and wave function reduction models would differ enormously very close to the initial singularity with possible experimentally testable differences predicted.[52]

In any case, more recent developments purport to solve some of the problems of the Copenhagen interpretation without resorting to the profligacy of MWI. The phenomenon of decoherence occurs when account is taken of the interaction of a macroscopic object, such as a measuring device or a cat, with its environment. For example, whether alive or dead, Schrödinger's infamous cat will interact with its environment. Either way many atoms in the air will be bouncing off it, and inhaled and exhaled if the cat is alive. This means that the alive and dead states will not interact, but 'decohere'. The state of the cat is then just the same as in the classical case. It is not in a superposition of states, but definitely alive or dead; we simply don't know which until we open the box.[53]

The leap is often made from many-worlds theories to the assertion that everything which can happen does happen, or 'everything which is not forbidden is compulsory'. It is far from clear that the physical theories in question achieve this (and we have already noted McMullin's criticism of MWI on these grounds), though they do if all possible theories occur as well as all possible values of constants and all possible initial conditions. In fact, of course, anything in the world can be explained on this basis. If anything that is logically possible will inevitably occur somewhere sometime, why not here and now?

Physicist Max Tegmark is bold enough to postulate just that.[54] For Tegmark, all structures that exist mathematically also exist physically. This he classifies as his 1a TOE (Theory of Everything).[55] He specifies no boundary conditions or values of physical constants because all are instantiated in the models to which they pertain. On the face of it Tegmark's theory is even more anti-Ockhamite than the others we have considered, though Tegmark disputes this (a point we return to in chapter 6).

Let's unpack Tegmark's idea a little. First, there is some confusion to be cleared up regarding the distinction between mathematical existence and physical existence. Many mathematicians would give mathematics an existence in something like an ideal Platonic world. Tegmark seems to mean more than this. He means that there is a physical reality, a universe, corresponding to all mathematical structures. That might at least be a clear and coherent, if controversial, claim, but Tegmark goes much further in stating that 'physical existence *is* the mathematical structure'.[56]

Now, since Tegmark's main interest is in universes which contain self-aware substructures (SASs, akin to my 'intelligent life'), this bizarre claim is in practice reduced to the more coherent one that 'if a mathematical structure contains a SAS, then the claim that it has physical existence operationally means that this SAS will perceive itself as existing in a physically real world, just as we do'. Tegmark's answer to Hawking's question, 'What is it that breathes fire into the equations and makes a universe for them to describe?'[57] is not God, but the idealist-sounding 'you, the SAS'.[58]

But Tegmark's idea is still of doubtful coherence in so far as he thinks a simulation, or a computer program, modelling a universe with SASs, has physical existence, even that a mathematical structure with SASs would have physical existence if it could merely be described formally, e.g. to a computer. So we are back to mathematical existence equals physical existence.[59]

This concentration on universes with SASs of course leaves the meaning of the existence of universes without SASs somewhat ambivalent, but in any case it would seem that they are there only for the sake of completeness and simplicity (again, we shall have to critique Tegmark's notion of simplicity in chapter 6).

Tegmark contends that the mathematical structure describing our world should be the most generic consistent with our observations and that our observations should be the most generic ones consistent with our own existence. By this he means that the mathematical structure of our universe, and our observations, should be typical of SAS-containing universes: there should be nothing special about them; they should be the most probable. One immediately hits a problem in that, although Tegmark lists a vast array of mathematical structures, none at all has so far been discovered which can consistently describe our universe, since we do not have a self-consistent theory of quantum gravity. Tegmark expends some energy eliminating certain mathematical structures as incapable of supporting SASs. Thus, for example, a certain level of complexity is required. He gives some discussion of dimensionality, concluding that to contain SASs a mathematical structure must possess only three spatial dimensions and one of time (see chapter 3).

Tegmark's discussion becomes more tied to our own type of structure as he considers variations in the fundamental physical parameters, as we have seen earlier in this chapter. Whilst a small island of parameter values, and a single dimensionality, consistent with the existence of SASs, are explained by his 1a TOE, I am not convinced that expanding the space of possible universes so dramatically is a price worth paying. In moving from a multiverse in which only the constants and initial conditions vary to his 'ultimate ensemble' theory, in which the mathematical structures are also varied, Tegmark not only confuses mathematical and physical existence, but further massively violates the principle of Ockham's razor. And as Leslie's fly on the wall analogy shows, it doesn't matter to the central argument that there are radically different universes which might support life, only that those like ours need to be fine-tuned.

Tegmark argues that he is making more rigorous the 'principle of fecundity' enunciated by philosopher Robert Nozick.[60] But the philosopher who is best known for advocating a view most like Tegmark's is David Lewis.[61] Whereas most philosophers accept the language of possible worlds as a convenient way of speaking about necessity and possibility (modal logic), Lewis maintains that such worlds really exist (modal realism). He feels that a true understanding of causality implies respect for counterfactuals such as 'If the brick had hit it, then the window would have broken', to the extent that a world in which the brick hit the window actually exists. Tegmark likens his position to that of Lewis, though Lewis goes much further in so far as there may be possible worlds not expressible in terms of mathematical structures. Lewis's position is highly counter-intuitive and one would want to ask why *this* universe is the way it is. In any case, as Putnam notes, Lewis's position is 'almost universally rejected by analytic philosophers'.[62]

We have already begun to see some of the problems associated with many-worlds theories, both scientific and philosophical. I shall give a more detailed critique in subsequent chapters.

## An Uncaused Universe?

### *Creation of Universes from Nothing*

Yet another line of attack from scientific naturalists is the suggestion that God can be done away with because (they believe) the universe can be shown to be uncaused. Strictly speaking they are here attempting to counter the cosmological argument, rather than the design argument which is the main subject of this book. Also this is one particular version of the cosmological argument, the *kalām*, which argues for a first cause in time. Nevertheless, because the attack has come from cosmology, I give just a brief discussion here.

The suggestion is that the universe may be uncaused in the sense that it came into existence spontaneously. Something like this is envisaged by physical chemist Peter Atkins in his book *The Creation*.[63] The argument is lent credence by a consideration of the vacuum in quantum theory. Rather than being devoid of all matter, in quantum theory the vacuum is a sea of activity—particles and their anti-particles are spontaneously coming into existence and annihilating in a split second. This phenomenon arises from Heisenberg's Uncertainty Principle. Readers may be familiar with the fact that in quantum theory the position and momentum of a particle cannot be measured accurately simultaneously (and the limitation is ontological not epistemological). In a similar way the energy contained within a given volume at a given time also cannot be known for certain, with the consequence that energy $\Delta E$ can be 'borrowed' from the vacuum for time $\Delta t$, where $\Delta E \,.\, \Delta t \approx h$ and $h$ is Planck's constant. Since gravitational energy is treated as negative energy, the universe's total energy is very close to zero. The possibility, first suggested by E. P. Tryon,[64] arises of a quantum fluctuation of the vacuum in which the whole universe can be created and persist for 15 billion years—we effectively have creation of the universe *ex nihilo*! Tryon states, 'I offer the modest proposal that our Universe is simply one of those things which happen from time to time'.

A question we are entitled to ask, and to which we return later, is, 'Where does the quantum vacuum itself, with its structure and the quantum laws which apply to it, come from?', and on this Tryon is silent. In addition Tryon's original proposal is fraught with scientific difficulties, not least the glaringly erroneous prediction that matter and antimatter subsist in equal quantities. More recently the idea has been combined with inflation, and quantum vacuum fluctuations also provide a means of obtaining many universes.[65]

*Stephen Hawking's Universe with No Boundaries*

A rather different idea is the 'no boundary' universe, which Stephen Hawking has developed with fellow cosmologist Jim Hartle.[66] Hawking gives a popular account in *A Brief History of Time* and returns to the theme, including some of the associated metaphysical speculation, in *The Universe in a Nutshell*.[67]

In this theory, essentially what happens is that space-time is 'smoothed out' as one recedes to the Big Bang itself, so that no singularity at the origin is reached. To achieve this, Hartle and Hawking postulate a quantum mechanical wave function for the whole universe, and utilize Feynman's 'sum over histories' formulation of quantum mechanics. In this formulation the probability that a particle originally at A ends up at B is found by summing the quantum mechanical probability amplitudes over all possible paths between A and B. In the classical limit, the contributions (wave oscillations) from neighbouring paths cancel, so that we are left with one path, identical to that calculated from Newton's laws.

When the sum over histories approach is applied to the universe as a whole, it describes the evolution of a whole spatial geometry. It turns out, however, that, in order for the sum to be mathematically well-defined, time must become imaginary in the very earliest epoch. Here the word 'imaginary' is being used in the technical, mathematical sense of complex numbers. In fact, time and space are treated alike, comprising a four-dimensional Euclidean space, and we can alternatively say that time has become 'spatialized'. Moreover, this four dimensional space is finite in size and there is no singularity, so it possesses no boundary or edge. Unlike in classical physics, there is therefore no need to specify boundary conditions in order to calculate the evolution of the universe in the Hartle-Hawking scheme. This scheme is meant to show how the universe with its present three-geometry arises from a zero three-geometry, i.e. from 'nothing'.

In *The Universe in a Nutshell* Hawking describes how the no-boundary proposal can be understood in the context of M-theory. He envisages our universe as a brane in which one of the extra spatial dimensions is blown up large like the three familiar space dimensions. Then a spontaneously created 'brane world' would have a corresponding history in imaginary time, but now our world would be a four-dimensional sphere which is the boundary of a five-dimensional bubble. That is, it is similar to the previous picture but with one extra blown-up dimension.[68]

Hawking attempts to make a good deal of metaphysical capital from the no boundary proposal. If it were true:

> There would be no singularities at which the laws of science broke down and no edge of space-time at which one would have to appeal to God or some new law to set the boundary conditions for space-time. One could say: "The boundary condition of the universe is that it has no boundary." The universe would be completely self-contained and not affected by anything outside itself. It would neither be created nor destroyed. It would just BE.[69]

And again:

> So long as the universe had a beginning we could suppose that it had a creator. But if the universe is really completely self-contained, having no boundary or edge, it would have neither beginning nor end; it would simply be. What place, then, for a creator?[70]

Hawking first put forward this idea at a conference at the Vatican and notes wryly: 'My paper was rather mathematical, however, and so its implications for the role of God in the creation of the universe were not generally recognized at the time (just as well for me).'[71]

It is not clear that Hawking has tempered his views in the years since he wrote *A Brief History of Time*, since he is still able to write, in *The Universe in a Nutshell*:

> If the histories of the universe in imaginary time are indeed closed surfaces, as Hartle and I proposed, it would have fundamental implications for philosophy and our picture of where we came from. The universe would be entirely self-contained; it wouldn't need anything outside to wind up the clockwork and set it going. Instead, everything in the universe would be determined by the laws of science and by rolls of the dice within the universe. This may sound presumptuous, but it is what I and many other scientists believe.[72]

We shall return to the metaphysical implications in a moment, which are not at all as Hawking sees them. We begin with the science, which is contentious to say the least.

First, there is the whole question of imaginary time. If there is no distinction between time and space, then how can time flow? How can anything change? The universe might just 'BE' but there is no way it can ever be other than it 'was' in the spatialized time 'era' (I use inverted commas since the terms 'was' and 'era' have illicit temporal connotations). If time is spatialized, and the histories in imaginary time are closed surfaces, as Hawking maintains, then there is no distinction between past, present and future. This wreaks havoc with our usual notions of causation, where one is accustomed to thinking that events can only be caused by strictly earlier events.[73]

A way round these problems is to see the Euclidean four-space of the Hartle-Hawking proposal as merely a calculating device, and not as an ontological reality. Then time will have a boundary, though not at a singularity, but at the three-dimensional surface of the four-space. If there *were* any metaphysical conclusions (but see below), then they disappear. Indeed one might expect such a line from Hawking himself, since he constantly professes himself to be a positivist.[74] In fact, philosophically he is best described as an 'instrumentalist', someone for whom all physical laws are merely ways of codifying observations and do not refer to real objects. Unfortunately, Hawking seems very muddled at this point, at least in his popular writings.

Thus, on the one hand, we read that '... we may regard our use of imaginary time and Euclidean space-time as merely a mathematical device (or trick) to calculate answers about real space-time'.[75] On the other hand, he later seems to say the opposite:

> ... This might lead us to suggest that the so-called imaginary time is really the real time, and that what we call real time is just a figment of our imaginations. In real time, the universe has a beginning and an end at singularities that form a boundary to space-time and at which the laws of science break down. But in imaginary time, there are no singularities or boundaries. So maybe what we call imaginary time is really more basic, and what we call real is just an idea that we invent to help us describe what we think the universe is like. But according to the approach I described in Chapter 1, a scientific theory is just a mathematical model we make to describe our observations: it exists only in our minds. So it is meaningless to ask: Which is real, "real" or "imaginary" time? It is simply a matter of which is the more useful description.[76]

This inability to distinguish real from imaginary time is repeated in *The Universe in a Nutshell.*[77] But the claim is quite absurd. I have already described some of the difficulties involved in ontologizing imaginary time, but in addition we can quite firmly state: we exist in real, moment-by-moment elapsing time, not imaginary time. But now, curiously enough, we find ourselves on common ground with what Hawking actually says in his technical articles, at least those which post-date the original Hartle-Hawking paper.[78] For example, the Euclidean (four-space) and Lorentzian (real space-time) regions are demarcated by the wave function being exponential in the former and oscillatory in the latter, and Hawking writes:

> The oscillating component in the wave function should be interpreted as corresponding to a lorentzian geometry and the exponentially growing component in the wave function should be interpreted as corresponding to a euclidean geometry. We live in a lorentzian geometry and therefore we are interested really only in the oscillatory part of the wave function.[79]

And again:

> The Lorentzian [real space-time] solutions will be the analytic continuation of the Euclidean [four-space] solutions. They will start in a smooth and non-singular state at a minimum radius equal to the radius of the 4-sphere and will expand and become more irregular.[80]

What Hawking is saying is precisely that the three-surface of the four-dimensional Euclidean space does indeed represent the boundary of real space-time. Indeed the calculations give a minimum size for the three-sphere, and imply that the universe evolves from that minimum size through an inflationary period to a classical Big Bang expansion, followed by collapse to a Big Crunch. In contradiction to his statement in *A Brief History of Time* quoted above, the universe does not begin at a singularity, though it does have a boundary, as I have just stated.

One is left wondering, with Quentin Smith, as to whether Hawking is wanting to 'baffle and intrigue' his popular audience, when those writings are in flat contradiction to his technical papers.[81]

The Hartle-Hawking model, and the quantum vacuum fluctuation models we considered earlier are clearly fraught with problems, but let us suppose for the sake of argument that some such theory does turn out to be valid.

First, let us note in passing that these newer theories resemble the old steady state theory in not assigning a definite beginning to time, and also to oscillating models with an infinite past. Thus, in a sense, no new philosophical or theological problem is raised that was not there with the steady state theory.

In fact, however, it is quite erroneous to conclude, even if any of these rather speculative theories were true, that the universe is then uncaused and there is no need for God. It is the laws of nature which operate to produce the quantum vacuum fluctuation—to repeat our earlier question, where do these laws come from (and the space or space-time on which they operate)? Barrow and Tipler acknowledge that the quantum vacuum is not truly nothing but has a rich structure which 'resides in a previously existing substratum of space-time'.[82] As Leslie notes, commenting on the Hartle-Hawking model:

> ... a zero volume *with three-dimensional geometry and sufficiently subject to the laws of quantum physics to allow for talk of 'tunnelling' from it* can look interestingly different from pure nothingness.[83]

Moreover, we are still very far from explaining all the cosmic coincidences necessary for such a universe to evolve and produce intelligent creatures. Indeed both the cosmological and design arguments still apply: the question 'Why?' is still unanswered, and the order in the universe unexplained (or as problematic as in other versions of the many-universes idea).

But there is something more to say. The claim of Hawking ('What place, then, for a creator?'[84]) and others, that if we can scientifically explain the origin of the universe (or show that it had no origin in time) we have removed the need for God, betrays an ignorance of the Christian doctrine of creation (NB the *kalām* argument arose in the

Arab world). Two brief points must suffice to show this. First, as Polkinghorne among others has pointed out, the Christian doctrine of creation is not concerned with the temporal origin of the universe but with its ontological origin.[85] That is to say, God is not invoked as the answer to the cosmologist's question, 'Who lit the blue touch paper of the Big Bang?', but as the Sufficient Reason required to answer Leibniz's more fundamental question, 'Why is there something—even an eternal something— rather than nothing?'[86] Going back much further than Leibniz, we find that Aquinas's classic Five Ways are not meant to show God as temporal Prime Mover, etc., but as the cause of all movement (more accurately, change).[87]

Secondly, the Christian doctrine embraces much more than the granting of existence to the universe. God is also upholding and sustaining the universe in existence, and without his doing so the universe would cease to exist. Even if Hawking were to obviate God's rôle in *creatio originans*, his argument would have no impact on God's rôle in *creatio continuans*.[88] And it is the latter, signifying the creation's total dependence on God, which is at the heart of the Christian understanding of *creatio ex nihilo*. As Willem Drees points out, the deist conception of a God who only winds up the watch is 'not a serious option within contemporary theology, because such a God would not be relevant to us and the ways we shape our lives'. Hence the removal of a beginning is 'not a death blow to theism, since this is not the kind of God theism defends'.[89]

In any case Hawking's view that science only leaves room for God at the very beginning is questionable in the light of science itself. This might have been a reasonable position to take in the days when science did seem to make the universe watch-like—an entirely clockwork, deterministic system. But as Hawking well knows, modern science shows there to be an openness and flexibility towards the future, as shown by quantum indeterminacy and the unpredictability of chaotic systems. Certainly there is room for God to act within the universe today.

Even Quentin Smith, who argues for atheism in debate with William Lane Craig, is led to the damning condemnation that Hawking's is 'probably the worst atheistic argument in the history of Western thought'.[90]

### Created by Aliens?

It has been suggested, most notably by cosmologist Edward Harrison,[91] that our universe was created, not by God, but by intelligent beings living in another universe. The idea is that even we humans are close to understanding how to make universes. Maybe just another few centuries and we shall be there—how much more likely that other intelligent life forms have got there before us, both in 'previous' universes and in our own.

I have mentioned how, at singularities, 'baby' universes might break off into space-time regions disconnected from our own, and these new space-time regions would constitute distinct universes. Harrison's proposal is that these new universes could in principle be created artificially. Just crush 10 kilograms of particles at energy ~ $10^{15}$ GeV into a black hole, and—hey presto!—you can expect a new, inflating universe to branch off at the singularity in the middle. Harrison argues that offspring universes will resemble their parents, but that there will be variation between offspring because of small differences in the constants of nature. However, some universes are more adapted than others for producing life, ultimately to advanced levels of intelligence, and hence producing yet more intelligent-life producing universes. There is a kind of evolutionary natural (or, more accurately, artificial[92]) selection process at work which will favour universes which reproduce in this way. Hence we should expect to be in a universe which, being produced through this mechanism, is long-lasting, containing billions of galaxies, stars and planets—in other words, conducive to the evolution of intelligent life forms such as ourselves.

What are we to make of this proposal? To me, it smacks of desperation, and I only consider it because it has been put forward by a respected cosmologist. If you want to avoid appealing to creation by God, as Harrison admits he does, on the grounds that this supposedly puts a stop to scientific enquiry, is this really the best that you can do?

First of all, clearly the physics involved is speculative, to say the least. We have noted that Stephen Hawking now discounts the idea of baby universes which he had earlier proposed. And Alan Guth, who discusses the creation of universes in the laboratory, writes: 'The mass density of a grand unified theory false vacuum [peculiar form of matter in which the energy density is at a local, rather than global minimum, and important for driving inflation] is not only beyond the range of present technology, it is beyond the range of any *conceivable* technology. ... The first step in trying to fabricate a laboratory universe is to create a patch of false vacuum. How exactly this can be achieved depends on the details of the high energy physics, which at present we have no way of knowing.'[93]

But even discounting that, has the proposal made any marked advance over other kinds of many universe theories? It is not clear how offspring come to resemble their parents, since all structure is lost when matter collapses into a black hole. There is nothing, no signature as it were, that one can imprint which will survive the process of collapse, beyond the total amount of energy that went into it. Moreover, the probability that a new universe will be formed at all through this mechanism might well be very low. A calculation of Guth's puts the probability at only about

$$10^{-10^{13}}$$

though it seems that by cooking the books you can make this probability anything you please (even unity). Even so, it would seem that the number of universes you could produce would not be able to compete with Linde's eternal inflation model (which we consider in chapter 8), so the latter will be far superior in terms of explanatory value.

Harrison's model is not simple either. It introduces extra, hypothetical entities, the advanced civilizations—why not rely instead on lots of naturally occurring black holes, as in the alternative model of Lee Smolin, which we discuss below? The topic of advanced life elsewhere in *this* universe, which might be adduced in favour of such life in other universes, is beyond the scope of this book, although much has been written about it. Suffice it to say that the SETI (Search for Extraterrestrial Intelligence) programme, using enormous amounts of computer processing power to examine radio signals from deep space, has failed to produce any evidence whatsoever for it. One argument, worth mentioning briefly, against the existence of extraterrestrial intelligent beings, which I find quite persuasive (and which, interestingly enough, Stephen Hawking also invokes[94]), is the so-called 'space travel' argument. If life were abundant, the chances are that there would be many more advanced civilizations than ourselves in our own galaxy, and furthermore, the chances are that a more advanced civilization would have actually colonized the galaxy. This has clearly not happened. Incidentally, the design argument does not of course preclude the existence of extraterrestrial intelligent life.

From the above, the aliens in Harrison's model would seem almost redundant to the explanatory scheme. They also resemble gods with a small 'g', intermediaries between God and the creation, like Plato's demiurge or the gods of Gnostic systems of belief. One of Hume's counters to the argument from design was that it did not necessarily lead you to a unique God, the God of Christian revelation, because the work of creation could be the combined effort of many different gods. Yet the hypothesis of one God is much simpler than the hypothesis of a multiplicity, and, as Swinburne points out, it leads one to expect uniformity in the laws of nature across time and space.

For Harrison, the aliens are indeed intermediary (perhaps one should call them 'angels'?), since he asks the question, 'Who or what created the first universe?', and allows that the answer might be God! Even if, in Harrison's scheme, God only starts the first universe, and others are created by superior intelligences, we are left with precisely the 'end-point to scientific enquiry' which Harrison sought to avoid. I really do not see that the alternative he offers, that there were in the beginning already many universes, some of which became 'intelligent', triggering ultimate domination by 'intelligent' universes, advances the argument much. There is still the problem of how the whole process got going, since if there were no 'intelligent' universes to begin with it is difficult to see how they first arose, and if there were, the whole theory seems redundant. And then, without the creation of universes by intelligent beings you would get a universe like ours anyway sooner or later on other types of many universe hypothesis (at least, so their proponents argue). What is more, it is completely impossible to distinguish the alternative modes of genesis, random selection from an ensemble or creation by aliens, given that we only have access to this particular universe.

I mentioned that cosmologist Lee Smolin has a similar scheme of creation of universes by black holes, but without the extra complication of the black holes being created artificially.[95] Does his theory fare any better than Harrison's?

Bypassing consideration of the low probability I quoted above from Guth, Smolin speculates that a new universe is spun off at the central singularity every time a black hole forms. The physical constants undergo a small amount of random shuffling each time this process occurs. Each new universe produces its own quota of black holes, more or fewer than its parent, but over many aeons (measured in some kind of 'absolute time') those universes with the most black holes inevitably become dominant. Our universe then arises by a process of natural selection among universes (where now the adjective 'natural' is more appropriate).

Like Harrison, Smolin has a theological, or rather atheistic, motivation for his proposal. He boldly claims: 'perhaps for the first time in history, we know enough to imagine how a universe like ours might have come to be without the infinite intelligence and foresight of a god'.[96]

Smolin makes a very specific prediction: we should be in a universe with the maximal number of black holes compatible with our own existence. The problem is, as Joseph Silk notes, that our universe is short of its maximal number of black holes by a factor of about 10,000.[97] Moreover, Smolin has some strange views about star formation, asserting that carbon is needed both for this and for black hole formation. Hence he explains the coincidences necessary for carbon manufacture as due to cosmological natural selection rather than, as does Hoyle, anthropically. But the physics here seems plainly wrong—witness the first generation of stars formed from primordial hydrogen and helium, and our knowledge from Penrose that the early (carbonless) universe would have been dominated by black holes unless entropy had been exceedingly low.

We have thus seen massive problems with both the Harrison and Smolin schemes. Aliens or no, could this be the second worst atheistic argument in Western thought?

Nevertheless, it seems that a many universes hypothesis in some form or other is the only really viable alternative to design, especially as it seems to be invoked within a number of the alternatives which we originally thought were different.

## Notes

1 Van Inwagen (1993), pp.134-136.
2 Leslie (1989), pp. 13-14.
3 Bradley (2001).
4 Bradley rejects an objective account of value, and repeats his criticism of the argument from fine-tuning based on the objective value of a life-bearing universe in Bradley (2002).
5 Davies (1992), p. 214.
6 *Ibid.*, p. 220.
7 Smart (1989), pp. 177.
8 Schlesinger (1988), pp. 125-127.
9 Van Inwagen, p. 135.
10 Van Inwagen, p. 212; Leslie (1989), p. 10.
11 Leslie (1989), pp. 17-18.

12 Leslie (1982), p. 143.
13 As noted in chapter 3, measure zero implies zero probability. The mathematical definition of measure, and of probability as a special kind of measure, is given in chapter 7.
14 As suggested to me in private correspondence by Peter Hodgson.
15 Tegmark (1998), pp. 24-40.
16 *Ibid.*, p. 40.
17 Smoot and Davidson (1993), p. 180.
18 Leslie (1989), p. 30.
19 Polkinghorne (1988), p. 23.
20 Leslie (1989), p. 17.
21 Van Inwagen (1993), pp.137-138.
22 Leslie points out that, strictly speaking, we only need vastly many rather than infinitely many universes, and van Inwagen also seems to see no necessity in an infinite number. This is the case provided that there is a positive probability for fine-tuned parameter selection, an important point to which we must return later.
23 Notably Ian Hacking (1987), and Roger White (2000).
24 See Garrett and Coles (1993).
25 Rees (2001), p. 164.
26 Rees (2000), p. 138.
27 Gale (1990), pp. 189-206.
28 Ellis and Brundrit (1979), pp. 37-41.
29 E.g. Wheeler (1973).
30 Leslie (1982), p. 147.
31 Hawking (1993), pp. 115-125.
32 Guth (1997), pp. 253-269.
33 This was at the 17th International Conference on General Relativity and Gravitation held in Dublin in July 2004.
34 Of course, the measuring apparatus *must* be strongly deterministic, else how could it work and be reliable? Moreover, there needs to be determinism at the macroscopic level so that, when I look at my notes from the experiment a few days after I have recorded them, I still see the same results on the page!
35 The oddity of this is noted by Polkinghorne in Polkinghorne (1984), p. 66.
36 Polkinghorne (1984), pp. 61ff.
37 Barrow (1988), p. 152.
38 Leslie (1982), p. 145.
39 *Ibid.*, p. 146.
40 *Ibid.*, p. 146.
41 McMullin (1993), p. 380.
42 Barrow (1988), p. 155.
43 *Ibid.*, p. 156.
44 Gell-Mann (1994), p. 138.
45 McMullin (1993), p. 380.
46 As John Polkinghorne remarks in private correspondence with me.
47 Davies (1982), p. 125.
48 Barrow and Tipler (1986), p. 495.
49 Penrose (1994), p. 312.
50 Lockwood (1989), p. 229.
51 Barrow (1988), pp. 157-158.

52 Barrow and Tipler (1986), p. 495.
53 This is an unavoidably very brief and simplified summary of a complex subject. For technical details see Omnès (1994). A simpler account is given in Omnès (1999), and some discussion at the popular level is to be found in Gell-Mann (1994), ch. 11.
54 Tegmark (1998), and repeated as his 'Level IV' kind of multiverse in Tegmark (2003).
55 In contrast to 1b and 1c TOEs in which only some things which exist mathematically exist physically, and nothing that exists mathematically exists physically, respectively; and class 2 TOEs in which the physical world is not completely mathematical.
56 Tegmark (1998), p. 47.
57 Hawking (1988), p. 174.
58 Tegmark (1998), p. 46.
59 This radical multiverse idea is also discussed less technically in Barrow (2002), pp. 277-281. In contrast to Tegmark, Barrow recognizes there is a problem in equating mathematical and physical existence, with the former being in a sense 'less real'.
60 Nozick (1981), pp. 128ff.
61 Lewis (1973, 1986).
62 Putnam (1992), p. 136.
63 Atkins (1981), pp. 99-115.
64 Tryon (1973).
65 See, for example, Vilenkin (1982); and Leslie (1989), pp. 79-81, for a useful overview.
66 Hartle and Hawking (1983).
67 Hawking (1988), pp. 136-141; Hawking (2001), pp. 82-86.
68 Hawking (2001), p. 196.
69 Hawking (1988), p. 136.
70 Hawking (1988), pp. 140-141.
71 Hawking (1988), p. 136.
72 Hawking (2001), p. 85.
73 See Taylor (1995), pp. 38-48.
74 E.g. Hawking (2001), pp. 31, 41, 59, 118, 127, 198.
75 Hawking (1988), p. 135.
76 Hawking (1988), p. 139.
77 Hawking (2001), p. 59.
78 As noted by Quentin Smith in Craig and Smith (1993), pp. 315-321.
79 Hawking (1984), pp. 272-273; quoted by Smith in Craig and Smith (1993), pp. 315-316.
80 Hawking (1987), p. 650; quoted by Smith in Craig and Smith (1993), p. 320.
81 Smith in Craig and Smith (1993), p. 320.
82 Barrow and Tipler (1986), p. 441.
83 Leslie (1989), p. 81.
84 Hawking (1988), p. 141.
85 Polkinghorne (1992).
86 Craig in Craig and Smith (1993), p. 281.
87 Although he could not prove it, Aquinas did, however, believe that the universe was finite on the basis of his understanding of the specifically Christian revelation. It is not clear that revelation must be understood in this sense, although it is important to emphasize, in distinction to, say, Greek thought, that God is not somehow subject to pre-existent matter when he creates—quite the reverse, God is in total control.
88 Craig in Craig and Smith (1993), pp. 282-283.
89 Drees (1990), p. 71.

90 Smith in Craig and Smith (1993), p. 322.
91 Harrison (1995).
92 As Barrow points out, Harrison's scheme is really 'unnatural selection' or 'forced breeding'. See Barrow (2002), p. 341, note 17.
93 Guth (1997), pp. 255-256.
94 Hawking (2001), p. 171.
95 Smolin (1997).
96 *Ibid.*, p. 219.
97 Silk (1997).

## Chapter 5

# How to Evaluate the Fine-Tuning—Probabilistic Framework

For nature is pleased with simplicity, and affects not the pomp of superfluous causes.

(Sir Isaac Newton, *Philosophiae Naturalis Principia Mathematica*, Book III.)

### Introduction

We have seen that the universe is seemingly fine-tuned for life, that the fine-tuning suggests design but that alternative explanations are possible. How are we to decide rationally between the alternatives? Is there some rigorous evaluation procedure we can use in this task?

I propose to use Bayesian probability theory as just the rigorous framework required. The Reverend Thomas Bayes was an eighteenth century nonconformist minister whose seminal work, *An essay towards solving a problem in the doctrine of chances*, was communicated to the Royal Society after his death by fellow nonconformist minister Richard Price. At the heart of Bayes's paper is the theorem which now bears his name and which forms the basis for Bayesian probability theory, also known as Bayesian confirmation theory.

In this chapter I explain what Bayesianism is and how it has coped with some of the philosophical problems associated with the scientific method. For Bayesianism is actually an approach to evaluating competing *scientific* hypotheses, being a rigorous formulation of the method of induction, whereby increasing numbers of observations of a particular pattern in nature give one greater confidence that the pattern is not accidental, but a universal law. Following Richard Swinburne, I propose to use the method to evaluate competing metaphysical rather than scientific hypotheses.

In fact there is no logical difference between applications of modern Bayesianism to scientific and to metaphysical hypotheses. Although a non-believer, John Earman, who is a strong proponent of Bayesianism, agrees that the method extends to metaphysical hypotheses. After all, if Bayesianism can be invoked to assess the evidential support for unobserved entities such as the Higgs boson (predicted by the standard model in order to give mass to the W and Z particles), why not for unobservables such as God, provided only that God makes a difference to the probability of things we *can* observe?[1]

## The Probability Calculus and Bayes's Theorem

I present the axioms of probability theory, together with some important consequences of them, in mathematical form in Appendix A. Here I summarize in words what that mathematical apparatus tells us more rigorously through the use of symbols, though I shall write down the fundamental formulae we shall need for what follows, and must inevitably include some symbols to do so.

We use the term probability in everyday language without thinking of the subtleties of meaning and interpretation which mathematicians and philosophers wrestle with. For the most part we shall be dealing with the philosophers' notion of the probability of a proposition, especially that kind of proposition which we call a 'hypothesis'.[2] Mathematicians on the other hand speak about the probability of an event, conceived of as a subset of possibilities in any application. The two formulations are equivalent, with the mathematicians' operations on sets corresponding to the philosophers' logical operations on propositions.

Examples of probability would be 'the probability that the Conservative Party will win the next General Election', or 'the probability that my next hand at bridge will be a Yarborough (i.e. contain no cards higher than a nine)'.

We denote the probability of any proposition $A$ by $P[A]$. We assign probabilities a numerical value between 0 and 1. To say that $A$ has a probability of 1 means that it is a necessary truth, i.e. there is no possible world in which $A$ can be false. Examples would include the propositions '$2 + 2 = 4$', and 'All boys are of the male sex'. Similarly if $A$ has a probability of zero it is necessarily false. So '$2 + 2 = 5$' and 'Sophie is a female boy' are necessarily false and have probability zero. Intuitively we can see that the more likely a proposition is to be true, the closer its probability should be to 1.[3]

Next we say that the probability of one or other of two mutually exclusive propositions being true is the sum of their individual probabilities. For example, the probability that when I throw a die it will show either 1 or 6 spots is the sum of the probabilities that it will show 1 and that it will show 6. On the classical interpretation of probability, which I shall describe briefly later, for a fair die this would be $1/6 + 1/6 = 1/3$. Our intuitive notions are confirmed if we note that $P[1 \text{ or } 2 \text{ or } 3 \text{ spots}] = 1/6 + 1/6 + 1/6 = ½$ (this is more likely than only 1 or 2 spots, and covers half the possibilities), and so on up to $P[1 \text{ or } 2 \text{ or } 3 \text{ or } 4 \text{ or } 5 \text{ or } 6 \text{ spots}] = 1/6 \times 6 = 1$ (this is certain because it exhausts all the possibilities).

In what follows we shall also need the vitally important concept of 'conditional probability'. We write the conditional probability of $A$ given $B$ as $P[A|B]$, reading this quantity as 'probability of $A$ given $B$'. As I state in Appendix A (axiom (A4)), the formal definition of $P[A|B]$ is $P[A|B] = P[A \wedge B]/P[B]$, where the symbol $\wedge$, also written '&', means 'and'. The probability of $A$ given $B$ is thus the probability of $A$ and $B$ divided by the probability of $B$.

As an example, suppose two dice are thrown and one asks the question, 'What is the probability that the total number of spots is 12?' Since this can only happen if both dice roll a 6, and there are 36 possible combinations, the answer is 1/36. But now suppose the first die rolls a 6, and we ask the question, 'What is the probability that the total number of spots is 12, given that the first die has already rolled a 6?' The answer now is 1/6, since the second die must also roll a 6, and there are now only 6 possibilities. On the other hand, the probability that the total is 12, given that the first die rolled anything other than a 6, is zero.

Before stating Bayes's theorem we need what I shall call the 'total probability rule'. Suppose that England have a probability of 0.6 of beating Australia at cricket if they win the toss and a probability of 0.2 of winning the game if they lose the toss. The probability of winning the toss is 0.5 and of losing it is also 0.5. The probability of both winning the toss and winning the game is 0.6 x 0.5 = 0.3. Similarly the probability of losing the toss and winning the game is 0.2 x 0.5 = 0.1. The overall probability of winning is the sum of these separate probabilities, i.e. 0.4. This is an example of a more general rule, namely the total probability rule

$$P[A] = P[A|B].P[B] + P[A|\sim B].P[\sim B]$$

where $\sim B$ means 'not $B$'.

We are now in a position to state Bayes's theorem. It is

$$P[B|A] = \frac{P[A|B].P[B]}{P[A]} \qquad (1)$$

or, substituting for $P[A]$ from the total probability rule,

$$P[B|A] = \frac{P[A|B].P[B]}{P[A|B].P[B] + P[A|\sim B].P[\sim B]} \qquad (2)$$

The theorem tells us how to obtain the probability of $B$ given $A$ if we know the probability of $A$ given $B$ and the probability of $B$ *simpliciter* (note that the probability of not $B$ is given by $P[\sim B] = 1 - P[B]$).

Let us see by way of example how Bayes's theorem might be applied. Suppose 1% of the population suffer from a certain disease, which lies dormant for many years before becoming quicky fatal. There is a diagnostic test which gives the following results. If a person has the disease the test is positive 90% of the time. If a person does not have the disease the test shows positive 10% of the time.[4] I hear about this disease on the television and become extremely anxious, although I have no symptoms. I go to my doctor and ask for the test. It is positive. What is the probability that I have the disease?

Most people answer 90% to this question. However Bayes's theorem gives the correct answer as follows.

Let $A$ = 'the test is positive' and let $B$ = 'I have the disease'. Then $P[A|B] = 0.9$, $P[A|\sim B] = 0.1$, $P[B] = 0.01$. It follows from Bayes's theorem that

$$P[B|A] = \frac{0.9 \times 0.01}{0.9 \times 0.01 + 0.1 \times 0.99} = \frac{1}{12}$$

The new information that the test is positive means, therefore, that I should revise the probability that I have the disease upwards from 0.01 to1/12, higher of course, but not nearly as alarming as the naïve figure of 0.9 I might have guessed at.

In some of what follows we shall also need to generalize beyond the two simple alternatives in (2) above of $B$ and $\sim B$. The generalization for many alternatives is

$$P[B_i|A] = \frac{P[A|B_i].P[B_i]}{\sum_{j=1}^{n} P[A|B_j].P[B_j]} \tag{3}$$

where the $B_i$, for $i = 1, 2, 3, \ldots, n$, are mutually exclusive and exhaustive alternatives, and the symbol $\sum_{j=1}^{n}$ means 'sum over dummy index $j$ going from 1 to $n$'.

Suppose the weather tomorrow will be sunny with probability 0.2, cloudy but with no rain with probability 0.3, and rainy with probability 0.5. If it is sunny Algy and Ernest will play golf with probability 0.8, if cloudy they will play with probability 0.6, and if raining with probability 0.2. I am absent in foreign parts on the day, but later hear that they did indeed play. What is the probability that the weather was sunny?

Here $n = 3$, and so let $B_1$ = 'sunny', $B_2$ = 'cloudy, no rain', $B_3$ = 'rain', and $A$ = 'Algy and Ernest played golf'. Then $P[B_1] = 0.2$, $P[B_2] = 0.3$, $P[B_3] = 0.5$, $P[A|B_1] = 0.8$, $P[A|B_2] = 0.6$, $P[A|B_3] = 0.2$, and the calculation we require is

$$P[B_1|A] = \frac{0.8 \times 0.2}{0.8 \times 0.2 + 0.6 \times 0.3 + 0.2 \times 0.5} \approx 0.36$$

In other words, the probability that it was sunny has been raised by 82%, from 0.2 to approximately 0.36, given the knowledge that the game was played.

From these examples we begin to see how the probability of a metaphysical hypothesis, such as the existence of God, might be raised when evidence such as the fine-tuning of the universe is taken into account.

## Interpretation of the Probability Calculus and Bayes's Theorem

The mathematics of the probability calculus is uncontroversial. As with any mathematical system, we state our axioms and work out their logical consequences. However, controversy does arise when we come to apply the mathematics. To what kind of propositions does the mathematics pertain? What does probability really mean? How do we assign probabilities to propositions? In this section I give a brief overview of what is in reality a complex subject area, referring the reader to the literature for a more comprehensive discussion.[5]

Classically, probability was related to the outcome of games of chance. Notions of symmetry led to the concept of 'equally likely outcomes' for throws of a fair die, tosses of a fair coin and the like. On this interpretation the probability of a proposition is equal to the ratio of the number of possible outcomes of an experiment in which the proposition is satisfied to the total number of possible outcomes. Thus a value of 1/6 was assigned to the probability that a fair die would land with the number 5 face uppermost because '5 uppermost' is one of 6, equally likely, possible outcomes. That seems straightforward enough for a symmetric die or coin, but the theory hits problems when there are different, but equally justifiable possibilities for the set of equally likely outcomes. Moreover, for the kinds of proposition we shall be dealing with, there will be no obvious kind of symmetry to appeal to at all.

In the 'relative frequency' interpretation, probability relates to the outcome of many trials of an experiment. Thus in many tosses of a fair coin, the proportion which land heads will tend asymptotically to ½, so the probability that a single toss will produce a head is ½. The probability calculus tells us how to manipulate probabilities defined as asymptotic proportions, and probability in this sense is also called 'statistical probability'.

One problem with the frequency approach is that it would seem to deny us the possibility of talking about the probability of a unique event, such as the outcome of the 2.30 at Ascot. Even if one can envisage hypothetical ensembles of runs of the 2.30, the problem is exacerbated when we try to apply this notion of probability to a scientific hypothesis. For example, it is hard to see how we can give any meaning to a statement of the form, 'The probability that general relativity is the correct theory of gravity is 0.99,' on this basis.

Another kind of probability is 'physical probability', which has to do with the extent to which one or more events cause another event. The outcome of my toss of a coin may be determined completely by the impulse I impart to it, the angle at which my thumb strikes it, the atmospheric conditions at the time, and so on; and so the coin may have a physical probability of 1 of landing heads on a particular toss. Indeed, if determinism were true all physical probabilities would be 0 or 1. Most physicists, however, believe that quantum theory is ontologically indeterminate and so the physical probability of a quantum event, such as the radioactive decay of an atom within a certain time, has a physical probability between 0 and 1.

The notion of probability which we will use is that most suited to the evaluation of competing scientific hypotheses, and is that propounded by modern advocates of Bayesianism. This is 'epistemic probability'. The adjective 'epistemic' indicates that we are dealing with what it is rational to believe. Epistemic probability then denotes 'rational degree of belief'. Since belief will be more or less rational depending on the evidence for it, epistemic probability is probability based on evidence. The propositions to which the probabilities are applied are then specific hypotheses. The conditional probabilities denote the probability that certain evidence will pertain if a particular hypothesis were true or, conversely, the probability that the hypothesis is true given the evidence. The probability calculus thus tells us how to revise our prior beliefs in the light of evidence.

The epistemic notion of probability can be further subdivided into objective and subjective interpretations. In the objective case there is deemed to be a logical relationship between hypothesis and evidence, and probability measures the extent to which the evidence is entailed by the hypothesis. The objective interpretation is thus a statement about how the world is.

This idea of there being a logical relationship between hypothesis and evidence goes back to the pioneers of confirmation theory, J. M. Keynes and Rudolf Carnap.[6] Richard Swinburne, who formerly referred to the logical theory as a correct account of epistemic probability, seems in his most recent thinking to have elevated 'logical probability' to be the primary concept, with epistemic probability subsidiary to it.[7] However, logical probability is an ideal concept, being 'that measure of inductive support that would be reached by a logically omniscient being (that is, one who knows what are all the relevant logical possibilities and knows what they entail, and has correct inductive criteria)'.[8]

Swinburne notes that in practice an investigator may not have perfect powers of logical reasoning, and so he now limits the term 'epistemic probability' to probability based on evidence, but also relative to the investigator's logical competence. However, although the investigator has no false logical beliefs or rules of inference, merely the limited capacity to draw deductive inferences, Swinburne sees this concept as 'extraordinarily vague'. Even so, his example of a mathematical conjecture, which has logical probability 1 or 0, but epistemic probability in Swinburne's sense less than but close to 1 based on the evidence of many trials, would seem to endow epistemic probability with useful content.

In defining the subjective interpretation, Swinburne loosens the requirement further, so that now an investigator may not even have the correct inductive and deductive criteria. Swinburne thus makes it sound as though only logical probability is worth having, but many would argue that this is an unattainable ideal, and, despite Swinburne's strictures, there are many philosophers who operate with the subjective interpretation.

Because the subjective interpretation is concerned with the beliefs of an individual agent, the probabilities involved are often called 'personal probabilities'. The probability calculus then shows the relationships that are required between the agent's beliefs for logical consistency.

These subjective probabilities are frequently related to the notion of fair bets which confer no advantage either to the person offering the bet or the one accepting it. Thus, suppose your subjective degree of belief that a certain horse called Dover will win the opening race at Ascot is $p$. Then define fair betting odds $k$, usually written $k$:1, by $k = (1 - p)/p$. This means that, if you bet on Dover, then for a stake $S$ your net return will be $kS$ if Dover wins and $-S$ if not. Suppose you are willing to accept any bets you judge fair. Then, for example, you would be willing to bet on Dover winning or losing and to accept a bet from someone else on Dover winning or losing.

Now it can be shown that, unless your subjective degrees of belief obey the rules of the probability calculus, it will be possible for someone to devise a betting strategy (known as a 'Dutch book') against you, whereby you will be certain to lose money, even though you judge all the bets to be fair. Suppose, for example, you thought the probability of Dover winning was 2/3 (odds 1:2) but the probability of him losing was only 1/4 (odds 3:1). Then someone could place a bet of £5 with you on Dover to win and £2 on him to lose. This person's net return would be $\frac{1}{2} \times 5 - 2 =$ £0.50 in the event that Dover wins and $-5 + 3 \times 2 =$ £1 if he loses. Either way you are out of pocket, and the reason is that the probability that Dover either wins *or* loses (and necessarily one or the other has to happen) ought to be 1 according to the probability calculus, but in your case is only $2/3 + 1/4 = 11/12$. Of course it is not necessary that anyone be a gambler in fact, only that his rational degrees of belief behave as defined in this way.

We can illustrate why personal degrees of belief can be represented by probabilities from an example due to Lindley. You are offered a choice between two options to win a prize. The options are either that it rains tomorrow or that a ball drawn out of an urn is black. You are told that the proportion of black balls in the urn is $p$. If $p$ is 1 clearly you will prefer the urn-drawing option; if $p$ is 0 you will prefer to take your chance that it rains tomorrow. At some value of $p$ intermediate between 0 and 1 you will be indifferent between the options: that value of $p$ is your degree of belief that it will rain tomorrow.

This interpretation of probability is subjective because it relates to an individual agent's beliefs. The agent's set of beliefs is consistent if it obeys the probability calculus, which provides an objectively rational system for testing and organizing one's beliefs. However, if a second agent were in the same position as the first with regard to his knowledge of the world, then he ought to assign the same probability values as the first agent. Thus, in this sense, notwithstanding the terminology, Bayesian personalism claims to be normative.

It is rather interesting that later in his book Swinburne is more accommodating to epistemic and subjective probability. By this time, building on the work of Alvin Plantinga,[9] he has also developed the notion of 'basic beliefs', starting points for belief system construction, rather like axioms in mathematics. Swinburne distinguishes between 'rightly basic' beliefs which one ought to have and 'actual basic beliefs' which one has in practice. He then states that, 'while the best beliefs to have are those that are logically probable on our rightly basic beliefs, beliefs that are merely epistemically or subjectively probable on these (or epistemically or subjectively probable on actual basic beliefs) are not likely to be greatly in error'.[10] He acknowledges that in practice an investigator can only operate on his own standards, using actual basic beliefs and subjective probability, but 'to the extent to which his standards are close to the correct ones, he will use rightly basic beliefs and logical probability'.[11]

In what follows the kind of probability being dealt with will be 'epistemic' in the broad sense of 'rational degree of belief', i.e. probability based on evidence, but I leave it somewhat fluid as to whether it is more refined than that, i.e. 'logical' or 'personal'. I look at some attempts to assign probabilities in a consistent, normative way. I also give arguments based on judgment, weighing up some of the criteria for making probability assignments, and drawing on the arguments of Swinburne and others in the process. All this could be construed as attempting to construct 'logical probabilities'.

Although I later assign actual numbers for purposes of illustration, I urge caution in arguing that it is really only the relative magnitudes of the probabilities in broad brush terms that can be accepted with any confidence. I hesitate to say at this stage that my probability assessments ought to command universal assent, though of course I would like them to. I certainly make no claim to omniscience! However, it will certainly be the case that if a reader accepts my judgments, especially regarding the relative magnitudes, he ought to accept my conclusions, based on the probability calculus; otherwise he is open to being fleeced in a series of, albeit hypothetical, bets.

## Some Bayesian Terminology

It will be useful to rewrite Bayes's theorem in terms of hypotheses and evidence and to define various terms in the equation. Substituting hypothesis $H$ for $B$, and evidence $E$ for $A$, in (1) above, we obtain:

$$P[H|E] = \frac{P[E|H].P[H]}{P[E]}$$

We introduce the following terminology:

(1) $P[H]$ is called the 'prior probability' of the hypothesis, i.e. the probability that the hypothesis is true before we take account of the evidence.

(2) $P[E|H]$, the probability of the evidence given the hypothesis, is also known as the 'likelihood' of the hypothesis.

(3) The factor $P[E|H]/P[E]$ is called the 'explanatory power' of the hypothesis $H$ with respect to evidence $E$.

(4) $P[H|E]$ is the posterior probability of the hypothesis, i.e. the value to which the prior probability of the hypothesis should be revised in the light of the evidence.

It is thus equal to the explanatory power of the hypothesis times the prior probability.

We shall be interested in comparing how well alternative hypotheses explain the same evidence. Given two hypotheses $H_1$ and $H_2$, and evidence $E$, Bayes's theorem yields:

$$P[H_1|E] = \frac{P[E|H_1].P[H_1]}{P[E]}$$

and

$$P[H_2|E] = \frac{P[E|H_2].P[H_2]}{P[E]}$$

It follows, by dividing the left and right hand sides of these equations, that

$$\frac{P[H_1|E]}{P[H_2|E]} = \frac{P[E|H_1]}{P[E|H_2]}.\frac{P[H_1]}{P[H_2]} \tag{4}$$

This useful equation enables us to make a direct comparison between the competing hypotheses, i.e. the ratio of the posterior probabilities is equal to the ratio of the likelihoods times the ratio of the priors.

For simplicity I have written the equations with the only conditionals being on $E$ or any hypotheses $H$. Strictly speaking, all probabilities, including the priors, should be conditioned on background knowledge $K$. $K$ will include all knowledge taken for granted in any application, such as tautologies and the rules of logic.

We also utilize the very useful vocabulary of confirmation. Thus, following Swinburne, White and other authors,[12] I define 'confirmation' to mean the raising of the probability of $H$ given $E$ and $K$, i.e.:

> Evidence $E$ confirms hypothesis $H$, given background knowledge $K$, if and only if $P[H|E \wedge K] > P[H|K]$

Similarly by 'disconfirmation' I mean lowering the probability of $H$ given $E$ and $K$, i.e.:

> Evidence $E$ disconfirms hypothesis $H$, given background knowledge $K$, if and only if $P[H|E \wedge K] < P[H|K]$

For completeness we can also add the concept of neutrality of evidence:

Evidence $E$ is neutral with respect to hypothesis $H$, given background knowledge $K$, if and only if $P[H|E \wedge K] = P[H|K]$

From the above definition of confirmation, it follows straightforwardly from Bayes's theorem that $E$ confirms $H$ if $P[E|H \wedge K] > P[E|\sim H \wedge K]$, i.e. the evidence is more likely to obtain if the hypothesis is true than if it is false. Thus it can be seen how Bayesianism captures our basic intuitions of inductive inference.

### An Example: the Weak Anthropic Principle

An example of relevance to the main topic of this book is that of the Weak Anthropic Principle (WAP). Garrett and Coles show, using Bayes's theorem, how the presence of life can in principle lead to predictions for the values of some of the physical constants, thereby putting the WAP on a genuinely explanatory footing.[13] To simplify these authors' treatment somewhat, suppose that according to some model of the universe M a parameter $\lambda$ can take values $\lambda_1, \lambda_2, \ldots, \lambda_n$. Let $L$ be the proposition that intelligent life evolves in our universe. Then Bayes's theorem gives

$$P[\lambda = \lambda_i | L] = \frac{P[L|\lambda = \lambda_i].P[\lambda = \lambda_i]}{\sum_{j=1}^{n} P[L|\lambda = \lambda_j].P[\lambda = \lambda_j]}$$

Here all probabilities should additionally be conditioned on M and background knowledge, but I omit these for simplicity.

Now assignment of the priors $P[\lambda = \lambda_j]$ is a difficult and controversial step, about which I shall have more to say in due course. Garrett and Coles are in favour of a particular, and rigid, method for doing this which I shall later criticize, but in the present instance they argue that application of this method is too difficult. They simply state that the prior will be broad rather than sharply peaked (NB this is in contradiction to the later paper of Evrard and Coles,[14] where their favoured method for prior probability allocation is actually used). Taking a broad distribution for the priors means that the $P[\lambda = \lambda_j]$ can be treated as roughly equal, and hence cancelled from both numerator and denominator in the above equation.

The likelihoods $P[L|\lambda = \lambda_j]$ depend on astrophysical theories of star and planet formation, plus the conditions needed for life to develop on a planet. Although much of this kind of knowledge is very tenuous, I would agree with Garrett and Coles that we can be confident that $P[L|\lambda = \lambda_j]$ will be sharply peaked about certain of the $\lambda_j$. Thus if there is a peak at $\lambda = \lambda_i$ then $P[L|\lambda = \lambda_i]$ will dominate the denominator above, and the peak will be translated into a peak at $P[\lambda = \lambda_i | L]$ in the posterior probabilities. In other words, if the development of life depends on $\lambda$ taking certain limited values (more likely belonging to a narrow range of values), then these values are what are likely to be found in practice, given that life has occurred.

In contrast, I believe also correctly, Garrett and Coles show that the evidence of life does not enhance the probability that the Strong Anthropic Principle (which states that life *must* occur) is true.

In subsequent chapters I shall be using Bayes's theorem to examine the more interesting question as to whether the evidence of fine-tuning (which seems required for a life-producing universe) enhances the probability that God designed the universe that way, and comparing that hypothesis with its chief rival, namely the multiverse hypothesis. In the meantime, we are now ready to examine how Bayesian confirmation theory meets some of the objections raised against it.

## A Theological Objection to the Use of Bayes's Theorem

Bayes's theorem may be regarded as formalizing a mode of argument known as 'Inference to the Best Explanation' (IBE). IBE involves accepting a hypothesis as the best explanation for one's evidence. The best explanation will be best in the sense of satisfying criteria such as simplicity, explanatory power and fruitfulness.

Robert Prevost is critical of the use of formal probability—Bayes's theorem—as a tool to assist IBE arguments in support of religious belief.[15] He thus endorses the informal use of 'judgment', as seen in the work of Basil Mitchell, in preference to the formal approach of Mitchell's successor in the Nolloth Chair at Oxford, Richard Swinburne.

Prevost seems to think that Bayesianism cannot capture our judgments about the effect of certain kinds of evidence, notably the evidence of evil in the world, on the theistic hypothesis. Now, as noted in chapter 1, my concern in this book is very limited. It is not to look at every kind of evidence, for and against the existence of God, but is limited to the evidence of a certain kind of order in the universe. In my view, the biggest problem for theism is the existence of evil in the world. Naïvely at any rate, evil would seem to count against the existence of a good God. That is not to say, however, that theism has no answer to the problem of evil, or cannot say anything in reply. If reasons can be adduced why a good God might allow evil, and indeed the amount and kinds of evil actually seen in the world, then the problem is at least mitigated. I see no reason in principle why such arguments cannot be incorporated into a Bayesian scheme. Although Swinburne believes the evidence of evil is neutral towards the hypothesis of theism, and he advances arguments in support of this thesis, even if evil were to disconfirm theism that would not be decisive. For a cumulative case for theism might well still work, if the confirmatory evidence outweighed the disconfirmatory.

By way of analogy, Prevost gives an example to illustrate why he thinks Bayes's theorem is inadequate:

> The explanation of a bank robbery will obviously include reference to an agent. If we know who committed the robbery, we can causally explain the event of the robbery by reference to the agent and his intention to rob the bank. But the explanation is made more forceful if we know the motive behind the bank robbery. Knowing that an agent had to find money to feed his children increases the explanatory power of the hypothesis that he committed the robbery, even if we know already that he did the crime. But this sort of explanatory power is not the kind represented by Bayes's theorem, and its evidential support must be assessed by a non-Bayesian judgment in much the same way as the theistic explanation of evil.[16]

But it would seem to be false that the explanatory power involving the need of the robber to feed his children cannot be captured by Bayes's theorem. Indeed the analysis is only marginally more complicated than the rather trivial examples I have given earlier in this chapter.

Let $K$ be background knowledge about crime C, i.e. knowledge apart from the need of suspect S to feed his children. $K$ might include evidence from witnesses, S's criminal record, and so on.

Let $N$ be the knowledge that S needs to feed his children, e.g. he and his wife are unemployed, their joint income (from social security) is below some threshold £I, their outgoings are £E, and they have $n$ children to feed.

Denote by $G$ 'S committed C'. Then

$$P[G|N \wedge K] = \frac{P[N|G \wedge K].P[G|K]}{P[N|G \wedge K].P[G|K] + P[N|\sim G \wedge K].P[\sim G|K]}$$

Now we can approximate as follows:

$$P[N|G \wedge K] = P[N|G]$$

and

$$P[N|\sim G \wedge K] = P[N|\sim G]$$

i.e. the probability that S needs to feed his children given that he is guilty and was near the scene, etc., is independent of the latter information and depends only on his guilt; and similarly for the case given that he is not guilty.

Now suppose that

(i) $P[N|G] = 0.1$, i.e. the proportion of the population who commit crimes of this sort who need to feed their children, is 10%;

(ii) $P[N|\sim G] = 0.01$, i.e. the proportion of non-criminals in this category of poverty is 1%;

(iii) $P[G|K] = 0.7$, i.e. the probability that S is guilty given $K$ alone is 0.7.

Real-life values for (i), (ii) and (iii) are all, in principle, obtainable from experience. Thus (iii) is saying that it is generally the case that when the police have evidence of quality $K$, there is a 70% chance that their suspect is guilty. Similarly (i) can be obtained from an analysis of crimes committed of the relevant kind and a social assessment of the economic circumstances of those known to have committed them.

With the above values we obtain $P[G|N \wedge K] = 0.96$. In other words, the extra information concerning S's poverty (in the sense of child-feeding need) raises the probability that he committed C from 0.7 to 0.96, an entirely plausible result.

I see no reason why, in a similar way, one cannot incorporate into a Bayesian analysis God's motivation in allowing evil, or why indeed, more generally, Bayesian confirmation theory should not be applicable to IBE arguments in support of theism. In a previous paper I have myself used the theory to criticize Hume's famous argument against miracles.[17]

Of course we may well not have exact values for the probabilities. It will no doubt be difficult to quantify the amount of evil in the world, and then to estimate the probability that God would allow such evil—given for example his purpose in bringing about a universe containing creatures with free will who have the possibility to inflict evil against his will. As we shall see, even in the case of cosmic fine-tuning, where we have more quantitative data to go on, it is not easy to translate such data into the probabilities we need. However, it is really only the relative magnitudes which are important for our arguments to carry, and Bayes's theorem *does* enable us to derive useful results based only on estimates or relative magnitudes, as we shall see.

## Prior Probabilities and the Criterion of Simplicity

One of the problems arising when we attempt to use Bayes's theorem is, 'What values should we use as inputs to the equation?' The problem is particularly acute for the prior probabilities. Another of Prevost's criticisms of Bayesianism concerns this area: even if the theory is usable there is necessarily conflict about the inputs, especially the prior probabilities, and to Prevost this undermines the method.

One possible way of assigning prior probabilities is to use the Principle of Indifference, or some variant of it. The Principle of Indifference (PI, also known as the Principle of Insufficient Reason) in probability theory[18] is a principle of ignorance. It states that, if you have $n$ mutually exclusive and exhaustive hypotheses $H_1, H_2, ..., H_n$, and you have no reason to prefer any hypothesis over any other, then you should assign a probability of $1/n$ to each.

The PI soon runs into difficulties. For example, does it make sense to say that a car is equally likely to be red or not-red? Or that it is equally likely to be red or green or blue or some other colour?[19] The first option gives a probability of 0.5 that the car is red and the second a probability of 0.25.

An example of this sort of ambiguity in mathematics is provided by Bertrand's paradox. We are required to calculate the probability that a randomly drawn chord of a circle has length greater than the side of an equilateral triangle inscribed in the circle. Kneale gives three solutions to the problem, corresponding to three ways of drawing a random chord.[20] We shall see that the ambiguous notion of 'randomness' poses a distinct problem when it comes to quantifying the fine-tuning. It is in fact a problem for both of our main hypotheses, namely design and multiple universes, though I shall argue that it is particularly acute for the latter.

Various attempts have been made to get round the problems associated with the PI. Especially worthy of attention is the form advocated by E. T. Jaynes,[21] not least since this is the method, to which I referred earlier, advocated by Coles and colleagues, and other authors, in the cosmological context.

Jaynes was worried about the subjective nature of Bayesian personalism, and wanted to ensure objectivity by specifying a unique method for determining the priors. This unique method he called the 'Principle of Maximum Entropy' (PME). The terminology comes from Shannon's theory of communication, entropy in this context being a measure of the uncertainty in a signal.

Since PME involves some relatively heavy mathematics, I refer those readers who are interested to Appendix B where I provide both an explanation of the method, and my assessment of it. Appendix B will be referred to again when I critique specific uses of PME in the cosmological context in chapter 7 (or rather, in mathematical detail, in Appendix E). Suffice it to say that I do not find the method satisfactory.

One way out of the problems associated with the Principle of Indifference, and its variants like the Principle of Maximum Entropy, is to refuse to set out criteria for prior probability determination at all. This is the position of Howson and Urbach: '... we believe that the addition of *any* criterion for determining prior distributions is unwarranted in a theory which purports to be a theory of consistent degrees of belief, and nothing more'.[22] However, earlier Howson and Urbach discuss certain artificial variants of natural laws, which people would intuitively reject. These include extra terms in a law of Galileo's which vanish just on the dates when the experiments occurred, and Goodman's law that all emeralds are 'grue', meaning green until midnight on 31 December 2010 and blue thereafter. At this point these authors *do* seem to see the need 'to discover the criteria and rationales by which theories assume particular prior probabilities'.[23]

It is true that Bayes's theorem shows how to relate an individual subject's degrees of belief consistently. Taking the prior probabilities and likelihoods as input data the posterior probabilities follow inexorably if the subject is to be rational. It is also true that the phenomenon of 'washing out of priors' can lead to convergence of posterior probabilities for individuals whose priors were noticeably different. That is to say, as more evidence comes in supporting a hypothesis, the value we took for its prior probability loses importance because its posterior probability tends to 1.[24]

Nevertheless, there is often a need to have some handle on prior probabilities, at least for comparison purposes. We turn for guidance to some of the criteria which have been used by scientists to choose between theories in practice. We have already met some of them in chapter 1, where we noted that the fact that scientists see these criteria as not only working in practice but of epistemic value is evidence of design. We also noted the interrelatedness of such notions as elegance, symmetry, beauty and simplicity.

For Wesley Salmon prior probabilities represent the plausibility arguments used by scientists.[25] Scientists make such judgments on the basis of their training and experience. Past success is the guide to future success, and the fact that serious hypotheses advanced by serious scientists stand a chance of being successful has been shown by Shimony.[26] Conversely, hypotheses put forward by cranks rarely succeed, and we are also entitled to question the plausibility of hypotheses put forward by serious scientists when they venture outside their own discipline. Here Richard Dawkins's meme theory and the panspermia theory of Hoyle and Wickramasinghe spring to mind.

Salmon also identifies formal criteria of consistency with other, accepted theories, for assigning high prior probabilities. A hypothesis which contradicts much of known physics stands very little chance of being a successful theory.

Salmon then goes on to write of material criteria which concern the structure and content of the hypothesis in question. Among material criteria are 'symmetry' and 'analogy'. As an example of symmetry, Salmon cites de Broglie's speculation, following the discovery that light waves exhibited particle behaviour, that matter might exhibit wave behaviour. Symmetry is now widely used in particle physics. Likewise analogy is widely used, e.g. drug testing on rats leads to hypotheses about the effects of drugs on humans, by analogy of the physiology of rats to humans.

But foremost in the material category is the criterion of 'simplicity'. Simplicity is indeed a widely used and important criterion for theory choice in science, possibly the most important. In short, other things being equal, a hypothesis which is simpler than a rival is likely to have higher prior probability. In chapter 1 we observed how simplicity is a generalization of the principle of Ockham's razor beloved of scientists. There is more to it than simply limiting the number of entities. In fact the notion of simplicity is notoriously difficult to make precise, as Mary Hesse makes clear.[27]

Why might simplicity be desirable in the first place? Hesse gives three reasons: pragmatic convenience, belief that nature is simple, and as a criterion of choice between scientific theories. None of these is entirely satisfactory, she says. Pragmatic convenience (a somewhat different notion from Salmon's pragmatism discussed above) is subjective, and hardly adequate since in any case theories are occasionally true but highly inconvenient. Belief that nature is simple is intuitively appealing, but as an induction from experience it is the result of an anthropic selection effect—a simple theory may only represent an aspect of nature manageable to the human mind. It is also logically circular as an inductive tool in so far as 'belief that nature is simple' is simpler than its alternatives. All these criticisms can of course be answered, but my appeal is particularly to the attitude of scientists themselves, who see simplicity as not only pragmatic but as having epistemic value, and who also believe that induction works.

When it comes to choice between scientific theories, the criterion of simplicity can certainly help to give a unique theory: the preference for a simple curve to fit data points is a prime example. But this in itself leaves open the question as to whether the simplest choice is more likely to be true, and the precise definition of simplicity in a theory.

Harold Jeffreys aims to answer both questions. In Appendix B, on PME, we note how Jaynes utilized an idea of Jeffreys to derive the prior probability for a parameter in a theory. But Jeffreys also addressed the more fundamental question of the simplicity of the form of a theory. He defines theory $A$ to be simpler than theory $B$ if the equations of $A$ are simpler than those of $B$ on the following definition. First, he restricts laws of nature to 'differential equations of finite order and degree'. These are countable[28] and hence satisfy the two important conditions: (i) that any law ought to be of positive prior probability; and (ii) that, if the number of laws is infinite, the prior probabilities should comprise terms in a convergent series summing to unity (see discussion on the axiom of continuity in Appendix A). The complexity of a law of nature is then 'the sum of the absolute values of the integers (degrees and derivative orders) contained in its equation, together with the number of its freely adjusted parameters'.[29] For example $y^2 = ax^3$ has complexity 6 and $d^2y/dx^2 + 2.345y = 0$ has complexity 4 (these examples are from Hesse). Jeffreys then claims that the simpler (i.e. less complex) law is *a priori* more probable.

This looks like a good try, but it is fraught with difficulty. For example, it is not even intuitively obvious that the differential equation above has the same complexity as $y = ax^2$. Then, the ordering does not take explicit account of transcendental functions like $y = \sin x$. Thirdly, for many laws the free parameters range over the real numbers, making any particular value of zero prior probability.

In fact, Jeffreys's definition seems to give rise to a simple contradiction. Thus $y = ax^2 + bx + c$ has complexity 7, whereas $dy/dx = 2ax + b$ has complexity 5. Yet the former is the solution to the latter!

Swinburne suggests that the problem of zero prior probability can be overcome by an approximating device.[30] Thus an equation $y = x$ should be understood to mean $y = (1 \pm r)x$, where $r$ is some small constant. This example would still seem to be too restrictive—why not $y = (1 \pm r)x \pm s$? More importantly, this would seem to contradict what Swinburne says elsewhere about the high prior probability of exact numbers—an inverse square law of gravity being more likely than an inverse 2.0001030456 power law for example. What he seems to be saying in the current context is that both power laws have zero prior probability, but a law with power in some range $-2 \pm r$ would have positive probability.

Karl Popper takes a similar definition of simplicity (or complexity) to Jeffreys, but argues instead that simpler hypotheses have more content, in the sense of restricting the possibilities in the world more, and are therefore more falsifiable than complex ones, and have lower rather than higher prior probability. For example, a straight line equation is more falsifiable than a circle, since it requires only three points for falsification rather than four. If every X is a Y but not every Y is an X (e.g. X is a subspecies of Y), then, according to Popper, 'All Ys are Zs' is simpler and more falsifiable than 'All Xs are Zs'.

However, it is clear that content and simplicity are not to be identified: 'All Xs are Zs' is simpler than 'All Xs and all Ts are Zs', but the latter has more content and is more falsifiable (NB we could relate this to the previous example by supposing that Xs and Ts are different kinds of Y).

In a case such as that just cited we are on more solid ground. When a hypothesis $H_1$ materially implies $H_2$, then $P[H_2] \geq P[H_1]$ (this is the third consequence, theorem (T3), of the first three axioms of probability listed in Appendix A). Furthermore, provided $P[\sim H_1 \wedge H_2] \neq 0$ the inequality is strict: $P[H_2] > P[H_1]$.

Applied to the above, provided there are some Ts not identical to any Xs, we can deduce that $P$[All Xs are Zs] > $P$[All Xs and all Ts are Zs].

It is a natural extension to the above analytic result to assume that a hypothesis $H_1$ with less content than $H_2$ will have higher prior probability even though the contents of the two hypotheses are not directly comparable.

One of the underlying problems here is that of language: a theory might be expressible in different ways using more or less economical language, in which case the simplicity is a function of the language rather than the theory itself.

Perhaps Salmon is right, and that simplicity, as for his pragmatic criteria, is a matter for judgment by the experts on the basis of their training and experience. To try to tie the concept down too narrowly, as does Jeffreys, may be impossible. In practice, what counts as simple will vary with context, and in using judgment a scientist will bring to bear the accumulated wisdom in his field over many years. There is no *a priori* reason why simplicity and induction should work. Perhaps scientists should take seriously the design option!

We shall need to exercise judgment in what follows. For example, we shall see that the assignment of probabilities to the contingent parameters involved in the fine-tuning argument is controversial. However, the fact that scientists themselves generally regard the fine-tuning of such parameters as *a priori* unlikely will be important. We shall also need to bring judgment to bear in considering what counts as simple when discussing alternative metaphysical explanatory hypotheses. We shall see that Swinburne's argument for the simplicity of God is certainly debatable, so to this extent we agree with Prevost that Bayesianism does not absolve one from arguments of a more informal, judgmental nature (not dissimilar surely to Salmon's plausibility arguments for scientific hypotheses). The important point is thus that, in exercising our judgment, we shall be acting in a way similar to scientists in their exercise of theory choice.

## The Ravens Paradox

As a final point in this chapter I offer a further good reason to give us confidence in the Bayesian approach to confirmation theory. This is that it is successful in solving a number of traditional problems with induction. Chief among these is the so-called 'ravens paradox', which was formulated by the great philosopher of science, Carl Hempel.

The hypothesis 'All ravens are black' is confirmed by observing an instance of a black raven. However, the hypothesis is logically equivalent to 'All non-black objects are not ravens'. The latter hypothesis is confirmed by observing a white tablecloth, but since the hypotheses are equivalent, a white tablecloth also confirms the hypothesis 'All ravens are black'. It would seem paradoxical that I should be able to confirm 'All ravens are black' without taking the trouble actually to observe any ravens but merely by remaining at my desk and observing that a host of non-black objects around me are not ravens.

Application of Bayes's theorem shows that confirmation of the hypothesis is indeed obtained either by sampling from the set of ravens and noting that instances are black or by sampling from the set of non-black objects and noting that they are not ravens. Crucially, the *degree* of confirmation is radically different in the two cases. I provide the proof in Appendix C, simply noting here that the Bayesian resolution of the paradox is entirely in tune with our intuitions about induction.

We have thus seen how Bayes's theorem provides us with a robust method for evaluating hypotheses. We proceed to use the theorem in the next chapter to examine the alternative explanations for the fine-tuning of the universe.

## Notes

1 See Earman (1992), pp. 143-154.
2 Sometimes it is the probability of a sentence, rather than a proposition, which is referred to in the literature. Richard Swinburne notes that this is mistaken because a sentence is merely a grammatically correctly formed combination of words. A proposition is what a sentence asserts (see Swinburne (1973), p. 2).
3 We shall have to amend the meaning of probabilities 0 and 1 in the case of continuous probability distributions, e.g. the probability of any particular real number, such as ½, being drawn at random from the interval [0,1] is zero, but some number will be! In general, the probability that the number chosen will lie in some sub-interval, e.g. [0.49, 0.51] will be non-zero.
4 It is quite common for diagnostic tests to show false positives.
5 E.g. Howson and Urbach (1993), Earman (1992), and Swinburne (ed.) (2002). A more introductory text is Hacking (2001).
6 See Keynes (1921), Carnap (1950).
7 Swinburne (2001), cf. Swinburne (1973).
8 Swinburne (2001), p. 64.
9 Plantinga in Plantinga and Wolterstorff (1983), pp. 46-55.
10 Swinburne (2001), p. 155.
11 Swinburne (2001), p. 167.
12 E.g. Swinburne (1973), pp. 3-4; Swinburne (1991), pp. 7-19; Swinburne (2001), p. 104; White (2000), p. 261; Howson and Urbach (1993), pp. 117-118.
13 Garrett and Coles (1993).

14 Evrard and Coles (1995).
15 Prevost (1990).
16 *Ibid.*, p. 32.
17 Holder (1998).
18 Not to be confused with McMullin's indifference principle in cosmology which we met in chapter 3.
19 This example is from Hacking (2001), p. 143.
20 Kneale (1952), pp. 184-185.
21 E.g. Jaynes (1968).
22 Howson and Urbach (1993), p. 418.
23 *Ibid.*, p. 163.
24 See Earman (1992), pp. 141-149, for a critical discussion of the phenomenon of washing out of priors.
25 Salmon (1990).
26 Shimony (1970).
27 Hesse (1967).
28 Mathematicians happily talk about a set containing an infinite number of elements being 'countable'. This means that the elements can be arranged in order so as to be in one-to-one correspondence with the natural numbers 1, 2, 3, 4, ...
29 This is Hesse's interpretation of Jeffreys, who gives varying definitions in his different works. Thus a slightly different version is given in Jeffreys (1961), pp. 47-50, though Jeffreys himself admits that this is unsatisfactory, and suffers from several problems.
30 Swinburne (1973), pp. 112-113.

# Chapter 6

# Comparing the Alternative Hypotheses

Let man then contemplate the whole of Nature in her full and grand majesty ... let him examine the most delicate thing he knows ... When I consider the short duration of my life, swallowed up in the eternity before and after ... I am frightened, and am astonished at being here rather than there, for there is no reason why here rather than there, why now rather than then ... The eternal silence of these infinite spaces frightens me.

(Blaise Pascal, *Pensées*, ii. 72; iii. 205, 206.)

## Introduction

We have seen that the initial conditions of our universe at the Big Bang, and the parameters which go into its laws of physics, are just right—'finely-tuned'—to the required very remarkable degrees of accuracy, for life to occur.[1] We have seen that a natural conclusion would be that the parameters were designed this way, but that there are alternatives on offer, most especially some form of multiverse hypothesis. We now need to examine these alternatives in a more rigorous way, utilizing the Bayesian apparatus described in the last chapter.

In this chapter, then, I show that two alternative hypotheses, which for convenience I shall label 'theism' and 'the multiverse hypothesis', each provide valid explanations for this fine-tuning. I shall also advance arguments as to why, of the two alternatives, theism might be preferred.

By theism, as discussed in chapter1, I mean the hypothesis that there is a Designer, or Fine-Tuner, who deliberately set the requisite parameters to their fine-tuned values, with the express intention of creating a life-bearing universe. This would seem, intuitively at least, to be a simple and natural explanation for the particularity of our universe. However, we need to examine this rigorously in comparison with its main rival. By the multiverse hypothesis I mean the postulated existence of many distinct space-time regions, characterized by different sets of values of the parameters, and which might be conceived to arise physically in several ways, as discussed in chapter 4. The vast majority of these space-time regions (loosely called 'universes') will not be fine-tuned, but the existence of the ensemble is taken to explain the existence of at least one that is.

I shall include in the analysis what might usefully be labelled the 'null hypothesis', namely that just one universe exists, as a brute fact. This covers what I have earlier dubbed the 'car park' objection to the argument from fine-tuning. We have seen that some cosmologists believe there is nothing to explain, arguing that any set of parameter values is improbable so we should not be surprised to observe a set which is compatible with our own existence. I have argued against this position, but believe that the Bayesian analysis will clarify its weakness, precisely by comparing it with alternative hypotheses which are genuinely explanatory.

One possible objection to the multiverse hypothesis is that it does not advance the case. Being based on a frequentist approach to probability, it invokes the existence of an ensemble of universes, a proportion of which possess fine-tuned parameter values.[2] But to a Bayesian, probability is not a proportion but 'rational degree of belief'. The probability of finding car ARW 357 in the car park does not depend on there being vastly many car parks; the probability of a coin landing heads does not depend on there having been many previous tosses. So, the argument goes, the probability of our universe being fine-tuned for life does not depend one whit on whether there is an ensemble of universes. It is the same as if the universe were a unique, brute fact.

The chief pioneer of this thesis, that multiple universes do not explain the fine-tuning of this one, is the philosopher Ian Hacking.[3] More recently, Roger White has given what I regard as an improved and more sophisticated version of Hacking's argument.[4] A subsidiary aim of this chapter is to show that White is mistaken. Given that a multiverse does indeed provide an explanation, it then becomes more pressing to weigh the arguments for theism over the multiverse.

Hacking's thesis related to Wheeler's oscillating universe theory, whereby universes are generated successively by expansion out of, and contraction back into, a singularity.[5] The idea is that the parameter values entering the laws of physics, and the initial conditions, are chosen randomly for each bounce. Hacking thought that the existence of a long sequence of universes did not enhance the probability that our universe would be finely tuned for life. He claimed that to think this was to be guilty of the inverse gambler's fallacy, akin to assuming that there has been a long sequence of tosses of a coin if you happen to see a sequence of 10 heads.

Hacking did not believe that his analysis applied to the case of coexisting universes, a scenario more closely associated with the name of Brandon Carter, whom Hacking interpreted as proposing that all logically possible universes exist.[6] I think White is right to see the two cases as similar, given the assumption that it is possible for either scenario to occur, and that fine-tuning conditions occur with positive probability. However, I think he is wrong to conclude that neither case would be confirmatory for many universes; rather I believe that the correct conclusion is that both cases would enhance the probability that there is a multiverse.

The reason White is wrong is essentially because ensembles do have explanatory power. It is true that the outcome of the next toss of a coin is independent of whether there have been previous tosses. But it is also true that, if you sit tossing coins long enough, you will eventually get a sequence of 10 heads. Hence it makes sense to invoke an ensemble as a competing hypothesis, even in a Bayesian framework. Again, this will emerge as we actually follow through the Bayesian analysis. I shall also provide examples which mimic the so-called 'observational selection effect', namely that we can only measure the parameter values of this universe.

My analysis in this chapter is highly simplified, though I believe it retains sufficient realism to bring out the main points I address here. One simplification which I make for convenience is the omission of background knowledge, on which all probabilities should be taken to be conditioned, from the equations. More substantially, like White, I only consider a finite number of possible universes, of which a small minority are 'fine-tuned'. This adequately mimics the more realistic, and more usually discussed, situation in which there are infinitely many universes and there is a positive, though small, probability that any universe is fine-tuned. However, it should be noted that it is doubtful whether even that scenario truly reflects reality. If, as would seem most likely, the number of possible universes is actually uncountably infinite, it might well be that the set of finely tuned universes is of measure zero on this set, as noted in the important paper, to which I first drew attention in chapter 3, by Collins and Hawking.[7] Certainly, any individual universe would be of measure zero. I believe this issue poses real problems for the many universes hypothesis. However, I do not consider this issue further here, leaving this important topic to chapter 7 and then, in more detail, chapter 9.[8]

I begin with an example which will illustrate many features of the main argument.

## The Case of Greystoke School

You are a pupil at Greystoke School, an establishment with precisely 100 pupils, and one day the Headmaster tells you that prize(s) may (or may not) be awarded according to one of the following schemes:

$H_1$: Precisely 1 prize is awarded, by drawing at random from a hat containing the names of all pupils on slips of paper. This is an inexpensive option but does seem open to criticism, e.g. it might reward the unruly or lazy pupil. We give it a probability $P[H_1] = 0.05$.

$H_2$: 100 prizes are awarded, one to each of the 100 pupils. Although politically correct in treating everyone equally, this is nonetheless a very expensive option, with the bursar finding it necessary to mortgage the school chapel in order to finance it. We accord it a probability $P[H_2] = 0.01$.

$H_3$: The Headmaster is a very intelligent man who knows his pupils well, and will make a decision on prize-giving based on merit. This seems to be the simple and rational way to go about things, and we give it a probability $P[H_3] = 0.1$.

$H_4$: No prizes at all are awarded. This is the simplest and cheapest solution of all, though a little mean, and we give it a probability $P[H_4] = 0.84$ (i.e. $H_1$, $H_2$, $H_3$ and $H_4$ in this case are mutually exclusive and exhaustive).

The next day you are told that you have been awarded a prize, but you are to keep the fact a secret and not discuss it with any other pupils since the school does not want to foment jealousy. Which of schemes $H_1$ to $H_4$ do you reckon was used to award the prize?

You argue as follows. Denote by $E$ the evidence that you have a prize. Then $P[E|H_1] = 0.01$; $P[E|H_2] = 1$. You know that if $H_3$ operates one prize will be awarded and the choice is between 10 outstanding pupils, of which you are one. Indeed, being better than average amongst this select group you have a chance of 0.3 of being chosen on this basis, i.e. $P[E|H_3] = 0.3$. If $H_4$ operates then it is obvious you could not have won a prize, i.e. $P[E|H_4] = 0$.

Substituting $E$ for $A$ and $H_j$ for $B_j$ in Bayes's theorem in the form of equation (3) in chapter 5, we obtain

$$P[H_i|E] = \frac{P[E|H_i].P[H_i]}{\sum_{j=1}^{4} P[E|H_j].P[H_j]} \tag{1}$$

where $i = 1, 2, 3, 4$. The above inputs for the $P[H_j]$ and the $P[E|H_j]$ then yield:

$P[H_1|E] = 0.01$
$P[H_2|E] = 0.25$
$P[H_3|E] = 0.74$
$P[H_4|E] = 0$

Hence hypothesis $H_1$ is disconfirmed and hypotheses $H_2$ and $H_3$ confirmed ($H_4$ is of course not merely disconfirmed, but falsified). The most likely policy adopted by the school was $H_3$.

It seems to me that Greystoke School provides a good, if not exact, analogy for the comparison, which I shall give in a moment, of the multiverse hypothesis with its alternatives. The pupils correspond to possible universes and the prizes correspond to existence. $H_1$, $H_2$, and $H_3$ correspond to a single brute-fact universe, a multiverse, and design respectively, with $H_4$ corresponding to what remains. But before we pursue the multiverse case in detail, there is a little more insight we can glean from Greystoke to help us.

Now the fact is that, given the secrecy policy and its strict observance, the only evidence you could have that a prize had been awarded is if you were given one. Thus you could not have evidence that Jones minor, although in the brightest 10, was awarded a prize, or even that Smith minimus, the school dunce who might have been sole prize-winner on hypothesis $H_1$, or a joint prizewinner on $H_2$, had been awarded a prize.

It is possible that someone might come by the knowledge that one of the 10 brightest pupils had been awarded a prize, without knowing who in particular, and without knowing whether anybody else in the school, in the brightest 10 or not, had been awarded a prize. But this would seem to be a rather contrived item of knowledge. If you win a prize, your knowledge is necessarily stronger than this, and implies it: if you win a prize and you are in the top 10, it follows trivially that somebody in the top 10 won a prize.

On the other hand, if I came by the knowledge that somebody else besides me had been awarded a prize, perhaps because this person broke the secrecy rule, I would be forced to conclude that hypothesis $H_2$ were true.

The secrecy policy corresponds to the main case which I shall consider, namely that in which we are assumed not to be able to know directly about the existence of universes other than our own. Certainly we cannot only know something as vague as that one or more of a set of finely-tuned universes exists (corresponding to one or more of the brightest pupils getting a prize). We do know that our universe exists and we might possibly be able to know more.

Knowing, or even suspecting on theoretical grounds, that there are other universes is equivalent in the Greystoke model to the secrecy rule being broken. Suppose I do indeed learn that more than one prize has been awarded (or hear rumours to this effect). Is there any way round the conclusion that policy $H_2$ was adopted?

The answer is 'no' if we stick with the way I phrased the situation earlier, but 'yes' if we can modify $H_3$ a little and think of a reason why the Headmaster would award 100 prizes. Suppose he really wants to give a prize to the best pupil in the school, but he wants to do this without upsetting any other pupil and without a secrecy policy. Moreover, the school is in receipt of a large donation from a generous benefactor. Hence he awards 100 prizes.

In this way the Greystoke analogy can be adapted so as to distinguish a hypothesis which modelled the existence of many universes as a brute fact from one which saw them as created by God, who presumably intended that within the ensemble some universes would be life-bearing (perhaps this is merely an extension of the recognition that most of *this* universe is lifeless, but nevertheless is 'charged with the grandeur of God'). This is not the main line of argument in this book, but I do briefly allude to it later as a proposal finding some support within the community of those interested in the science-theology relationship.

We now come to our promised central argument, setting up our hypotheses, the evidence we have, and the various probabilities required for the application of Bayes's theorem.

**The Alternative Hypotheses and their Prior Probabilities**

For simplicity's sake, then, let us suppose that there are exactly 100 possible universes. Label them $U_1$, $U_2$, $U_3$, ..., $U_{100}$.

Suppose further that 10 of these universes are fine-tuned for life. For convenience suppose these are $U_1$, $U_2$, ..., $U_{10}$.

Suppose our universe, which is clearly possible and clearly fine-tuned for life, is $U_1$.

Let us consider three mutually exclusive but not exhaustive hypotheses, $H_1$, $H_2$ and $H_3$, defined as follows:

$H_1$: There is no designer and only one universe exists, as a random choice from the 100 possible universes;

$H_2$: There is no designer and all 100 possible universes exist, comprising the multiverse;

$H_3$: There is a designer, assumed for the sake of argument to be something like the Christian God.

In order to utilize Bayes's theorem we shall need to estimate the prior probabilities of each of these hypotheses. These will look familiar, though in contrast to the illustrative Greystoke case, we do have to provide justification for them. This is of course a notorious problem for Bayesian confirmation theory, as discussed in the previous chapter. However, for our purposes we do not need to be too concerned to get accurate estimates. Illustrative numbers will do (broadly speaking, what matters is simply whether one number is much bigger than another or not), and those given are, I would suggest, intuitively plausible on the basis of the arguments advanced:

(1) $H_1$: Richard Swinburne argues that $H_1$, the existence of a single, uncaused universe as a brute fact, is not a simple hypothesis, certainly when compared with the existence of God, who is a simple being.[9] This is because one would have to ask a host of questions of such a universe. Why is this universe the way it is, e.g. the size it is, having the exact constituents it does, and so on? On the other hand, Quentin Smith argues that an uncaused initial space-time singularity is as simple as God, utilizing similar reasoning to Swinburne's—the singularity has zero dimension, zero temporal duration, etc.[10] However, this line of reasoning seems to assume, in the manner of Peter Atkins, that the singularity gives us *creatio ex nihilo*. Rather, as I have already explained in chapter 4, pre-existing physical laws (where do they come from?) operate on a substratum of a pre-existing space-time to give a quantum vacuum fluctuation—and the vacuum is far from nothing in quantum theory. In any case the idea of anything coming from *absolutely* nothing seems implausible, to put it mildly.

Even if the singularity did give us *creatio ex nihilo*, there would be a fundamental difference between it and God, namely that the universe is contingent and would be without any reason for its coming into existence. In contrast, God is uncaused in the sense that he is necessary: he exists eternally and permanently.[11]

In the light of these considerations let us take $P[H_1] = 0.05$ as a starting point for our assignment of probabilities (remember that what really matters now is the magnitude of our probability assignments for $H_2$ and $H_3$ *relative* to that for $H_1$, not the absolute magnitude of $P[H_1]$).

(2) $H_2$: Richard Swinburne and others argue that $H_2$ is a far from simple hypothesis and therefore of low prior probability. As we have seen in chapter 4, John Leslie[12] also regards $H_2$ as massively anti-Ockhamite. So does Roger Penrose, at least regarding the version relating to Everett's interpretation of quantum mechanics.[13] William of Ockham inveighed against the multiplication of entities, and $H_2$ multiplies entities (universes) with a vengeance.

On the other hand it could be argued that instantiation of all possible universes is simple. Such an argument might mimic Swinburne's own argument for the simplicity of God—an infinite number of universes is simple compared to one universe! This seems to me to be highly counter-intuitive, but one way to argue the point is to suggest that simplicity is really not about the number of entities but about the number of kinds of entities. That neatly sidesteps the issue because $H_2$ is now only postulating one kind of entity, namely a physical universe.[14] However, surely Swinburne is right to assert that the simplest hypothesis is one which utilizes the minimum of *both* the number of kinds of entities *and* the number of entities.[15] For example, when Leverrier tried to explain the irregularity that had been observed in the orbit of Uranus he postulated the existence of one extra planet. As Swinburne points out, he could have postulated 726 tiny planets with a common centre of gravity at the postulated position of Neptune.[16] Indeed there are plenty of other possibilities—some extra kind of force operating on Uranus but not the other planets, a modification of Newton's law of gravity plus the existence of two further heavenly bodies, and so on. But one extra entity of an already existing kind was the minimum requirement to satisfy the observations, and Neptune was duly observed. The counterclaim of Bradley, that a theory postulating a hundred more stars in the Milky Way is no better or worse than the original theory with fewer, only provided that the new theory is equally consistent with the evidence,[17] seems frankly ridiculous; it is a licence to multiply invisible entities having immeasurable effect to a quite uncontrolled and mindless degree.

A second way to argue for the simplicity of $H_2$ is to invoke the notion of *algorithmic complexity*, which relates to the number of lines needed by a computer program to generate the theory. On this basis $H_2$ is then simple essentially because it is simple to state, using very few lines of computer code. This is the position of Max Tegmark.[18]

We observed in chapter 4 that Tegmark's ultimate ensemble is in any case not as comprehensive as possible. Indeed it leaves out vast numbers of universes not describable as mathematical structures, and Tegmark is very focused on universes not terribly dissimilar from our own (perhaps it is imagination that is lacking here). As Swinburne points out,[19] there are innumerable possible universes in which persons are not embodied and so for which fine-tuning is not necessary. So the problem is to explain why we exist as embodied creatures in a fine-tuned universe, a fact which would seem highly improbable except on the basis of design by a God who saw this as a good to be realized.

Confining ourselves for a moment to the mathematical structures on which algorithmic complexity can be applied, let us ask whether this really is the most rational account of simplicity. We consider an example of Swinburne's.[20] Suppose we have a well-founded theory which tells us that there are at most 10 possible kinds of quark. An experiment is designed to look for 5 of them but just 3 show up. Now formulate three hypotheses about precisely which quarks exist, and compare them for simplicity on the two grounds of algorithmic complexity and number of kinds of entity employed. The hypotheses are:

$h_1$: all kinds of quark exist except the two which didn't show up,
$h_2$: only the 3 kinds exist which showed,
$h_3$: all kinds exist except the two which didn't appear and a third named one.

Now, on the algorithmic criterion for simplicity, the order of increasing complexity is $h_1$, then $h_2$ and $h_3$ equal second. This is because, given the background theory, only two kinds of quark need to be specified for $h_1$ and three for each of $h_2$ and $h_3$. This seems, Swinburne says (and I agree), counterintuitive. On the other hand, the number of kinds of entity criterion gives the order $h_2$, $h_3$, $h_1$, because the number of kinds of quark involved is 3, 7 and 8 respectively. The difference in the two cases seems to be whether you give more weight to the abstract notion of physical existence based on mathematical possibility or to the more concrete reality of what is known for certain to exist physically.

We noted in chapter 4 some other problems with Tegmark's particular formulation of the multiverse hypothesis, notably its confusion of mathematical and physical existence. As we shall see in chapter 9 the notion that 'everything that can happen will happen somewhere sometime' is also far from straightforward in terms of physical realization. An algorithmically simple-to-specify set of universes does not so easily slide into a physically existing set. Besides which, the criterion of simplicity in terms of fewest numbers and kinds of entities seems intuitively so much more plausible.

Swinburne's verdict on the hypothesis of many actual universes introduced to explain the fine-tuning of ours is: 'But to postulate a large number of such universes as a brute uncaused fact merely in order to explain why there is a fine-tuned universe would seem the height of irrationality.'[21]

As I say, the many universes hypothesis certainly seems to me to be highly counter-intuitive, and I am inclined to Swinburne's view of simplicity. That being so, let us follow through the consequences by supposing that $H_2$ is not very probable, at least compared with $H_1$, and let us assign $P[H_2] = 0.01$.

(3) $H_3$: Swinburne argues that God is a simple hypothesis. John Polkinghorne too regards $H_3$ as of greater elegance and economy than $H_2$.[22] The idea of God as simple is a traditional one in Christian theology, expounded most notably by St Thomas Aquinas.[23] Swinburne gives a rather different interpretation to the concept of divine simplicity from Aquinas, however. Thus God is simple because he has infinite capacities (e.g. in terms of power and knowledge). For example, a being who can both create and mould matter is simpler than one who can only mould it, like Plato's demiurge. Were God's capacities limited to some finite value, one would have to ask, 'Why do the divine capacities take precisely the values they do?' Infinity as a measure of the divine capacities is thus taken to be simple, simpler than seemingly arbitrary finite numbers.

This is the same kind of simplicity that makes an inverse square law of gravitation a simpler physical law than an inverse $r^{2.000142}$ law. The latter is both unnatural and has physically unsatisfying consequences.[24] Following Dirac and Polanyi one would believe the $1/r^2$ law in preference to the $1/r^{2.000142}$ law despite experimental evidence supporting the latter—at least up to a point, since one would need to be pretty convinced of the reliability of the experiment, the elimination of errors of all kinds, and so on, to abandon so aesthetically pleasing a law as $1/r^2$.

In saying that the existence of God is a simple hypothesis and that of an uncaused universe a complex one, Swinburne parts company with Richard Dawkins. About beliefs in a deity Dawkins argues:

> All that we can say about such beliefs is, firstly, that they are superfluous and, secondly, that they *assume* the existence of the main thing we want to *explain*, namely organized complexity.[25]

He goes on to argue, in the same passage, that, in order to engineer all the organized complexity in the universe, 'that deity must already have been vastly complex in the first place'.

There are a number of confusions here. First, God is not being offered as an alternative to the theory of evolution. The point is that something is not truly explained merely by saying how it came about from something simpler. God is the explanation for why the laws (and initial conditions) are ordered as they are with the result that complex organisms arise from simpler ones—Dawkins offers no explanation at all for this. The comparison is not between God and evolution but between God and an uncaused universe in the case of the cosmological argument and between God and a universe with uncaused order in the case of the design argument.

In any case, evolution does not offer a complete explanation. Thus it does not explain the consonance between, for example, our notions of blue and green and what actually pertains, as is shown by the Goodman paradox to which I drew attention in chapter 1. For anybody who had the concepts of grue (green until, let us now say, midnight tonight, and then blue) and bleen (vice versa) would have had the same survivability until midnight tonight. It is very remarkable indeed that induction works, or at least seems to work, and that *our* concepts are the ones it works with. We noted in chapter 1 that our ability to understand the cosmos (from quarks to the Big Bang) is inexplicable by evolution.

Further to Dawkins, who we have seen offers no explanation, it might well be that God is a simpler explanation for the existence and fruitfulness of the laws of nature governing the behaviour of matter than that these are a brute fact.

There are problems with Swinburne's approach. Thus we are not comparing one being against another, i.e. a being with infinite capacities as against one with finite capacities, but an infinite being against a physical universe. This is a bit like comparing chalk and cheese, far removed from comparing two candidate equations to express a natural law which differ only in the number of free parameters, so it is difficult to justify the probabilities. Moreover, Swinburne wants the infinite capacities of God to count as simple, but not the infinite number of universes which would be the realistic version of $H_2$. However, again we are not comparing like with like, but this time this is to the advantage of theism. Infinitely many universes might be simpler than 483 of them, even if we insist that an infinity is more complex than one. On the other hand, it is hard to give a meaning to God possessing one unit of power, so *any* limitation on God's power would seem to be arbitrary.[26]

Bradley, who, as we noted above, does not accept that the number of entities should count in a criterion of simplicity, argues, following Hume, that there are many theistic hypotheses, so, contra Swinburne, 333 gods are as likely as one. Now in Appendix A (in discussing the axiom of continuity) we observe that it simply cannot be the case for logical consistency that all the natural numbers have equal probability (since that would have to be zero and then the sum of the probabilities would not be one). It seems to me that Swinburne is right to argue for the simplicity of one over many gods, not only because one would have to ask, 'Why 333 (or whatever) in particular?', but also because we would want to know why we do not see the marks of the different deities' handiwork in the cosmos: instead, what we do see is a uniformity across time and space of consistency in physical laws (which is virtually a precondition for cosmology to be possible in the first place).[27]

Another objection raised against the God hypothesis is that it introduces another kind of being, and hence of causation, from that which we see operative in the physical world. We have noted that it is in favour of theism that God is necessary rather than contingent. However, it is not the case that the only kind of causation we see is one physical event causing another. We also see what Swinburne calls 'agent causation', so that theism postulates, not a different kind of causality from that of which we have experience, but the same kind on a large scale as we see on a very small scale—'intentional causality, by agents seeking to bring about their purposes seen in some way as a good thing'.[28]

Bradley makes the further point that what counts for Swinburne is the capacity of a universe to produce complexity, especially in the form of brains and other organs, 'for the embodiment of conscious beings'. But Swinburne is a mind-body dualist for whom, as for Descartes, the psycho-physical correlations between mind and body are opaque to science and determined by the inscrutable fiat of God.[29] Hence there is no necessary connection between the conditions for the emergence of complex organs and the existence of minds—a stone would do as well as a brain.

I think this ignores the importance for Swinburne of what conscious beings can do through complex bodies, but in any case, it is an argument which carries only if one is committed to mind-body dualism. The popular alternative among Christian theists of non-reductive physicalism, in which mind or soul emerges as a property of the organized complexity of the brain, would not be open to this objection.

George Schlesinger has introduced another, rather interesting argument as to why we should assign a relatively high *a priori* probability to $H_3$.[30] We encountered Anselm's ontological argument for the existence of God back in chapter 1. Obviously if the argument is correct then $P[H_3] = 1$. Of course we observed that the argument is disputed, though it is notoriously difficult to refute. What is important for Schlesinger, however, is not the actual success of the argument but the very fact that it has been attempted, and that 'some of the most illustrious minds sincerely believed in the validity of the argument'. The attempt shows that there is a human tendency to regard theism as true 'merely on the basis of tautologies and inductive logic'. In contrast, 'It is not the case that a considerable number of philosophers have ever contemplated the possibility of establishing the existence of an external world through a reasoning process analogous to that of the ontological argument'. This asymmetry makes $P[H_3]$ much greater than $P[H_1]$.

On balance, then, it seems intuitively plausible that $H_3$ is the most likely of our hypotheses. Let us take $P[H_3] = 0.1$.

Note that on grounds of simplicity it could be argued that it is *a priori* probable that there is absolutely nothing (the equivalent of $H_4$ in the Greystoke analogy). After all, as Leibniz pointed out long ago, nothing is much simpler than something. This is why I have made the above hypotheses non-exhaustive and to sum to much less than one. Of course the evidence of the existence of an actual universe will make the *a posteriori* probability of nothing existing zero.

**The Evidence to be Considered**

We consider two alternative items of evidence, as does White, though our definitions are framed rather differently from his:

$E_1$ = a fine-tuned universe exists,
$E_2$ = our universe exists.

There is a problem with $E_1$ as our evidence, which might strike the reader straight away (I alluded to it in the discussion of Greystoke), though I reserve comment until later. Meantime we keep these alternatives as reflecting White's treatment.

Our next step is to estimate the so-called 'likelihoods' to go into Bayes's theorem, namely the probabilities, first of $E_1$ given $H_1$, $H_2$, $H_3$, and then of $E_2$ given $H_1$, $H_2$, $H_3$.

**The Probability of a Fine-Tuned Universe Given $H_1$, $H_2$, $H_3$**

Now from the definitions of $H_1$ and $H_2$, and the assumption that 10 of the 100 universes are fine-tuned for life, it is evident that

$P[E_1|H_1] = 1/10$
$P[E_1|H_2] = 1$

It is harder to judge, given a designer, what the probability is that he would create a fine-tuned universe. But if the designer is something like the Christian God, we would expect him to exercise his creativity, and we would expect him to do so by creating as 'interesting' a universe as possible, so most likely a universe with life—a universe containing life might well be a good which God would will to bring about.[31] The probability of $E_1$ given $H_3$ will then be high, let us say

$P[E_1|H_3] = 0.9$

**The Probability of Our Universe Given $H_1$, $H_2$, $H_3$**

From the definitions of $H_1$ and $H_2$, and the hypothesis that our universe is one of 100 possible universes, we have

$P[E_2|H_1] = 1/100$
$P[E_2|H_2] = 1$

As for the probability that a designer would create a universe with life, we have to use our judgment to estimate what the probability would be that he would create *this* life-bearing universe. On the assumption that $U_1$ is in some sense 'better' than the other life-bearing universes, though with some reservations (perhaps regarding the amount of evil in this universe) we would expect[32]

$$0.1 < P[E_2|H_3] < 0.9$$

Let us choose

$$P[E_2|H_3] = 0.3$$

### The Probability of $H_1$, $H_2$, $H_3$ Given That a Fine-Tuned Universe Exists

The form in which we require Bayes's theorem is just that of equation (1) which we used for the Greystoke example. We have specified three non-exhaustive hypotheses $H_1$, $H_2$ and $H_3$. The 'hypothesis' which completes the set is that which stipulates that none of $H_1$, $H_2$ or $H_3$ is true, i.e. $\sim (H_1 \vee H_2 \vee H_3)$. I deliberately leave this vague—it might include, not simply no universe existing, but other possible causes for a universe or universes arising, such as Leslie's axiarchism to which I referred briefly in chapter 1. Hence we substitute $\sim (H_1 \vee H_2 \vee H_3)$ for $H_4$ in equation (1) to obtain

$$P[H_i|E] = \frac{P[E|H_i].P[H_i]}{\sum_{j=1}^{3} P[E|H_j].P[H_j] + P[E|\sim (H_1 \vee H_2 \vee H_3)].P[\sim (H_1 \vee H_2 \vee H_3)]}$$

for $i = 1, 2, 3$

It is clear from writing down the equations that if $P[E|H_i] = 1$ for any hypothesis $H_i$, then $E$ does indeed confirm $H_i$, in the sense that $P[H_i|E] > P[H_i]$, if both $P[H_i]$ and $P[E]$ are less than 1. So my point (against White) that the existence of fine-tuning, or our particular finely-tuned universe, confirms the many worlds hypothesis, is proved, almost trivially.

For the numbers estimated above, and now also substituting $E = E_1$, we have for each $i$:

$$P[H_i|E_1] = \frac{P[E_1|H_i].P[H_i]}{0.105 + P[E_1|\sim (H_1 \vee H_2 \vee H_3)].P[\sim (H_1 \vee H_2 \vee H_3)]}$$

$$= \frac{P[E_1|H_i].P[H_i]}{0.105 + P[E_1|\sim (H_1 \vee H_2 \vee H_3)] \times 0.84}$$

Entering the values of our earlier estimated prior probabilities and likelihoods into these equations, we infer the following:

(1) $H_1$ is always disconfirmed (as one would expect since, notwithstanding the 'car park' argument, it does not explain fine-tuning);

(2) $H_2$ is always confirmed (again as one would expect since this is why $H_2$ was invoked); and

(3) $H_3$ is confirmed provided that $P[E_1|\sim (H_1 \vee H_2 \vee H_3)] < 0.95$ (again as expected, since this is why we are invoking a designer). This last condition is only violated if a hypothesis we have not considered, within $\sim (H_1 \vee H_2 \vee H_3)$, can provide very good reason for us to expect fine-tuning.

There is a problem here to which I alluded briefly earlier. $E_1$ is not actually the evidence we possess. Remember, $E_1$ is the knowledge that at least one of $U_1, U_2, ..., U_{10}$ exists. But if $E_1$ were our evidence, then we would not know which or how many members of this subset of possible universes exist. Our evidence is surely the stronger $E_2$: we know that our universe, $U_1$, exists. Of course, as White points out, $E_2$ implies $E_1$, so we also know $E_1$ to be true, but White correctly demolishes the fallacy that if $E_1$ raises the probability of a hypothesis then $E_2$ must also. No, White is right to assert that 'in the confirming of hypotheses, we cannot, as a general rule, set aside a specific piece of evidence in favour of a weaker piece'.

The upshot of this is of course that we must go on and evaluate the posterior probabilities of $H_1$, $H_2$ and $H_3$ given $E_2$ on the basis of Bayes's theorem without such prior assumptions. When we do so we shall find that our conclusion regarding $H_2$ is different from White's, but before proceeding let me attempt to clear up another possible problem, also alluded to in the discussion of Greystoke.

I have stated that our evidence is $E_2$. Perhaps, however, our evidence is not weaker, but stronger than this. Perhaps we can have evidence for other universes as well as our own.

Discussions of multiverse theories generally assume that we can have no causal contact with other universes. If these universes are conceived as other, remote regions inhabiting the same space-time as ours this will be because they are beyond (and usually very far beyond) the horizon defined by the length of time light will have taken to reach us since the Big Bang. We cannot in principle observe such regions. If, on the other hand, such universes are conceived as existing in space-time realms distinct from ours, e.g. if we accept Hugh Everett's interpretation of quantum mechanics in which space-time is continually branching owing to quantum splitting,[33] then again (*a fortiori*) we shall not be able to observe such universes. However, in either case we might have theoretical reasons for believing that other universes exist, e.g. Linde's theory of chaotic inflation seems to generate many causally disconnected mini-universes,[34] and, if Everett's were to be the correct interpretation of quantum mechanics, it too would give theoretical grounds for believing in many universes. (Note that in either case, one might still ask about the 'range' of universes so produced: what is the measure of these universes on the space of all possible universes?[35])

Considerations such as these, which are not without their problems, might lead one to amend our evidence to

$E_3 = \mathrm{U}_1$ exists and we have theoretical reasons for believing in other universes.

What would be the effect on the likelihoods? Because $E_3 \rightarrow E_2 \rightarrow E_1$ we know from theorem (T3) in Appendix A that $P[E_3] \leq P[E_2|] \leq P[E_1]$ and $P[E_3|H_i] \leq P[E_2|H_i] \leq P[E_1|H_i]$. The question is, how strong are these inequalities, and especially the latter ones for the different $H_i$? Naïvely one might expect $P[E_3|H_1] << P[E_2|H_1]$, since common sense would suggest that we are unlikely to have reasons for believing in more than one universe if only one actually exists. $P[E_3|H_2]$ is likely to be proportionately not so much less than $P[E_2|H_2]$, i.e. unity, since it is not unreasonable to have reasons for more than one universe if there really are more. The most difficult likelihood to evaluate would be $P[E_3|H_3]$. Whilst this would be less than $P[E_2|H_3]$, it is by no means clear that it would be substantially less. As noted earlier, some theologian-scientists favour the idea of God creating many universes, e.g. Arthur Peacocke argues that it is the potentiality of the ensemble for producing cognizing subjects which counts, not that of one universe in particular.[36] Such thinkers are equally unruffled by the seeming waste in biological evolution, with its dead ends and multiple extinctions, seeing this rather as God's mechanism for producing intelligent life. Perhaps God's handiwork could be seen as even more glorious on such a view. With these kinds of assumptions, the sums might still favour theism.

I am not able to pursue these considerations in any detail in this chapter, or indeed this book, for the purposes of which the simpler assumption that our evidence is $E_2$, and that we cannot know of the existence of other universes, is sufficient.

## The Probability of $H_1$, $H_2$, $H_3$ Given That $\mathrm{U}_1$ Exists

For the numbers we have estimated above we obtain

$$P[H_i|E_2] = \frac{P[E_2|H_i].P[H_i]}{0.0405 + P[E_2|\sim(H_1 \vee H_2 \vee H_3)].P[\sim(H_1 \vee H_2 \vee H_3)]}$$

$$= \frac{P[E_2|H_i].P[H_i]}{0.0405 + P[E_2|\sim(H_1 \vee H_2 \vee H_3)] \times 0.84}$$

from which it follows that

(1) $H_1$ is always disconfirmed;

(2) $H_2$ is always confirmed; and

(3) $H_3$ is confirmed provided that $P[E_2|\sim(H_1 \vee H_2 \vee H_3)] < 0.31$, i.e. that no alternative hypothesis makes it as likely as probability 0.31 that $U_1$ exists (again, reasonable assuming we have captured the hypotheses most likely to explain the existence of $U_1$).

A simple consequence of Bayes's theorem (see equation (4) in chapter 5) is the result:

$$\frac{P[H_3|E_2]}{P[H_2|E_2]} = \frac{P[E_2|H_3]}{P[E_2|H_2]} \cdot \frac{P[H_3]}{P[H_2]}$$

from which it follows that the ratio of the posterior probabilities is greater than 1 if the ratio of the likelihoods times the ratio of the priors is greater than 1. For our choice of values the ratio of the posterior probabilities is 3, i.e., given evidence $E_2$, $H_3$ is 3 times more likely than $H_2$ (chiefly of course because we have given $H_3$ a much larger prior probability than $H_2$).

## White's Fallacy

We are now in a position to expose the fallacy in White's reasoning. White lists the possible properties of universes as $T_1$, $T_2$, ..., $T_n$ (these represent combinations of parameter values taken in the laws of physics, and initial conditions), and he lets $T_1$ be the configuration necessary for life to evolve. He then lists the universes which exist as 1, 2, 3, ..., $m$, where $m$ is variable (the many universes hypothesis has $m$ large), and uses the notation $T_ix$ to signify that universe $x$ in the sequence instantiates properties $T_i$. Next he picks out one of the existent universes $\alpha$ and labels this our universe. His footnote 6 is highly instructive, since it contains the essence of the fallacy he is committing:

> The name '$\alpha$' is to be understood here as *rigidly designating* the universe which happens to be ours. Of course, in one sense, a universe can't be *ours* unless it is life-permitting. But the universe which happens actually to be ours, namely $\alpha$, might not have been ours, or anyone's. It had a slim chance of containing life at all.

Let us try to unpack just what is wrong here.

First, White presupposes that $\alpha$ is one of 1, 2, ..., $m$, regardless of $m$! That is to say, he presupposes that our universe exists regardless of how many universes there are. By doing so, he is bound to miss the point of having $m$ large.

By defining $\alpha$ as a rigid designator of our universe, White is committing a modal fallacy when he goes on to assert that $\alpha$ might not have been life-permitting. Indeed, instead of rigidly designating our universe, on White's treatment $\alpha$ might as well denote any randomly chosen universe—in fact, it would seem that this is exactly what $\alpha$ does represent.

It is certainly true that, if $x$ is randomly chosen from 1, 2, ..., $m$, then

$$P[\mathrm{T}_1 x] = 1/n$$

which is independent of $m$. What this is really saying, to use White's phraseology, is that a randomly chosen universe has a very 'slim chance' of being *our* universe, and this is, of course, true.

It would seem that White is taking the essential properties of our universe to be its position in a temporal sequence or its location, however measured, amongst the coexisting universes. If these are chosen randomly, then, to repeat, it is most unlikely that the universe which arises at that particular location in time or space, or in that particular branch of that particular branching of space-time, is fine-tuned so as to bring us into existence. As Manson and Thrush point out, White's 'This Universe' objection to the explanatory value of the multiverse is akin to the 'This Planet' objection to the existence of a single vast universe with very many planets explaining life on Earth. Life might well be very improbable on any randomly selected planet, but nobody doubts the argument that the existence of very many planets gives many possibilities for getting the right conditions to be found somewhere, and we do not need any further special explanation for why it should be found *here*.[37]

Let us start from the more logical tack that our universe by definition possesses as its essential properties those represented by $\mathrm{T}_1$ (though this might still not be quite what is required—see below). The probability that our universe exists is then equal to the probability that $\mathrm{T}_1$ is instantiated. We then have

$$P[\alpha \text{ exists}] = P[(\exists x)\mathrm{T}_1 x | m = k] = 1 - (1 - 1/n)^k$$

where, following White's notation, we have made this probability conditional on the number of universes $m$ being equal to $k$.[38] The probability that our universe exists is then equal to $1/n$ if there is only one universe but increases as $k$ increases, tending to 1 as $k$ tends to $\infty$.

Bearing in mind our earlier treatment, this still does not seem to be quite right, for two reasons. First, we have clearly over-simplified. $\mathrm{T}_1$ now denotes the properties of universe $\mathrm{U}_1$ in our earlier notation—we have ignored the other life-permitting universes $\mathrm{U}_2$, $\mathrm{U}_3$, ..., $\mathrm{U}_{10}$. But as we have seen from our earlier analysis, our evidence is that *this* life-permitting universe exists, not merely that some life-permitting universe exists (in this, White would seem to concur).

Secondly, it will be apparent that our analysis does not preclude $\mathrm{T}_1$ being instantiated more than once. Indeed, the claims of multiple universe enthusiasts that, if $m$ is infinite, there will be many, indeed infinitely many, replicas of our universe, including genetically identical copies of me, would seem to be upheld (given of course our assumptions, notably that the probability of $T_1$ being instantiated in any universe is positive). However, this raises yet further problems, e.g. about just what it means to be me, and also indicates that the probability that $T_1$ is instantiated is not after all the same as the probability that $U_1$ exists. Indeed it seems again to contradict the definition of $\alpha$ as a rigid designator of our universe. In fact, this second issue highlights an important difference between White's treatment and mine. In my treatment it is 'being $\alpha$' which is the essential property, rather than instantiation of $T_1$ as it seems to be for White.

A yet further issue is of course the notion of random choice in all this. This is problematic for various reasons, e.g. just why should universe configurations be equiprobable? There is also the measure zero problem referred to earlier. Nevertheless this notion is widely used in the literature, especially among many universe proponents: we are simply modelling it as random choice of universe from 1, 2, ... , *m*, and (in this section, following White) of parameter sets for those universes from $T_1$, $T_2$, ..., $T_n$.

## The Observational Selection Effect, Dice-Throwing and Shooting

White attempts to tackle the 'observational selection effect' criticism levelled originally at Hacking. The observational selection effect is essentially the point that I have already made, with qualifications, namely that we can only observe this universe (note that the observational selection effect as I understand it works *in favour* of many universes). McGrath[39] cites the following situation, which attempts to model this effect:

> Case A: Jane takes a nap at the beginning of a dice rolling session, on the understanding that she will be woken as soon as a double six is rolled and not before. Upon being woken she infers that the dice have been rolled a number of times.

White reckons that Jane will only be justified in her inference if there is already a high prior probability that the dice would be rolled many times. We take White's example, in which the dice rollers plan to roll just once, unless they win the lottery that day, in which case they roll many times. Let us suppose that their chance of winning the lottery is one in a million.

Let us take three hypotheses and assign them prior probabilities:[40]

$H_1$: The dice rollers fail to win the lottery, with the consequence that they throw only once: $P[H_1] = 1 - 10^{-6}$.

$H_2$: The dice rollers win the lottery, and they roll between one and twenty four times, inclusive: $P[H_2] = 10^{-6} \times \{1 - (35/36)^{24}\} \approx 0.5 \times 10^{-6}$.

$H_3$: The dice rollers win the lottery, and they roll twenty five or more times: $P[H_3] = 10^{-6} \times (35/36)^{24} \approx 0.5 \times 10^{-6}$.

Now it can be seen that the antecedent probability that there are many throws is low, indeed it is overwhelmingly likely that there is only one throw. Denote by $W$ the evidence that Jane is in fact woken. Let us write down the likelihoods $P[W|H_i]$ and calculate the posterior probabilities $P[H_i|W]$ for each $i$:

$P[W|H_1] = 1/36$
$P[W|H_2] = 1$
$P[W|H_3] = 1$

It follows that $P[W] = \sum_{j=1}^{3} P[W|H_j].P[H_j] = (1 + 35 \times 10^{-6})/36$, and so

$P[H_1|W] \approx 1 - 36 \times 10^{-6}$
$P[H_2|W] \approx 18 \times 10^{-6}$
$P[H_3|W] \approx 18 \times 10^{-6}$

White is thus correct to assert that $P[H_3|W]$ is not probable. This is because $H_3$ started out with a low prior probability. However, $P[H_3|W] >> P[H_3]$, so $H_3$ is confirmed in the usual sense of Bayesian confirmation theory (note that $H_1$ is disconfirmed, as one would expect, since the probability that $H_1$ is false, given that Jane is woken, is 36 times the *a priori* value). Really this is precisely the point that Swinburne and others have been making. Both many universe theories and design find themselves confirmed by the existence of our fine-tuned universe; which hypothesis one plumps for depends on the prior probabilities.

I really fail to see the difference that White does between McGrath's Case A above and his Case B:

> Case B: Jane knows that an unspecified number of players will simultaneously roll a pair of dice just once, and that she will be woken if, and only if, a double six is rolled. Upon being woken she infers that there were several players rolling dice.

Given that Jane is woken she can go through the same Bayesian analysis as before to calculate the probability that 1, between 1 and 24, or more than 24 players were throwing. We can mimic the previous case by saying that only 1 person throws unless he wins the lottery, in which case he invites an unspecified number of friends to throw simultaneously with him.

White argues that the analogy we are really seeking is a modified form of McGrath's Case B, Case B*:

> Case B*: Jane knows that she is one of an unspecified number of sleepers each of which has a unique partner who will roll a pair of dice. Each sleeper will be woken if and only if *her* partner rolls a double six. Upon being woken, Jane infers that there are several sleepers and dice rollers.

White is correct to say that in these circumstances Jane's reasoning would be wrong. But why should each sleeper's partner only roll the dice once? If the sleepers represent life-bearing universes and the dice throwers parameters to be instantiated, the multiple universe advocate will surely insist that each life-bearing universe is given many opportunities to be realized. On being woken Jane would correctly infer that her partner had rolled many times.

A similar point arises with the analogy of the shooter in the wood, which White takes over from John Leslie.[41] You are in a wood into which a shot is fired at random and hits you. White argues that knowing you are shot does not enhance the probability that you are part of a crowd. But we *are* part of a crowd in the sense that our universe is contingent and there are many other possible universes, which may or may not be instantiated (this is what fine-tuning seems to be telling us). Supposing the shooter to be possessed of a fully automatic self-loading, rapid-fire machine gun, fitted with a silencer, rather than a single-shot rifle, your chance of being shot would certainly go up (as would the chance of many others of being shot). This seems a better analogy, with the people in the wood representing universes and the gunshots, rather incongruously, corresponding to 'bringing into existence'. You would be justified in arguing, not that many other people are in the wood, but (even though you could not hear them) that many shots have probably been fired. One shot, like one roll of the dice, representing one choice of parameters and initial conditions, is most unlikely to bring our universe into existence, unless there is some sort of manipulation ('design') going on; many shots make that more likely. This is just another way of saying what we have been saying all along: the fine-tuning of our universe disconfirms the hypothesis of a single universe but confirms both the many universes hypothesis and design.

## Another Objection to the Multiverse

D. H. Mellor[42] has another objection to the notion that a multiverse is explanatory of life in our universe. He recognizes that the multiverse explanation has shifted the ground from explaining why we exist to explaining why we exist here. It is like asking, not why fish exist, but why fish exist in water. And the answer is the obvious one, namely that water has what fish need, and similarly, *this* universe has what is needed for life. So the question is: does the existence of a multiverse (water + dry land) make it more likely that fine-tuning (water) exists so that life (fish) can exist in it?

Mellor thinks the answer to this question is 'No', but for an entirely different reason to White. Mellor's reason seems to be that what is important for explanation is a high physical probability, not a high epistemic probability. Neither a single universe nor the multiverse makes the physical probability that there is a universe suitable for life high, so the latter is no advance over the former.

The initial conditions of our universe make for a high physical probability that the universe is suitable for life, because in large measure they determine the physical conditions for the formation of galaxies, stars, planets, etc. But the initial conditions themselves have no physical probability at all. By their very nature they determine what comes after, but are not physically caused themselves.

The same is true in the case of a multiverse. Our universe's initial conditions might be determined by other physical conditions, say in a previous Big Crunch, or at the breaking off of a new space-time region from the centre of a black hole. These physical conditions can be traced back to yet earlier conditions, going back either to a single, original set of initial conditions, or (as most multiverse proponents would want) *ad infinitum*. Either way there is no ultimate physical causation, and so no high physical probability (indeed no physical probability at all)—either for an initial set of initial conditions or for the sequence of physical states as a whole and hence for the initial conditions of 'our universe'.

I think this is correct but it only reinforces the fact that we are, *pace* Mellor, in the realm of epistemic and not physical probabilities. Certainly this is the case when we assess the prior probabilities of a single universe versus a multiverse (and God) on grounds of simplicity and so on. It is also the case when we assess the likelihoods, because now the questions are of the kind: 'What are the possible ranges of values of the parameters for each hypothesis? How many combinations of them are realized? What is the probability that a fine-tuned set is realized?' The existence of any particular combination of values is not ultimately a question scientific naturalism can explain; again we see that we are forced to choose between metaphysical hypotheses, whether the existence of a single universe, some kind of multiverse, or God, basing our evaluation on judgments of epistemic probability.

## Some Concluding Remarks

In this chapter we have utilized the apparatus of Bayesian confirmation theory to compare three possible explanations for the fine-tuning of our universe. We find that the evidence disconfirms the notion that there is just one universe existing as a brute fact. This is unsurprising since the brute fact theory simply does not explain the evidence of fine-tuning.

More substantially we find that the evidence of fine-tuning confirms both the multiverse hypothesis and theism. Given the plausible assumptions we have made concerning the prior probabilities of each hypothesis, and the likelihoods (probabilities of the evidence given each hypothesis), we find that theism is to be preferred. We have seen that what really counts in the analysis is the ratio of the prior probabilities and the ratio of the likelihoods, since which hypothesis wins is determined by the product of these ratios. We have seen that a hypothesis which postulates the existence of all possible universes entails the existence of ours, whereas theism only makes ours quite likely. On the other hand, arguments from simplicity would seem strongly to favour theism. Hence our conclusion.

Whilst favouring theism, I do of course acknowledge, in contrast to White, that the evidence also confirms the multiverse hypothesis. The fundamental problem with

White's thesis lies in his use of the term 'this universe'. Indeed, in contradiction of his use of the term 'rigid designator', he seems to treat 'this universe' as simply any universe chosen at random from the ensemble of universes, whether the ensemble comprises a temporal sequence, as in Wheeler's model, or a set of coexisting universes, as in Carter's model. Certainly *that* universe, arbitrarily chosen like that, has a slim chance of being fine-tuned for life, and a much slimmer chance still of being the universe which produces us. In my way of expressing the matter *that* universe has a very small chance of being *our* universe, i.e. of being *this* universe.

Another way of expressing this is to say that our universe is most unlikely to be the 327th universe in a sequence starting at some arbitrary time in the past, or to be centred on particular co-ordinates $(x, y, z)$, measured from some origin in space, or to be any particular randomly chosen branch of an ever-splitting Everett-style multiverse (whose location might be measured in some system of co-ordinates in a multi-dimensional hyperspace). So it is indeed surprising, and improbable, that our universe occurs when and where it does (i.e. *now* and *here*). But that it arises sometime, somewhere is not surprising or improbable, only assuming that there is a positive probability of any generated universe having the requisite finely-tuned parameters—or, more accurately, that all possible universes are instantiated (a rather more demanding requirement). My chance of winning the lottery this week is very tiny, but if I keep entering the lottery my chance of winning sometime, no doubt if I outdo Methuselah in life-span many times over, approaches unity. Alternatively I could guarantee winning by buying all the lottery tickets sold this week. If I am long-lived, or buy all the lottery tickets, which one wins would not matter to me, only that I did win. Similarly, when and where our universe occurs are not essential properties of it; that it is fine-tuned and produces ourselves are.

Thus we are left with a puzzle, though this is not the same puzzle as White identifies. The puzzle now is, 'Why does our universe occur now rather than much earlier, given that there have been many previous universes?' or 'Why does our universe occur here, rather than anywhere else, given an ensemble of coexisting universes?'. This would, however, seem to be a rather trivial, even obscurantist, puzzle, certainly in comparison with White's fallacy.[43]

Although I have criticized White's argument, I do not wish to leave the reader with the impression that all is well with the many universes hypothesis in its various forms. Indeed the hypothesis suffers from a number of problems, some of which have been hinted at above:

(1) Are the infinitely many universes genuinely physically realizable?

(2) Is the set of life-bearing universes actually of measure zero in the space of possible universes?[44]

(3) Is the infinitely many universes hypothesis testable?

(4) Is the hypothesis simple, and therefore of high prior probability?

(5) What is the nature of the explanation provided by the many universes hypothesis? It would seem to be such as to explain literally anything by a shrug of the shoulders—'we just happen to be in a universe like that'.

(6) Why is there, in this universe, *more* fine-tuning than is required for life?[45] Probabilistically we would expect to be in a universe which had just enough fine-tuning for life.

(7) Why does the order necessary for life persist in this universe?

These are just some of the problems with the infinitely many universes hypothesis. However, that it does not provide an explanation for fine-tuning *at all* is not one of them. We shall be returning to this list in subsequent chapters since, although we have shown that many universes are theoretically explanatory, these problems would appear seriously to diminish the power of the explanation they provide.

In fairness, it should of course be acknowledged that the design hypothesis also has its problems (e.g. one we have seen here, that God might well not make *this* universe). Nevertheless, our conclusion that both theism and many universes are confirmed by fine-tuning would seem to be robust, and our preference for theism at the very least highly plausible.[46]

## Notes

1 As discussed in previous chapters the classic exposition is Barrow and Tipler (1986), though many other authors have discussed 'fine-tuning'.
2 See Garrett and Coles (1993) for this criticism.
3 See Hacking (1987).
4 See White (2000), repeated in Manson (ed.) (2003), pp. 229-250.
5 E.g. Wheeler (1973).
6 See Carter (1974).
7 Collins and Hawking (1973).
8 Professor Quentin Smith, in commenting on my paper which forms the basis of this chapter, noted that such problems might be addressed either by using Abraham Robinson's non-standard analysis, i.e. by assigning infinitesimal values to the probabilities, or by partitioning the continuum-many possible universes into finitely many natural kinds and considering the probability that a natural kind is instantiated. However, I do not hold out great hope for either approach. Robinson himself says: '... the non-standard methods that have been proposed to date are *conservative* relative to the commonly accepted principles of mathematics ... This signifies that a non-standard proof can always be replaced by a standard one, even though the latter may be more complicated and less intuitive.' See Robinson (1996), p. xv. Regarding the second approach, one may well encounter problems of the kind I mention later concerning the evidence we have, which is precisely that *this*

fine-tuned universe exists. I return to the measure zero problem in chapter 9, giving a reason different from that of Collins and Hawking for why it might arise.

9 See Swinburne (1991).
10 Smith in Craig and Smith (1993), p. 250.
11 Craig in Craig and Smith (1993), pp. 272-275.
12 See Leslie (1982), p. 146.
13 Penrose (1994), p. 312. Note, however, that for Penrose it is more serious that the Everett interpretation does not solve the 'measurement problem' it was set up to do.
14 This point is raised, for example, in Manson and Thrush (2003), p. 70.
15 Swinburne (2001), p. 85.
16 Swinburne (2001), pp. 98-99.
17 Bradley (2002), p. 389.
18 Tegmark (1998), p. 44.
19 Swinburne (2003), p. 122.
20 Swinburne (2001), p. 242.
21 Swinburne (2003), p. 117.
22 E.g. in Polkinghorne (1986), p. 80, but in many other places as well.
23 St Thomas Aquinas, *Summa Theologiae*, 1a. 3.
24 We noted Paley's discovery of the stability of planetary orbits governed by the inverse square law when discussing the dimensionality of the universe in chapter 3.
25 Dawkins (1988), p. 316.
26 Of course it is generally agreed that God's knowledge and power are limited to what can logically be known or done.
27 Swinburne (1991), pp. 141-142.
28 Swinburne (2003), p. 118.
29 Swinburne's dualist position is expounded in Swinburne (1997); and Swinburne (2003) certainly concentrates on the capacity of a universe to produce human bodies.
30 Schlesinger (1988), pp. 141-143.
31 As noted in chapter 4, contra Bradley (2001, 2002), I consider a life-bearing universe to possess objective value which God would wish to realize in preference to featureless universes.
32 It is rather interesting that Swinburne comes up, independently, with numbers at least superficially similar to mine (in Swinburne (2003), pp. 108-114). He argues that it is good for God to bring about a world with 'human beings', but qualifies this because of the risk of the abuse of significant freedom which they possess. Acknowledging uncertainties in the ability to estimate he comes up with probabilities in the range 0.2 to 0.8. The main point about such figures is that, although there is an artificiality about them, they are 'significant'.
33 In addition to our earlier discussion in chapter 4 see, for example, Leslie (1982), pp. 145-146.
34 Linde (1987). We return to inflation in chapter 8.
35 See chapter 9.
36 See, for example, Peacocke (1993), pp. 107-109.
37 Manson and Thrush (2003).
38 Here the symbol $\exists$ means 'there exists'. The formula can be derived from standard probability reasoning as follows. The probability that a random universe instantiates $T_1$ is $1/n$. The probability that it does not is $1 - 1/n$. The probability that all $k$ universes do not instantiate $T_1$ is $(1 - 1/n)^k$, so the probability that at least one of them does is $1 - (1 - 1/n)^k$.

39 See McGrath (1988).
40 The calculation of these probabilities is similar to that in note 38. For example, given a win on the lottery the probability of then obtaining a double six within the first 24 throws is $1 - (1 - 1/36)^{24}$.
41 See Leslie (1988).
42 Mellor (2003).
43 Certainly Quentin Smith thinks so, in his remarks to me. However, some authors do take the problem seriously—see Taylor (1995). Taylor argues that a finite universe is metaphysically more satisfactory than infinitely many universes, since it removes such paradoxes of the infinite. An example he quotes is of the man who claims to have been counting backward from eternity and is now just finishing −5, −4, −3, −2, −1, 0. The problem is, why did he not finish counting yesterday, or the day before, or the year before, given that he has been counting from eternity? More starkly, if something happened today, given an infinite past it would have happened earlier, and hence could not have happened today. The counting example comes from Conway (1984). Taylor maintains that the argument is valid given a form of the Principle of Sufficient Reason, and whilst this principle is not necessary, a theory which supplies a reason is to be preferred to one which does not. Manson and Thrush also give some discussion of the possibility of our universe, or indeed simply the Earth, being located elsewhere in the multiverse.
44 As we have noted above, this was suggested in Collins and Hawking (1973), and it is a topic to which we return in chapter 7, and in more detail in chapter 9.
45 See Penrose (1989a), p. 354, and chapter 7 where we discuss Penrose's findings.
46 I am most grateful for the helpful and encouraging comments received on the paper from which this chapter is drawn, Holder (2002), from Professor Quentin Smith.

Chapter 7

# The Multiverse—a Viable Alternative to Design?

Fish say, they have their stream and pond;
But is there anything beyond?

(Rupert Brooke, *Heaven.*)

## Introduction: Fine-tuning and the Invocation of Many Universes

As we have seen in earlier chapters one possible inference to draw from the fine-tuning data is that the constants of physics and the initial conditions at the Big Bang were fixed by God who wished to create an anthropically fruitful universe. A counter strategy often adopted by those who wish to deny design is to postulate the existence of a multiverse, i.e. an ensemble of infinitely many universes, in which the constants and/or the initial conditions take on all possible values. We should then not be surprised to find ourselves in a universe with the parameters ours has, since we could not find ourselves in, and hence observe, any universe whose parameters differed by more than the smallest amount from ours. The kind of opponent of design I am describing usually wishes to adopt the position that all physical events can be explained solely, and exclusively, in terms of other physical events, a position I have dubbed 'scientific naturalism'.

We have seen that the multiverse hypothesis in its various forms does provide an explanation for the fine-tuning, as does design. In the last chapter I argued that design fared better on a Bayesian comparison, because on grounds of simplicity and economy the prior probability of a multiverse should be taken as much less than that of design. I also noted that there were a number of outstanding problems with the multiverse notion which we would need to revisit, and which might well adversely impact on the hypothesis's explanatory power.

In this chapter, then, I provide the promised critique of the multiverse hypothesis as an alternative to design. Among the problems identified with the hypothesis are

(1) the existence of infinitely many universes depends critically on parameter choice;

(2) the probability that any universe in an ensemble is fine-tuned for life is zero;

(3) the physical realization of any ensemble will exclude an infinity of possibilities;

(4) the hypothesis is untestable and unscientific; and

(5) the hypothesis is not consistent with the amount of order found in this universe, nor with the persistence of order.

If these factors are taken into consideration the conclusion of the last chapter will be much stronger, because the prior probability of many universes will be further reduced and because the 'likelihood' entering Bayes's theorem will also be reduced.

In this chapter I shall concentrate on only one particular mode of existence of multiverse. This is as the simultaneous existence of infinitely many regions (really sub-universes, but we call them universes for short) in a single encompassing space. As noted in chapter 4, following earlier work by George Ellis, Ellis and Brundrit describe just such an ensemble comprised within a low density, open and infinite 'embracing' space.[1] It seems to me that this is the least controversial means of obtaining many universes.[2] Nowadays the universes are more often conceived as bubble domains in inflationary models, and, whilst briefly alluding to inflation here, I shall devote more space to that topic in the next chapter.

## Measure, Probability and the Principle of Indifference

A serious problem which pervades the whole discussion of the 'anthropic coincidences', whether trying to explain them in a single universe or by invoking many universes, is that it is difficult to assess the number of possible allowed combinations of free parameters and hence the proportion of them which allow life to develop. Dennis Sciama points out that, in order to determine whether or not our universe is 'super special' we require a 'still-to-be-constructed measure theory on the ensemble space of the universes'.[3] A measure is a mathematical function with certain properties, notably additivity: the probability of the union of two disjoint sets is the sum of the individual probabilities (indeed additivity of infinite disjoint unions is required, as given by the axiom of continuity presented in Appendix A). Probability, here conceived in mathematicians' terms as a mapping from a set of sets onto the real line, is a special case of measure: the probability of the whole space is 1, whereas measure in general is not limited in value.

Such a measure theory as advocated by Sciama would greatly improve the rigour of anthropic arguments by providing a basis for assigning probabilities to the parameters which describe the universes. Paul Davies has made a similar point to this in his book *The Mind of God*.[4] And, more recently, John Barrow acknowledges that 'Every attempt to define probability for cosmological problems precisely and so give numerical answers to questions like "what is the probability that the universe has certain properties which will allow life to exist in it?" has so far failed'.[5]

The measure problem is closely related to the problem, to which I referred in chapter 5, of assigning prior probabilities on the basis of minimal information. To see how the problem is manifested, suppose that a particular parameter $\lambda$ could lie theoretically anywhere in the range 0 to $l$. If equal intervals of $\lambda$ are equally likely, then the probability that $\lambda$ lies between $a$ and $b$, where $0 \leq a \leq b \leq l$, is $(b - a)/l$. This is the length of the interval $(b - a)$ divided by the length of the whole interval $l$ (or, in probability theory terms, $(b - a)$ multiplied by $1/l$, the probability density function for a so-called 'uniform distribution').

Clearly, the larger the value of $l$ the smaller the probability that $\lambda$ lies within any particular finite interval $[a, b]$. Naïvely one might expect that the probability $(b - a)/l$ would tend to zero as $l$ tends to infinity. However, there is a problem about actually taking the limit as $l$ tends to infinity because the probability density function would still have to integrate (i.e. add up) to 1, a property known as normalization. The axiom of continuity (see Appendix A) is then violated, and we are heading for paradoxes of the kind associated with the maximum entropy method if we persist in using 'improper priors' (see Appendix B).

All this of course begs the question, 'Why should we take such a uniform distribution?' To do so seems to be justified only on the basis of the Principle of Indifference or something like it, and we have seen that this leads to inconsistency. Thus we could equally well take any function of $\lambda$ and assign that a uniform distribution, or any distribution we please, and get an entirely different answer. What the normalized probability distribution for any of the parameters in question should actually be is simply unknown.

Of course this raises the key question as to whether the fine-tuning really is improbable. It is a rather more pressing version of the question as to whether there really is anything to explain. How can we assert this, if we do not know what probability distributions to use for the possible values of the parameters? The ranges of values of parameters which are life-permitting may look narrow, but this is arguably irrelevant if we do not know how to translate a seemingly narrow range into a probability.

Such considerations have led some authors, notably philosopher Neil Manson,[6] and philosophers Timothy and Lydia McGrew and mathematician Eric Vestrup,[7] to the rather extreme conclusion that no inferences at all can be drawn from the fine-tuning. Others, such as Robin Collins, although aware of the problem, nevertheless persist in taking a uniform distribution over the parameter in question.[8] For Collins this expresses a restricted principle of indifference, according to which one should assign equal probabilities to equal ranges for a parameter which corresponds directly to a physical magnitude.[9]

Collins takes the gravitational force as an example. Let $\alpha_G$ denote the measured value of its strength in standard dimensionless units. Collins produces arguments purporting to show that the life-permitting range is within 0 to about 3000 $\alpha_G$ and the range which permits a universe at all is something like 0 to $10^{40}\alpha_G$ (the value of the strong force in the same dimensionless units). Hence the probability of a fine-tuned universe is approximately $3 \times 10^{-37}$. Collins then says that even if the possible range of values for any parameter were infinite, as McGrew *et al.* expect to be the case, the fine-tuning argument would still carry through since he abandons the axiom of continuity.[10]

My own reaction to this undoubtedly serious problem is more cautious and is essentially three-fold. First, as throughout this book, I would want to reiterate that my aim is to follow, in so far as possible, the reasoning processes of the scientists themselves. Now scientists in general do think that the parameter values are contingent and could be other than they are. As we have seen, there are some who think there may be only a single self-consistent set of physical laws with unique parameter values. I have argued that that still leaves an enormous puzzle as to why the only consistent set of physical laws should be life-producing. But many cosmologists have been led to speculate about a multiverse precisely because they think that, not only are the parameter values contingent, but the values taken are of extremely small probability. It certainly looks highly plausible that the values taken are of small probability, even if there is no unique way of translating measure (e.g. even the 'natural measure' of length of interval on the real line) into probability. We shall in fact see how for some parameters the measure is zero, which creates acute problems for the many universes hypothesis.

That brings me to my second point, namely that the measure problem is actually worse for the multiverse hypothesis than for the hypothesis of design (theism). That is because, in order for the design argument to work, all we really need to be able to assert is the plausible statement that the probability of the parameter values being life-producing is low. Design will then explain why they are as they are. In contrast, as we shall see shortly, many universes can only explain why they are as they are by making further assumptions about probability distributions.

My third point is that, although in general it is difficult to assign probabilities, in at least one case the fine-tuning we are speaking of looks like a genuine probability. As we saw in chapter 3, the probability that there exists the amount of order we find in our universe is almost unimaginably tiny. Moreover, as we shall see later, this probability is vastly smaller than one would expect on the many universes hypothesis, although quite to be expected on the basis of design. Indeed this presents us with a very serious weakness of the many universes hypothesis when compared with design.

Whilst remaining aware of the measure problem, then, my approach in this chapter will nevertheless be to take account of statements of probability made by leading cosmologists. In so far as possible I shall take these statements at face value and explore their logic. My contention is that such statements are in fundamental tension with the invocation by these same authors of many universes as an explanation for fine-tuning.

My analysis focuses on two of the most important elements of fine-tuning. These both relate to initial conditions in the early universe rather than fundamental constants of physical theory. They are the initial density and isotropy of the universe. The analysis shows

(1) that the existence of an infinite ensemble depends on critical assumptions which may not be probable;

(2) that the probability that any universe within the ensemble is finely-tuned might actually be zero, in which case the explanatory value disappears; and

(3) that the ensemble is in any case not physically realizable.

I briefly allude to how inflation might impact on these conclusions, though deferring more detailed discussion to the next chapter.

Finally, I consider certain other general problems with the infinitely many universes hypothesis as an explanation for fine-tuning. These include the kind of explanation offered, its testability, and, as mentioned above, whether the amount of ultra-fine-tuning *this* universe actually possesses is explained.

**Critical Density**

We have seen in chapter 3 how, according to Barrow and Tipler, in order for the universe to be life-producing, the energy density $\rho$ at the Planck time, when the universe is $10^{-43}$ seconds old, must be equal to the critical density $\rho_c$ to an accuracy of between $10^{-56}$ and $10^{-60}$.

We now examine how Barrow and Tipler attempt to evade the conclusion that $\rho$ is designed to be very close to $\rho_c$ by invoking many universes.

Barrow and Tipler state: '... because in an infinite universe there is a finite probability that an arbitrarily large region obeying [this constraint] will occur somewhere if the initial conditions are *random*, we would expect to observe [this constraint]'.[11]

We need to try and unpack the meaning of this very important statement, remembering the qualifications made earlier about probability statements. Barrow and Tipler give us no guidance.

At face value the statement would appear to mean that, in a multiverse conceived in this way, there is a probability $p$, lying strictly between 0 and 1, that a region with density satisfying the condition will occur. But what is meant by 'random initial conditions'? Presumably this means that $\rho$ is chosen randomly, but from what probability distribution? Barrow and Tipler do not tell us, so we are left to fend for ourselves. Let us try some possibilities.

Suppose first that the initial value of $\rho$ is a uniform random variable lying between 0 and $\rho_c$. Then there will be a finite probability, of order $10^{-57}$, that a given universe with a single value of $\rho$ would have the required density. How $p$ relates to this latter probability is not made clear. If $p$ is very low, the appeal to an infinite universe with regions of differing $\rho$ is nugatory.

One might have expected the stronger claim that in an infinite universe, given random initial conditions, an arbitrary region satisfying the near-flatness condition is bound to occur, i.e. will occur with probability 1—that is the usual motivation for the appeal to an infinite universe. If one could engineer more than $10^{60}$ universes, each with the initial value of $\rho$ chosen from the above distribution, then $p$ would indeed approach unity.

Were it possible to partition space into infinitely many regions with density randomly chosen between 0 and $\rho_c$ (though see below), then the probability would indeed be 1 that one with density in the required range would exist. The anthropic reasoning of Barrow and Tipler would then be correct: we can only observe a region of this kind.

But why limit the random choice of $\rho$ to the range 0 to $\rho_c$? We have been considering the value of $\rho$ to be randomly chosen for each region. Now let us consider the density $\rho_{tot}$ of the ensemble as a whole. There would seem to be no reason to restrict $\rho_{tot}$ to the range $(0, \rho_c]$.[12]

To avoid the problems about an infinite range mentioned above, suppose that $\rho_{tot}$ has a physically realizable maximum value $\rho_{max}$ (this may be physically realistic if we discount the existence of classical black holes with literally infinite density). Presumably it will be the case that $\rho_{max} >> \rho_c$. The probability that $\rho_{tot} \leq \rho_c$ is then very small, on the assumption that $\rho_{tot}$ is drawn from a uniform distribution on the interval $(0, \rho_{max}]$. Moreover, if $\rho_{tot} > \rho_c$ then the universe is finite. In fact it is overwhelmingly likely, given that $\rho_{tot}$ is randomly chosen from such a uniform distribution, that the universe will be finite. But if the universe is finite, there are not infinitely many regions of arbitrary size! The argument from random choosing of $\rho_{tot}$ to infinitely many universes in which the 'right' values for life will automatically occur breaks down. In other words, the many universes hypothesis already implies a very special condition (i.e. $\rho_{tot} \leq \rho_c$) on the system as a whole.

Let me summarize this argument. Postulate an infinite universe in which arbitrarily large regions exist whose density is chosen randomly between 0 and $\rho_c$. For the sake of argument assume that this implies that there exists with certainty a region with $\rho$ satisfying the near-flatness condition. The anthropic explanation for our existence succeeds. However, *in order for there to be infinitely many regions the overall density of the universe $\rho_{tot}$ must be below $\rho_c$*. But the probability that there actually exist infinitely many regions might well be low, since if $\rho_{tot}$ is chosen randomly from the range 0 to $\rho_{max}$, then it is highly probable that the universe is finite.

Thus we are far from having eliminated the finely-tuned density of the universe as a 'cosmic coincidence'. $\rho_{tot}/\rho_c$ for the universe as a whole must be less than unity, and the probability of this may well be extremely small.

Now the argument can of course be thrown back at us that we have assumed this uniform distribution for $\rho$ without warrant. In fact we have no idea what the distribution for $\rho$ should be. This is true. My point is that neither do Barrow and Tipler have a clue as to what this distribution should be. They certainly do not tell us, but just vaguely assume that an infinite universe with random selections of $\rho$ will automatically give some regions suitable for life. This assumption relies on the critical, but apparently arbitrary further assumption that $\rho_{tot}$ for the whole ensemble is less than $\rho_c$.

There is a further point. Given an infinite universe, it is actually impossible to determine what the value of $\Omega_0$ (the value of $\rho_{tot}/\rho_c$ at the present time) is, and hence to extrapolate back to its tightly constrained value in the very early universe. To assign it a value is therefore to make a 'metaphysical' assumption. Without such a metaphysical assumption, anathema to the scientific naturalist, the hypothesis of an infinite universe fails.

## More on Measure—and a Possible Way out of the Flatness Problem?

Whilst the above seems to me to be a robust line of reasoning, it is nevertheless important to acknowledge one possible response. This is to take issue with my claim that we cannot know what probability distribution to take for $\rho$, and furthermore to produce an argument for a distribution which makes proximity to $\rho_c$ probable rather than extremely unlikely. That is the response of Evrard and Coles,[13] and more recently Kirchner and Ellis,[14] both pairs of authors advocating the use of Jaynes's Principle of Maximum Entropy (PME), to which I alluded in chapter 5, and which I discuss in more detail in Appendix B. Philosopher Jeffrey Koperski endorses this approach, even though there are question marks over the method and any results may only be provisional.[15] He believes it refutes the scepticism of Manson and McGrew *et al.* because it at least shows the possibility in principle of deriving objective measures and drawing conclusions from them—whether or not these favour theism or a multiverse.

Since again the mathematics of my critique of this application of PME is rather heavy I refer the reader to Appendix E for the details. Suffice it to say that I identify the following problems:

(1) As is common with applications of Jaynes's method, non-normalizable measures are derived. These are in conflict with the axioms of probability theory and lead to paradoxes and ambiguities.

(2) For example, the uniform distribution over the finite interval $[a, b]$ at least has the merit of normalizability. It is also defended on grounds of simplicity by Swinburne. However, Kirchner and Ellis derive a non-normalizable measure over such finite intervals which leads to demonstrable ambiguities.

(3) Both Evrard and Coles and Kirchner and Ellis find that if a probability distribution goes to infinity for a particular value of a parameter, e.g. for $\Omega_0 = 1$, then the parameter is overwhelmingly likely to take that value. This is how the flatness problem gets solved and the claim is made that, far from it being unlikely that $\Omega_0 = 1$, this is overwhelmingly probable. The trouble is that that conclusion is built into the method, so it is merely a question of 'What you put in is what you get out'.

(4) The Evrard and Coles version has the unfortunate property that it assigns different probabilities to the same model of the universe at different times.

(5) Kirchner and Ellis find that the minimum information measure for the cosmological constant $\Lambda$, about which I shall have more to say in chapter 8, does not favour the small non-zero values compatible with observation. Although this worries them they fail to draw the natural conclusion that our universe is, after all, *unlikely*. Instead they specialize their treatment to a fixed value of $\Lambda$ and just consider the probability distribution for $\Omega_0$, the problems with which I have noted in (3) above. They thus miss the possibility that PME might even support design of $\Lambda$!

## Isotropy

I reported in chapter 3 the remarkable finding of Barry Collins and Stephen Hawking that 'the set of spatially homogeneous cosmological models which approach isotropy at infinite times is of measure zero in the space of all spatially homogeneous models'.[16] Moreover, such asymptotic isotropy would appear necessary for the universe to be life-producing.

We need to examine this very important seeming anthropic coincidence in more detail, starting from its background in the work of Charles Misner.

Misner had introduced the 'chaotic cosmology' programme, to which I briefly alluded in chapter 3, with a view to showing that the present large-scale structure of the universe, including its isotropy, is largely independent of initial conditions.[17] As noted in chapter 3, this is a case of what McMullin calls the 'indifference principle' in cosmology—the idea that there is nothing 'accidental' about the universe.[18] Applied to the initial conditions of the Big Bang, this asserts that, whatever they were, the universe would evolve in the same way.

Collins's and Hawking's paper dealt the death blow to chaotic cosmology. They used the standard (Bianchi) classification of solutions to Einstein's equations of general relativity, and examined the stability of these solutions to perturbations in initial data. In practice, spatially homogeneous models may be grouped into three classes, using the terminology I introduced in chapter 3: those that are closed, 'just open' and open. Models in the first group do not last long enough to approach isotropy and those of the third group do not in general tend to isotropy. Collins and Hawking write:

> Those models of the second class which are sufficiently near to the Robertson-Walker[19] models do in general tend to isotropy, but this class is of measure zero in the space of all homogeneous models. It therefore seems that one cannot explain the isotropy of the universe without postulating special initial conditions.[20]

In other words, the set of asymptotically isotropic universes is a negligible fraction of the total set of possible universes. Note that in the previous two sections, when we were struggling to ascertain whether mean density close to the critical value could be at all likely, we were already working with the simplified (Friedmann-Lemaître-Robertson-Walker) homogeneous and isotropic model!

Collins and Hawking are aware of possible criticisms of their finding. We are clearly not yet at time infinity, so perhaps we are in a universe which is still young, has been very nearly isotropic up to now, but may yet tend to anisotropy. They are simply 'unhappy' about believing this, finding it much more plausible that the universe is becoming more rather than less isotropic. This seems rather lame, but all I can do for the purposes of this book is to assume that they are right, that we are necessarily in an asymptotically isotropic universe (because only so can we have galaxies), and follow through the logic of their position.

Collins and Hawking justify consideration of this measure zero set of cosmological models by appealing to a postulate of Dicke[21] and Carter[22], namely that 'there is not one universe but a whole infinite ensemble of universes with all possible initial conditions'. As in the case of finely-tuned density, this appeal to a multiverse is also highly problematical—indeed much more so.

The appeal to a spatially infinite universe does not help in this case because the probability that any region within the ensemble is asymptotically isotropic is not just low, but zero (that is what 'measure zero' means on any reasonable translation from measure to probability). This destroys the explanatory power of an infinite number of universes (as noted by Earman[23]). A zero probability times an infinite number of possibilities is a mathematically indeterminate quantity. Thus there is absolutely no guarantee that a spatially infinite universe can provide a region of sufficient size with asymptotic isotropy, and hence, *a fortiori*, with life. If the properties of the various regions of the infinite universe are random, the number of suitable universes could be any finite number or zero.[24]

Moreover, the number of finite regions above a given size within an infinite universe, although infinite, is only countably infinite.[25] This means that there will be an infinite number of possible universes that are *not* realized (just as there is an infinite set of numbers between zero and infinity which are not integers). We return to this important topic in chapter 9. Here let us recall from chapter 4 the important further reason why the measure of the parameter set for our universe might be zero, namely that the number of anthropic constraints exceeds the number of free parameters, making it fortunate indeed *a priori* that there should be an anthropically fruitful parameter set at all.

It is often baldly stated that if all possible universes existed the probability that one like ours would exist is 1. We should therefore not be surprised to live in one like ours, because only such a one would be observable. We now see that this claim is fallacious. Any subset of universes which exhibit the right properties to produce life is of measure zero in the space of all universes, and therefore occurs with zero probability, thus vitiating the explanatory value of the infinity. Furthermore, it is not possible that all possible universes co-exist, at least not as sub-universes in a single space-time overarching universe, a point we return to in chapter 9.[26]

## Does Inflation Help?

The existence of a multiverse is often postulated as an alternative to 'design', the argument that the fine-tuning of the universe is evidence that the parameters in question were deliberately chosen by God with the express intention that the universe would give rise to life. As indicated in chapter 4, another strategy for avoiding design is the proposal that some better physical theory will sooner or later be found to explain the 'cosmic coincidences'. We have seen that inflation is the strongest contender for such a theory. Inflation apparently solves a number of problems, though we have also seen that this does not negate the argument from fine-tuning, but merely transfers our awe at the fine-tuned parameters to the theory which can now apparently produce at least some of them!

Inflation is itself a growth industry in modern cosmology and we defer detailed discussion of this important topic to the next chapter. Here we just note the unusual nature, for science, of what inflation is required to do, namely explain initial conditions (not, in other words, to counter empirical inadequacy); and that even on its own terms it has had to undergo numerous mutations to maintain consistency. Problems include the fact that inflation relies on Grand Unified Theories which are untestable in the laboratory, but where they do make predictions these are in conflict with experiment, and the theory also seems to need fine-tuning! Most importantly from the point of view of this chapter, one is in any case virtually driven towards a many universes scenario in order to guarantee that inflation happens somewhere sometime!

## Further Problems with the Many-Universes Hypothesis

There are a number of problems of a more general nature—scientific, philosophical and metaphysical—with regard to the postulation of a multiverse, to which I briefly alluded at the end of the last chapter, and to these I now turn.

### *Testability*

One of the problems associated with the multiverse hypothesis in its various forms is its lack of testability. Experimental or observational verification is at the heart of scientific method, yet this seems to be lacking in this case even in principle. In science such verification does not have to be direct. Some exotic particles are believed to exist because of their effects. For example, the Higgs particle is predicted to exist in order to give mass to other particles, and its existence implies measurable effects in many high energy scattering experiments, even where the Higgs particle itself is not produced. Although not yet directly observed, the measurable effects already put limits on its mass.

In the case of the multiverse conceived as an ensemble of sub-universes in an infinite space-time, as in the Ellis-Brundrit scenario, there cannot even be indirect observational evidence of the other universes' existence. There is a barrier imposed by the finite speed of light which means that there is a natural horizon from beyond which signals cannot yet have reached us. This applies equally to the causally disconnected mini-universes produced by chaotic inflation (see next chapter), and *a fortiori* to the temporal and other-dimensional MWTs of Gale's classification. By definition a causally disconnected universe cannot cause any effects in our own universe.

As Polkinghorne points out, this means that the existence of many universes provides, not a scientific, but a metaphysical explanation of the fine-tuning of this universe. The reason he says this is that the existence of these worlds is completely insensitive to any empirical data—they are unobservable. The fact is that, whether we like it or not, we are faced with alternative metaphysical explanations, e.g. either the universe is unique and a brute fact, or there are infinitely many universes (some form of multiverse), or the universe is designed (although we consider these to be the main options, there is also the logical possibility that God designed and created a multiverse, a hypothesis to which I alluded briefly in chapter 6).

### *The Nature of the Many Universes and their Plausibility*

It is worth contemplating for a moment what we are being asked to swallow if we are to believe in a multiverse. Let us ignore for a moment the measure zero problem and assume that a positive fraction of universes is life-bearing. It is still the case that the vast majority of universes will be totally dead. Of the minute proportion bearing any resemblance to ours, there will be some in which an 'I', virtually identical with me up to now, fell under a bus before completing this chapter; some where there is even more unimaginable evil and suffering than in this one; some where conditions are benign and Eden-like; some in which gorgons or unicorns or wyverns actually exist; and so on, and so on. Just simply trying to contemplate the infinitely many universes makes us realize how bizarre the hypothesis is.

### *What Kind of Explanation is Provided by the Multiverse?*

Because of its lack of observable consequences, the appeal to a multiverse provides a metaphysical explanation for life rather than a scientific one. But the theory is also unscientific in another sense. This is because it provides a 'catch-all' kind of explanation.

Multiverse theories remind me of the argument put forward by Christian fundamentalist Philip Henry Gosse in the nineteenth century to reconcile a literal reading of Genesis with geology. Nature is really cyclical and God created it instantaneously in mid-cycle—Adam with a navel, trees in Eden appearing to be 50 years old, fossil birds with half-digested food in their stomachs![27] Anything can be explained on this basis and no observation can possibly contradict the theory. Multiverse theories are equally sterile. Yes, they explain everything, by the simple formula, 'If it can happen, it will happen somewhere sometime, so don't be surprised!'. But they cannot be falsified: they are completely insensitive to the empirical facts. This is a far cry from the normal kind of explanation sought in science. Scientific naturalist Richard Dawkins ought to reject it since this is precisely why he rejects religion, e.g.: 'Scientific belief is based on publicly checkable evidence. Religious faith not only lacks evidence; its independence from evidence is its joy, shouted from the rooftops...'.[28] But of course, as we have seen, one must adopt a metaphysical position of some kind, whether it be a multiverse, just one universe, or theism.

This leads to a further problem with multiverse theories, namely that they provide a disincentive to do science. If anything can be explained, then any uncomfortable observation can simply be greeted with the cry, 'We just happen to be in a universe which has that feature.'

Sometimes the charge of providing a disincentive to do science has been levelled at the theistic hypothesis. However, in that case the charge does not stick. The theistic hypothesis might lead one to expect a universe with certain features, e.g. that it exhibits purpose and a moral order. Moreover, the idea that the universe is the good creation of God has historically led to a thoroughgoing motivation to do science.[29] The multiverse hypothesis gives us no reason to expect any particular features in this universe, apart from the fact that it should be a universe which we can observe.

### *How Much Fine-Tuning is There in Our Universe and Why Does Order Persist?*

If the many-worlds hypothesis is to be transformed from the realms of metaphysics to physics, the scientific naturalist must surely provide us with some observational consequences. Dennis Sciama has suggested that, under the many-universes hypothesis, 'we would not expect our universe to be a more special member of the ensemble than is needed to guarantee our development', whereas by contrast 'a unique universe might be expected to be characterized by very special conditions indeed'.[30] More recently, Alexander Vilenkin, in yet another demonstration of the penchant of cosmologists for grand principles, has dubbed the neo-Copernican idea that our universe should be only a typical member of an ensemble 'the principle of mediocrity'.[31] Max Tegmark means the same thing when he predicts from his 'ultimate ensemble' proposal, in which all mathematical structures have physical existence, that 'the mathematical structure describing our world is the most generic one that is consistent with our observations' and that 'our observations are the most generic ones that are consistent with our existence'.[32] Indeed Tegmark boldly proclaims, 'Any clearly demonstrated feature of "fine-tuning" which is unnecessary for the existence of SASs ['self-aware substructures'] would immediately rule out the 1a TOE [theory of everything in which all mathematical structures have physical existence]'.

Another variant on these proposals for how a multiverse theory should look derives from philosopher Nick Bostrom's Self-Sampling Assumption (SSA).[33] Bostrom argues that 'One should reason as if one were a random sample from the set of all observers in one's reference class'.[34] Now defining the 'reference class' is a thorny issue for Bostrom but what is clear is that he takes observers in a general sense, to include non-human observers. So the difference between Bostrom on the one hand, and Sciama and Vilenkin on the other, is that for Bostrom it is observers who are sampled from, whereas for Sciama and Vilenkin it is universe configurations. Tegmark would seem to side with Sciama and Vilenkin here, since he is talking about the mathematical structures and observations being generic, rather than observers (SASs) themselves.

There are some knotty philosophical issues involved here which Bostrom is concerned to unravel in his book. Whilst there is much to agree with in the book, e.g. his fundamental affirmations that the fine-tuning does indeed require explanation, and that both fine-tuning and design are candidates, I am not convinced that SSA is the right approach. In particular it seems to me to give paradoxical results in some circumstances, or fails to resolve paradoxes satisfactorily, one notable example being the way it handles the so-called Doomsday Argument. This states essentially that we are more likely to find ourselves temporally where we do in the sequence of humans if our species is shortly to die out than if it is long-lived. I examine this argument, and the application of SSA to it, in Appendix D.

For our purposes it would seem that not too much depends on these distinctions. Indeed, although I adopt the Sciama and Vilenkin view here, it turns out that Bostrom derives a similar result to that which follows by applying SSA.[35]

The main point of the above is that we have identified a highly significant difference between what one would expect on the basis of a multiverse and what one might expect on the basis of design, albeit a difference which does not involve any causal contact with, or observation of, other universes. A unique universe might be expected to be extra-special; a random member of an ensemble of universes would be no more special than would be required for our existence.

Unfortunately for the scientific naturalist the news on this potential observational difference between theories is not good for multiverse proponents, for Roger Penrose has suggested that our universe is indeed more special than would pertain on a multiverse hypothesis, at least in one very important respect. Penrose (see chapter 3) notes that, regarding the initial entropy of the universe, i.e. the amount of order the universe started off with, a precision of

$$1 \text{ part in } 10^{10^{123}}$$

is required. However, the order required to manufacture the solar system and its inhabitants, simply from the random collisions of particles, is vastly less than this, though still very great[36]—something like

1 part in $10^{10^{60}}$

A multiverse thus offers us an explanation of why there is a universe fine-tuned for life but the ultra-fine tuning our universe actually possesses is an unexplained brute fact. Possible ways round this problem include inflation, which we shall consider in more detail in chapter 8, and about which Penrose is especially dismissive, and vague appeals to Mach's principle (which concerns the origin of inertia) to link local and global structure.[37]

A further problem concerns the persistence of order in this universe. Presumably in an infinite ensemble of possible universes, many will be identical to ours up to, say, the present moment or midnight on 31 October 2008, and then dissolve into chaos. The question, 'Why does the order our universe possesses persist?' is one which finds no answer from the notion that ours is simply a random selection from an infinite ensemble.[38]

Imagine a monkey sitting at a typewriter for untold aeons. The animal is vastly more likely to produce 'To be or not to be' at some stage and then sink into chaos than to produce the whole of *Hamlet*. Similarly, random selection of universes from a vast ensemble is far more likely to produce a solar system embedded in chaos, or a finely-tuned epoch followed by chaos, than a universe with the order, and persistence of that order, which our universe actually possesses. In contrast theism offers us the explanation that total order, in both space and time, is to be expected from the creation of a good God.

### Probabilistic Comparison of Hypotheses Revised

The criticisms of this chapter would imply that, whatever values we had previously placed on the prior probability of the existence of a multiverse, and of the likelihood of the hypothesis, these should both be reduced.

Thus we can now see that the many-universes hypothesis is defective in explanatory power because the probability that any universe in an ensemble is fine-tuned is zero. There is therefore no guarantee that a fine-tuned universe will exist given the hypothesis, whereas in the last chapter we assumed that the hypothesis was of unimpeachable explanatory power.

In the last chapter, although noting that the question was debatable, I argued, following Swinburne, Polkinghorne, Leslie, Penrose and others that the multiverse hypothesis is distinctly non-simple and uneconomical in comparison with theism. Now we can see that the prior probability of the existence of many universes ought to be reduced further because their existence depends critically on parameter choice, because the hypothesis is untestable, and because it is inconsistent with the amount of order in *this* universe.

Given all this, the hypothesis inevitably loses much further ground to theism.

We complete the probability analysis following further consideration of the 'measure zero' problem in chapter 9.

## Conclusions

I believe that the above considerations, taken together, mount a cumulative case against the postulation of a multiverse as an alternative to design. First, the infinitely many universes comprising the multiverse are invoked to explain the fine-tuning of this one. They fail to do so because (i) the existence of infinitely many universes may itself be improbable; (ii) the probability of the occurrence of fine-tuning in any universe or sub-universe of an ensemble would appear to be zero; and (iii) the realization of all possible universes in an ensemble is impossible.

I have referred to inflation, deferring more detailed discussion of this to the next chapter. Preliminary indications are that inflation does not solve the problem because (i) the awe one felt at the finely-tuned initial conditions of the universe is now transferred to the theory which produced those numbers automatically; (ii) inflation needs fine-tuning anyway; and (iii) the infinitely many universes produced by inflation suffer from the same problems as those in the original scheme. In any case physicists in the inflation industry seem to be pursuing metaphysics rather than physics, since the GUTs which are utilized in inflation are untestable in the laboratory, and inflation seems to be contradicted by some fundamental observations.

That brings us to further philosophical problems suffered by multiverse theories. The many universes are unobservable. Therefore the postulation of their existence is immune to empirical investigation, i.e. this is a metaphysical rather than scientific hypothesis.

Consideration of the bizarre nature of the universes which we are expected to believe exist in the ensemble further adds to the implausibility of the hypothesis. Furthermore as a 'catch-all' type of explanation they could potentially discourage scientific progress. Hard-nosed scientific naturalists should reject their existence.

One suggestion for a difference between a unique universe and a universe which is a member of an infinite ensemble is that the latter would not be expected to be more finely-tuned than is necessary for life. Ours seems to be vastly more special than required. Moreover the persistence of order in our universe is unexplained on the multiverse hypothesis.

Finally, even discounting the above, considerations of simplicity and economy would lead one to assign the existence of infinitely many universes a low prior probability compared with the existence of God. As shown in the previous chapter, a simple Bayesian analysis would then lead one to conclude that the probability that God exists given fine-tuning and other background knowledge is greater than the probability that a multiverse exists given the same evidence. This conclusion is vastly strengthened if the findings of the present chapter are also taken into consideration.[39]

## Notes

1 Ellis and Brundrit (1979).
2 Thus I ignore the other alternatives discussed in chapter 4, the temporal and other-dimensional MWTs of Gale's classification.
3 Sciama (1989), p. 111.
4 Davies (1992), pp. 204-205.
5 Barrow (2002), pp. 338-339.
6 Manson (2000).
7 McGrew, McGrew and Vestrup (2001), reproduced in Manson (ed.) (2003), pp. 200-208. In a footnote these authors also mention the possibility, to which I drew attention in chapter 4, of varying parameters simultaneously. I argued that, contra what McGrew *et al.* say here, a full analysis of the life-permitting region of parameter space is likely to show this to be of measure zero, thus lending even greater support to the fine-tuning argument.
8 Collins (2003).
9 Collins (forthcoming), preprint. Swinburne endorses a similar approach in Swinburne (2001), pp. 116-118. See my comment in Appendix B, note 10.
10 Collins was supported in debate by Alex Pruss, who also rejects the axiom of continuity, against the McGrews, who strongly favour it, at a symposium in 2003, the proceedings of which were kindly forwarded to me by chairman Neil Manson. These proceedings (including the paper referred to in the preceding note) have been submitted to *Philosophy of Science*.
11 Barrow and Tipler (1986), p. 411.
12 The shape of the brackets here indicates that the value 0 is to be excluded whereas the value $\rho_c$, and in the following paragraph $\rho_{max}$, is to be allowed. Nothing much hinges on this in this section, though the distinction is important in discussion of Jaynes's method (see Appendices B and E).
13 Evrard and Coles (1995).
14 Kirchner and Ellis (2003).
15 Koperski (forthcoming), preprint. I am grateful to the author for forwarding me this ahead of publication.
16 Collins and Hawking (1973).
17 Misner (1968).
18 McMullin (1993).
19 H. P. Robertson and A. G. Walker derived the metric, the generalized form of the distance between two points in space-time, for a homogenous isotropic universe, and showed that it was limited to three forms. The Belgian priest Abbé Georges-Henri Lemaître found expanding universe solutions to the Einstein equations, and outlined the earliest version of the Big Bang theory (though the actual name 'Big Bang' was coined much later by Fred Hoyle and was meant to be disparaging). The Russian meteorologist Alexander Friedmann

had also independently found expanding universe solutions, which he sent to Einstein who at first dismissed them as erroneous and physically uninteresting. The cosmological models which derive from the Einstein equations and the Robertson-Walker metric are variously referred to as Friedmann-Lemaître-Robertson-Walker (FLRW) or Friedmann-Robertson-Walker (FRW) or simply Robertson-Walker (RW) models.

20 Collins and Hawking (1973), p. 333.

21 Dicke (1961).

22 Cited by Collins and Hawking as B. D. Carter, Cambridge University preprint (1968), but eventually published as Carter (1974) in Longair (ed.) (1974), pp. 291-298; reprinted in Leslie (ed.) (1990a), pp. 125-133.

23 Earman (1987). Earman discusses a 1979 paper in which George Ellis postulates an infinite universe with many regions in different states of expansion and contraction and possessing different degrees of homogeneity and isotropy. Earman comments: 'But if the feature in question is unusual with a vengeance—measure zero—then the probability that it will be exhibited in some mini-world in the Ellis model is zero; ...' And, as we recall from chapter 4, advocates of the Everett view, including Carter himself, have not shown that that model gives the comprehensive range of parameter values required to overcome the measure zero problem either—though they often baldly assume otherwise.

24 See Kingman and Taylor (1966), p. 269, for further discussion of 'measure zero'.

25 Mathematicians speak quite comfortably about varying 'degrees' of infinity. Indeed such degrees of infinity can be defined in a precise and rigorous way. The 'lowest' level of infinity is 'countable' infinity. A set is countably infinite if its elements can be put into one-to-one correspondence with the natural numbers, 1, 2, 3, ... It turns out, rather counter-intuitively perhaps, that the rational numbers (fractions) can be put into such a one-to-one correspondence, but the real numbers (which include all non-recurring decimals like $\pi$ and $\sqrt{2}$ as well as the fractions) cannot. In a well-defined sense there are therefore the same 'number' of fractions as natural numbers but more reals than fractions or natural numbers—and, importantly for the present discussion, the natural numbers and fractions have measure zero on the space of reals.

26 NB consideration here of the countability of finite regions strengthens Earman's earlier point about measure zero sub-universes—see Earman (1987).

27 See Ramm (1955), pp. 133-134.

28 Dawkins (1989); this idea is often repeated in Dawkins's writings.

29 As argued for example by Hooykaas (1972); and by Jaki (1974).

30 Sciama (1989), p. 111.

31 See Vilenkin (1995a, 1995b).

32 Tegmark (1998), p. 5.

33 Bostrom (2002).

34 *Ibid.*, p. 57.

35 *Ibid.*, pp. 76-78.

36 Penrose (1989a), p. 354.

37 Davies (1982), p. 129.

38 This problem is recognized by Barrow in Barrow (2002), pp. 280-281, though he argues that the infinite number of different histories diverging into chaos may be less likely than those that remain law-like.

39 I am grateful to an anonymous referee for providing detailed and helpful comments on an earlier draft of the paper, Holder (2001a), on which this chapter is based.

# Chapter 8

# Inflation to the Rescue?

I'll fit any dog's leg that you hand me with inflation.

(William Unruh, as reported in *Science*, 30 August, 1996).

### Some Problems and their Solution

As I have indicated in earlier chapters, one suggestion for getting round the apparently finely-tuned initial conditions of our universe is to produce a better physical theory which either explains them or does away with them. Inflation is the only real current contender for such a theory, which perhaps explains why the theory has produced a booming economy of its own, with a seemingly exponential expansion in numbers of papers written on the subject!

There are in fact three problems with standard Big Bang cosmology which it is claimed are solved by inflation: the magnetic monopole problem (see below), and the flatness and horizon problems we have already met. We need to examine both the nature of the problems and the solution offered in a little more detail.

We have seen how physicists envisage that, as one traces the history of the universe back to its earliest moments, the forces of nature were unified. During the Planck era one requires a theory which combines quantum mechanics with gravity. Superstring/M-theory is the chief contender for this, but is currently unable to make testable predictions. Then, after $t > t_P \approx 10^{-43}$ secs, during the GUT era, the forces apart from gravity are supposed to be unified. As the temperature falls, to about $10^{29}$ K at time $t \approx 10^{-35}$ seconds after the Big Bang, the strong force and the electroweak force split apart in 'phase transitions' (the process is also referred to as 'symmetry breaking'). When the temperature has fallen much further still, to about $10^{15}$ K at time $10^{-10}$ seconds, the weak force and electromagnetism separate. But it is the much less theoretically and observationally secure GUT era which is important in the present context.

In areas of the universe which are causally separated, i.e. which have not had time to communicate through light rays, the phase transitions of the GUT era would proceed at different rates. The result would be regions with different symmetries, and 'topological defects', flaws in space somewhat analogous to imperfections in crystals, would form where the regions met. Magnetic monopoles are topologically stable knots which form in this way and are the simplest such defects. The problem is that there were originally something like $10^{80}$ distinct causally separate regions which subsequently coalesced to form our present observable universe; hence there should be something like $10^{80}$ magnetic monopoles for us to observe, about the same as the number of protons. Except that we would not be here to observe them, given the further problem that the mass of these monopoles is about $10^{16}$ times that of the proton! A universe with mass density so dominated by magnetic monopoles would have collapsed in only a few hundred years. The universe has of course not collapsed, but neither have any monopoles at all been detected. Inflation claims to solve the magnetic monopole problem because just one horizon volume, rather than the $10^{80}$ horizon volumes of the standard model, expands to embrace our presently observable universe. Thus inflation would provide at most one monopole in the visible universe, which probably we would never detect.

But is the monopole problem really a problem for the standard Big Bang model? It is certainly commonly supposed that it is, for example inflation theorist Andre Linde baldly states: 'According to the standard hot-universe theory, monopoles should appear at the very early stages of the universe, and they should now be as abundant as protons.'[1] This statement is, however, quite erroneous, as Roger Penrose has pointed out.[2] It is the GUTs which predict monopole production, not the standard Big Bang theory. The problem has therefore been imported into standard Big Bang cosmology along with the import of GUTs. So in this case inflation has merely solved a problem of its own making!

Martin Rees is aware of this and wryly comments: 'Skeptics about exotic physics might not be hugely impressed by a theoretical argument to explain the absence of particles that are themselves only hypothetical. Preventive medicine can readily seem 100 percent effective against a disease that doesn't exist!'.[3] As pointed out by Earman and Mosterin, this would be alright if the GUTs were themselves plausible on other grounds.[4] But in fact the GUTs are highly speculative and without experimental support, as I explained in chapter 2. They have been introduced as a kind of analogy to the much better experimentally attested electroweak unification. But since the energies at which the GUTs come into play are so high, $10^{13}$ times those achievable in the laboratory, the chances of experimental corroboration seem remote. Ledermann and Schramm, leading particle physicists, point out that to build an accelerator that achieves the energies required, with current technology, would require a machine 'so large as to stretch to the nearby stars'.[5]

As Earman and Mosterin point out, the usual conclusion here would be to cast doubt on the GUTs: 'But if you are committed to the GUTs, you have a problem: the monopole problem.'[6] If inflation solves the monopole problem, that merely shows that the theory is internally consistent, but 'other things being equal there is no sufficient reason to take the absence of monopoles as evidence for inflation rather than as evidence against GUTs.'[7] Things would only change, say Earman and Mosterin, both if there were some independent reason for believing in GUTs, and if the only way then to solve the monopole problem would be to invoke inflation. Neither condition seems to be satisfied at the present time.

In contrast to the monopole problem, when it comes to the horizon problem we are undoubtedly dealing with a question thrown up by the standard Big Bang model itself. Indeed this problem had been identified long before inflation was thought of. The high degree of isotropy of the universe today apparently points to very special conditions at the earliest time we can sensibly speak of.

The first thing to note, however, is that this is not an *empirical* problem for standard Big Bang cosmology. It does not concern any prediction made by the theory which has been contradicted by observation.[8] And, as Earman and Mosterin point out, it is just not the case that standard Big Bang cosmology fails to explain the isotropy of the universe: it simply does so on the basis of, admittedly very special, initial conditions. But to explain the current state of any physical system by applying the laws of physics to initial conditions is to provide a perfectly normal kind of scientific explanation. What is at stake, therefore, concerns the style of explanation offered rather than empirical adequacy. Cosmologists seem unwilling to take initial conditions at the beginning of the universe as given (cf. McMullin's 'indifference principle'). Is this perhaps because they fear to face the embarrassing question, 'Given by whom?'

Earman and Mosterin make the further criticism that, even on its own terms, inflation has not shown that it actually solves the horizon problem. They note that the problem should really be called a 'uniformity problem', since what is required is a mechanism for smoothing out non-uniformities near the Big Bang. Inflation can ensure that there is no longer causal separation, but substantial overlap, between regions which grow into our present observable universe, but it still needs to demonstrate that smoothing occurs. This it has so far failed to do (see below).

The case of the flatness problem is similar. It is sometimes inaccurately claimed that standard Big Bang cosmology fails to explain why the density parameter $\Omega$ is very nearly 1 at earliest times. In fact, for all three types of solution to Einstein's equations mentioned earlier—i.e. the open, closed and flat Friedmann-Lemaître-Robertson-Walker (FLRW) models of the last chapter (and Appendix E)—$\Omega$ tends to 1 as time $t$ tends to zero.[9] More accurately, as we have seen, for compatibility with present observations, $\Omega$ at the Planck time needs to be equal to 1 to an accuracy of about 1 part in $10^{60}$. So the problem is of exactly the same kind as that for the horizon problem—special initial conditions are required for the universe to evolve the way it has up to the present. The flatness problem is, therefore, equally one of style of explanation and not of empirical adequacy. I examined an attempt to solve the 'problem' by invoking the Principle of Maximum Entropy in Appendix E, noting my sceptical conclusions in chapter 7. Inflation's solution is to provide a mechanism which drives $\Omega$ towards 1. As a result, inflation actually makes the prediction that $\Omega_0 \approx 1$.

The horizon and flatness problems are inextricably linked, a fact which inflation theorists originally thought a good thing. If there is enough inflation to solve the horizon problem, then the universe will be very close to flatness today. A major problem is that the universe actually appears open today (i.e. $\Omega_0 < 1$), and if that is the case, there cannot have been enough inflation to solve the horizon problem![10] What is surprising is that inflation theorists do not seem fazed by this, and are quite happy to drop their one fundamental prediction, namely $\Omega_0 \approx 1$. We return to the question of observational support for inflation below, since the most recent observations may provide somewhat more encouragement for inflation theorists (though even this statement needs qualification, as we shall see).

Returning to the horizon problem for a moment, this problem is solved by inflation by pushing non-uniformities beyond the horizon. This means of course that they can reappear at some time in the future, as follows. According to inflationary theory, the tiny region which at $10^{-35}$ seconds expanded exponentially to produce our present observable universe was much smaller than a horizon distance ($= c \times 10^{-35} \approx 3 \times 10^{-25}$ cm, where $c$ is the velocity of light) at that time. Hence the universe had plenty of time to come to a uniform temperature. But if you go far enough outside that original tiny region, beyond the horizon, you clearly get to other regions which are causally separate. If these regions are at the same temperature, that means you have special initial conditions, which inflation was designed to explain. If they are at different temperatures, they will eventually impinge on each other to give non-uniformities. But the question then arises, 'Why do we perceive uniformity at our point in space-time, whereas there will be other points which do not?'. The answer is again down to initial conditions, which seem inescapable on either model.

It is also not clear that inflation actually provides a mechanism for smoothing out non-uniformities within a causally connected region as is generally claimed. To show this requires the consideration of inhomogeneous and non-isotropic solutions to Einstein's equations. It is then required to demonstrate that a positive cosmological constant (which is supposedly what drives inflation) gives rise to exponential expansion, and that the expansion smooths away non-uniformities. It would appear that some solutions do this, but that it is not the case in general: 'the results proven to date do not support the idea that in a generic expanding universe the presence of a positive cosmological constant will produce exponential expansion, which in turn will smooth away all non-uniformities' (Earman and Mosterin). Besides which the theory does not even guarantee the positive cosmological constant required to power the expansion![11]

To Roger Penrose this is, in any case, all demanding far too much.[12] It is logically impossible that generic non-uniformities must inevitably be smoothed by inflation, essentially because a present uniform state is highly *non*-generic and improbable—and because measure is preserved with time as the system evolves (deterministically) according to the Einstein equations, a point which comes up in my Appendix E. According to the second law of thermodynamics, as we saw in chapter 3, it is vastly more likely that the universe be in a non-uniform (high entropy) state. Realistically (in contrast to the idealized FLRW representation) there is a fundamental asymmetry: the universe begins in a highly non-generic low-entropy big bang singularity and ends at a generic high-entropy big crunch singularity. Thus, argues Penrose, the whole idea of inflation is misconceived, and the theory is in the same position as the older chaotic cosmology.[13]

The reader will recall my discussion of how Collins and Hawking demolished chaotic cosmology by showing that the measure of the set of asymptotically isotropic cosmological models is zero. I have argued that this poses very severe problems for those who wish to deny design, including of course advocates of a multiverse. If inflation is to be the solution of the horizon problem, then a similar treatment of measure is required to show that inflation might actually be probable. Ideally one would be looking for a proof that the set of models which do not inflate is of measure zero. Unfortunately, Hawking and Page have shown that, when an appropriate inflation-driving scalar field (called an 'inflaton' field) is included in the standard FLRW cosmological models, whilst indeed the measure of the set of models which inflate is infinite, nevertheless so is that of the set which do not inflate![14] To move from a result like this to actual probabilities is highly speculative for reasons we have discussed earlier (there would seem to be conflicting ways of assigning probabilities), although this has not prevented other authors from attempting to get probability estimates. Earman and Mosterin again: 'We conclude that even within the restricted class of homogeneous and isotropic cosmologies, inflationary cosmologists have not been able to establish, without allying themselves with highly speculative hypotheses, that the presence of a scalar inflaton field makes it objectively highly probable that the universe will inflate in such a way that the perceived explanatory inadequacies with the standard Big Bang model are overcome.'[15]

Earman and Mosterin give a simple Bayesian comparison of inflationary and standard Big Bang cosmologies. Supposing that inflation drives $\Omega$ to 1, it will be the case that a wider range of values of $\Omega_P$, $\Omega$ at the Planck time, will lead to $\Omega_0 \approx 1$ than for the standard Big Bang, where we have seen that $\Omega_P$ must be right to about 1 part in $10^{60}$. But it is more likely that $\Omega_P$ belongs to a wide range than to a narrow range.[16] It follows that a particular range now is more likely on the basis of inflation than on the standard Big Bang, i.e., for any $\delta$,

$$P[1 - \delta < \Omega_0 < 1 + \delta \mid \text{Inflation}] > P[1 - \delta < \Omega_0 < 1 + \delta \mid \text{Standard Big Bang}]. \quad (1)$$

If the prior probabilities $P$[Inflation] and $P$[Standard Big Bang] are comparable, then it follows that

$$P[\text{Inflation} \mid 1 - \delta < \Omega_0 < 1 + \delta] > P[\text{Standard Big Bang} \mid 1 - \delta < \Omega_0 < 1 + \delta].$$

One might want to question whether the priors really are comparable, given the complexities of inflation, and seeming conflicts with observation. However, Earman and Mosterin make another point, namely that in reality $\Omega_0$ takes just one value and hence $\Omega_P$ takes just one value in either theory. Instead of the inequality (1) we would then have an equality, thereby removing the explanatory advantage of inflation, and making the comparison solely dependent on the priors.

**A Brief History of Inflation**

We have already seen that inflation is problematic in its claims. In fact, even if it solves the flatness and horizon 'problems', inflation does this at the expense of introducing problems of its own. In this section, we briefly consider the development of inflation, beginning with Guth's original model.

First, the model needs fine-tuning! Guth's model, and subsequent variants, rely on a choice among GUTs. These GUTs contain unknown parameters. As we have seen, the energy régime at which the GUTs apply is beyond that achievable in the laboratory, making it extremely difficult to choose between theories and to determine the parameters. Inflation gives rise to bubbles of the new phase of matter, in which the forces are differentiated, surrounded by the old phase in which the forces are still united (just like bubbles of steam in boiling water). In the original model the rate of bubble formation depends very sensitively on these unknown GUT parameters and it is assumed that the rate of bubble formation is very low.

A far worse problem than the need for fine-tuning is the 'graceful exit problem', which leads to a fundamental conflict with observation. This concerns 'the difficulty of finding a smooth ending to the period of exponential expansion'.[17] This is because the energy in the bubbles is stored in the bubble walls and can only be released to fuel particle creation through many collisions of large bubbles. Unfortunately what happens, as pointed out by Stephen Hawking and others, is that the expansion speed is such that the bubbles remain in finite clusters in the expansion, rather than 'percolate' to form an infinite region. The result is that the universe is intolerably inhomogeneous and there is no mechanism for particle creation to start the Big Bang proper.

Andrei Linde[18] (and independently Andreas Albrecht and Paul Steinhardt[19]) realized that the graceful exit problem could be solved if the bubbles were so big that our universe is contained in a single bubble. This could be achieved by slower symmetry breaking. However, this model, known as the 'new inflationary universe', also needed fine-tuning! The 'slow roll-over' transition again depends on a special choice of parameters to achieve the required energy density function.

The new inflationary universe also had a serious problem pointed out by Hawking, namely that the bubble would have to be bigger than the universe at the time.[20] Although this problem could in turn be resolved, a further one concerning too great variations in the temperature of the microwave background could not, and doubts were also raised about the kinds of phase transition required. And all this in addition to the model's need for fine-tuning![21]

Linde's 1983 'chaotic inflationary model'[22] seems to get round these problems by requiring no dubious phase transitions and it can also give satisfactory predictions for the microwave background temperature fluctuations.[23] It is chaotic because it starts from a random initial distribution of scalar fields.[24] These scalar fields determine the different modes of symmetry breaking (and hence different-looking laws of physics) in different domains. In this way we end up with a 'cluster of causally disconnected mini-universes' with (supposedly) every sort of universe existing somewhere, i.e. we are back to a many-worlds type of scenario. Our type of universe will arise for particular choices of scalar field $\phi$.

In superstring theories, which as we saw in chapter 2 pertain to the first $10^{-43}$ seconds of the universe and remain highly speculative, the strings vibrate in more than the three dimensions that we experience, but these extra dimensions get compactified so as to be undetectable. Linde speculates that compactification may lead to a variety of space-time dimensions in his mini-universes.

Inflation has developed into a quite massive industry, with many papers being produced—far too many, Alan Guth admits, even for him to keep up with (over 2000 between 1987 and 1997)![25] Guth says that at least 50 varieties of inflation had been produced by 1997 and he lists double, triple and hybrid inflation, mutated hybrid inflation, hyperextended inflation, and inflation that is gravity driven, spin driven, string driven, and vector field driven. He and a colleague came up with 'supernatural inflation' only to find that the term had already been used twice before! This protean tendency has continued unabated to the present day. Writing in 2003, Paul Shellard lists 111 inflationary models, noting, I suspect with tongue in cheek, that 'The most difficult model to rule out may well be supernatural inflation'![26]

All this is perhaps surprising when the observational evidence is lacking and the GUTs remain speculative hypotheses virtually untestable in the laboratory. In practice it seems that nothing is sacred. General relativity is ditched in some versions, and the link with particle physics abandoned through the use of arbitrary inflaton fields no longer linked to GUTs. Peebles's comment that 'the inflationary universe allows the imagination to roam free' would seem to be amply borne out.[27] Even so, it seems that fine-tuning is unavoidable. As Guth notes, even the standard model of particle physics needs the input of arbitrary parameters to ensure that the results come out right. For example, the ratio of 160,000:1 for the $W^+$ particle mass to the electron mass, and the ratio of $10^{36}$:1 for the gravitational force to the electrostatic force between two protons, are both rigged.[28] We simply don't understand why the electron is so light or gravity so weak, but Guth expresses the pious hope that 'the correct fundamental theory, when it is finally understood, will lead naturally to an inflaton field with the right energy density diagram, along with an explanation of the other parameters, such as the mass of the electron and the strength of gravity'.

The fine-tuning required by inflationary models is a serious drawback since inflation was meant to explain fine-tuning! Even Linde's chaotic 'eternal inflation' requires very specific, though highly speculative, assumptions about the physics which applies at extreme densities. And the solution offered to the problem as to why our universe is as it is seems remarkably like the anthropic argument we have already met in our original discussion of the flatness problem. Only if inflation occurs can we be here; inflation occurs in regions where the $\phi$ field is slowly varying; and such regions must occur somewhere in an infinite universe. But of course all this does is get us back to the position we were in before inflation was thought of! Indeed Barrow and Tipler make just this point, and it is worth quoting them at length:

> After all, if we wish to appeal to a particular property occurring inevitably in a random initial state, why should we bother conjuring up the $\phi \approx$ constant state necessary for inflation to occur? Why not argue that in a chaotically random, infinite initial data set there *must* exist a large, virtually homogeneous and isotropic region, expanding sufficiently close to flatness ($\Omega_0 = 1$) so that after fifteen billion years it looks like our universe? In fact, special initial data of this type must arise infinitely often in causally disjoint portions of an infinite random initial data set. If we argue that life can only evolve in causal futures of these special initial data sets we have no need to invoke inflation or any further theory of cosmology at all: all is statistics.[29]

But we have seen that even if all is statistics, the statistics may not work in favour of many universe (multiverse) proponents. We still need to ask what is the measure of the set of inflating mini-universes in which the parameters are right for life. It would appear that my point about the set of realized universes above a given size being of measure zero applies equally well to Linde's chaotically produced universes as to the original Ellis and Brundrit scheme (see next chapter).

## Observational Problems with Inflation

An important question to ask is, 'How does inflation fare with regard to its experimental or observational consequences?' One major problem, as noted in chapter 2, is that most GUTs predict that the proton is unstable, in particular the earliest and simplest GUT predicting a half life of between $10^{27}$ and $10^{31}$ years. This is one of the few tangible predictions of GUTs but proton decay is immensely difficult to detect. As Guth himself notes, the evidence is against proton instability, with one experiment reporting no certifiable decays, implying that the half life must be at least $2 \times 10^{32}$ years.[30]

A supposed success of inflation is that it provides an explanation for the density perturbations which are necessary for galaxies to form by gravitational collapse—if the density were totally uniform, galaxy formation would be impossible. Density perturbations give rise to temperature perturbations (non-uniformities), 'frozen in' from very early in the universe's history ($t \sim 300{,}000$ years), in the microwave background radiation. Such perturbations have indeed been detected by the COBE ('Cosmic Background Explorer') satellite. But certainly a major problem for the original inflationary scheme was that the predicted magnitude of the density fluctuations was far too great.

It would seem that these problems can be circumvented by severing the link between cosmology and particle physics and imposing arbitrary inflaton fields, but this seems a very high price to pay, and abandons a major motivation for introducing inflation in the first place. Guth admits as much when he writes: 'It must be admitted that the ad hoc addition of such a field makes the theory look a bit contrived. To be honest, a theory of this sort *is* contrived, with the goal of arranging for the density perturbations to come out right. We still appear to be a long way from pinning down the details of the particle physics that underlies inflation.'[31]

Another major problem involves a *prima facie* conflict with some quite well-established results in astrophysics. Because inflation predicts that $\Omega_0 = 1$, it therefore seems to yield a value for the age of the universe of only about 8 billion years.[32] This is inconsistent with models of stellar evolution. In particular, there are globular clusters (galaxies of a particular kind) which are believed to be up to 15 billion years old.

Current best estimates of $\Omega_0$ come out at about 0.3.[33] Even so, the bulk of the contribution to $\Omega_0$ is from so-called dark matter whose identity is uncertain. The main reason for believing in such invisible matter is that stars in the outer regions of spiral galaxies like our own seem to be moving too fast for consistency with estimates of mass in the galaxies based on visible matter alone.

It is only theory which might lead one to expect $\Omega_0 \sim 1$,[34] and even then some aspects of Big Bang theory imply a low value of $\Omega_0$. Thus nucleosynthesis calculations of light element abundances yield a constraint on $\Omega_0$ of $0.011 \leq \Omega_0 \leq 0.11$, although they would be consistent with a higher value if the dark matter, as postulated, is non-baryonic in form (a number of hypothetical exotic particles have been suggested as candidates).

## Einstein's Biggest Blunder

It is possible that inferences from recent observations of supernovae in very distant galaxies might modify the above. These seem to be further away than their redshifts would indicate.[35] One possible interpretation of this is that the expansion of the universe is accelerating with time, indicating a positive cosmological constant $\Lambda$. To recap from chapter 3, this is essentially a repulsive force originally introduced by Einstein into his field equations of general relativity in order to give a static universe, but subsequently abandoned when the expansion of the universe was discovered by Hubble. Einstein regarded the addition of the $\Lambda$ term as his biggest blunder, since by omitting it he could have predicted the cosmic expansion ahead of Hubble's discovery.

In Appendix E I wrote down the Friedmann equation of cosmology, which is derived by applying Einstein's equations to an idealized homogeneous and isotropic universe, first for the case without $\Lambda$, and then including $\Lambda$. Until recently physicists had assumed that $\Lambda$ was zero, and even the present observations constrain it to be very small. Positive $\Lambda$ would make an effective contribution $\rho_\Lambda$ to the total energy density of the universe $\rho_u$, which can be written $\rho_u = \rho + \rho_\Lambda$.

On division by the critical density $\rho_c$, $\rho_\Lambda$ translates into an additional contribution $\Omega_{\Lambda 0}$ to the current energy density parameter $\Omega_0$. The observations show that $\Omega_{\Lambda 0} \sim 0.6$, and adding this to the matter contribution $\Omega_{\rho 0} \sim 0.3$ might therefore just be consistent with flat space ($\Omega_0 = \Omega_{\rho 0} + \Omega_{\Lambda 0} = 1$); such a value of $\Lambda$ would also increase the age of the universe.[36]

Even if a small value of $\Lambda$ is confirmed, however, physicists are left with a serious problem. They believe that it is the energy density of the quantum vacuum which gives rise to $\Lambda$, and, as noted above, that $\Lambda$ in turn powers inflation. This is because, paradoxical as it may seem, the pressure associated with the (positive) vacuum energy density is negative.[37] Unfortunately, as we saw in chapter 3, the calculated magnitude of $\Lambda$ is $10^{120}$ times greater than is compatible with observation (and with a life-producing universe for reasons similar to other cases of fine-tuning). Lawrence Krauss describes what would happen if $\Lambda$ were to take the calculated value: 'If the constant were as large as quantum theory naively suggests, the space between your eyes and your hand would expand so rapidly that the light from your hand would never reach your eyes.'[38] As it is we can see not just to the ends of our arms but to the farthest reaches of the universe. Krauss is in agreement with many other cosmologists that this gigantic mismatch of theory and observation is the most perplexing puzzle in physics today.

It would seem that the enormous value of $\Lambda$ due to the quantum vacuum energy must almost exactly cancel the $\Lambda$ term introduced for the wrong reason by Einstein, (the two differing only when we reach the 120th significant figure). Thus a small value of total $\Lambda$ (quantum plus Einstein) would represent yet another example of ultra-fine-tuning. The cancellation of the two terms to such remarkable accuracy constitutes 'the cosmological constant problem'.

In a seminal paper, Steven Weinberg applied the Weak Anthropic Principle, coupled with the idea that there might be subregions or eras of the universe (effectively amounting to distinct universes) with differing values of $\Lambda$, to explain the value $\Lambda$ actually takes in our universe.[39] We can only exist in a universe in which $\Lambda$ is small enough to allow galaxies to form. If $\Lambda$ is too large the exponential expansion will interfere with the formation of gravitational condensations. Now galaxies were starting to form at a redshift $z_g \approx 4$,[40] at which time the density of matter $\rho_g$ was larger than today's value $\rho_0$ by a factor of $(1 + z_g)^3 \approx 125$. Weinberg argued that the cosmological constant contribution to energy density, $\rho_\Lambda$, would not interfere with galaxy formation if $\rho_\Lambda < \rho_g \approx 125\ \rho_0$. This in turn implies an upper limit for $\Omega_{\Lambda 0}$ equal to about $125\ \Omega_{\rho 0}$.[41] There being no anthropic reason for $\Omega_{\Lambda 0}$ to be very small Weinberg estimated the likely observed range of $\Omega_{\Lambda 0}$ as $\Omega_{\Lambda 0} \sim (10\text{-}100)\ \Omega_{\rho 0}$.

An important question, analogous to that we considered for initial entropy, is, 'Is the observed value of $\Lambda$ too special to be explained as arising from random selection among an ensemble of universes?' The latest observations referred to above would seem to indicate that $\Omega_{\Lambda 0} \sim 2\ \Omega_{\rho 0}$. This is lower than Weinberg's lower bound, but perhaps not hugely so. We are certainly at liberty to opt for the theistic explanation for this remarkable fine-tuning, as against many universes with the attendant problems thereof which we have discussed elsewhere. Moreover, in the case of the order in the universe, there would seem to be good reason for God to create a totally ordered cosmos, rather than one with just sufficient order for life. The reason for God choosing a value of $\Omega_{\Lambda 0}$ in the range $0 < \Omega_{\Lambda 0} < 10\ \Omega_{\rho 0}$ as opposed to a value in the range

(10-100) $\Omega_{\rho 0}$, given that either would be conducive to life in the universe, is arguably less clear.

Weinberg has returned to this topic in a more recent paper, and attempted a more detailed calculation.[42] First he notes that the average value of $\Omega_{\Lambda 0}$ is a better estimate of what we are likely to observe in our sub-universe than the upper bound. This is an example of what Vilenkin has dubbed the 'principle of mediocrity'[43] and is analogous to Sciama's view that our universe should not be 'too special' on the many universes hypothesis (as we noted in the last chapter). But, so argues Weinberg, the average value of $\rho_\Lambda$ is likely to be comparable, not with $\rho_g$, but with $\rho$ at the later time (lower redshift) when accretion of matter by growing galaxies is occurring at the greatest rate. He then uses a slightly more sophisticated model of galaxy formation than in the previous paper in an illustrative calculation of the probability distribution for $\rho_\Lambda$. This is essentially the posterior distribution given that observers exist. Weinberg's Bayesian analysis assumes that the probability of there being observers given a certain value of $\rho_\Lambda$ is proportional to the number of condensations produced based on the galaxy formation model. He further assumes that the *prior* probability distribution for $\rho_\Lambda$ is flat (since $\rho_\Lambda$ can in principle take values enormously large compared with the range for which condensations are possible), and therefore drops out of the equation. The end result is that, even if core collapse for most galaxies occurs as late as $z \approx 1$, the mean value of $\rho_\Lambda$ is still greater than 10 $\rho_0$, which he acknowledges exceeds current experimental bounds on $\rho_\Lambda$.

Not all cosmologists accept the 'cosmological constant' explanation for the acceleration. An alternative is that the universe is filled with some mysterious fluid labelled 'quintessence' which exerts negative pressure.[44] The name is taken from the fifth element in ancient philosophy, of which the celestial bodies were supposedly comprised, and which was latent in all things. The modern idea is to avoid the fine-tuning required of $\Lambda$ by having the energy density of quintessence vary with time, rather than stay constant as the vacuum energy density would. In a sense, then, quintessence is a more general form of dark energy than vacuum energy, since there is more flexibility in the way it can evolve. But then, it seems to me that, in this instance as elsewhere, the removal of fine-tuning has been bought at a price—lack of simplicity and the introduction of mysterious hypothetical substances which seem cooked up to give just the answer one wants.

The supernova observations are in any case not clear cut. There may be intervening galactic dust responsible for making the images weaker, and we are also unsure that we are observing stars of the same nature as nearer ones which explode as supernovae. Hence $\Lambda$ (or the amount of quintessence) may actually be zero after all, as many cosmologists still believe, leaving us with $\Omega_0 \approx 0.3$. An alternative strategy then adopted by inflationary theorists is to abandon one of the chief predictions of inflationary theory, namely flatness, and opt for 'open inflation'.[45] Again, open inflation depends on a particular choice of potential energy function in order to give a slightly curved, rather than strictly flat, space.

The problem is that none of these latest findings of either observation or theory can be regarded as definitive. Research in this area is intense and ongoing, and data from a variety of sources is coming in and being analysed. Results from the balloon-borne telescope BOOMERANG were analysed by Melchiorri and colleagues.[46] These authors claimed to constrain total $\Omega_0$ (including matter and cosmological constant contributions) to the range $0.85 < \Omega_0 < 1.25$ at the 68% confidence level. This would be consistent with flat space. Data from NASA's Wilkinson Microwave Anisotropy Probe (WMAP), when combined with other data, seemed to support the breakdown $\Omega_{\rho 0} \sim 0.3$, comprising 0.05 baryonic and 0.25 dark matter components, and $\Omega_{\Lambda 0} \sim 0.7$.[47] This flat cosmology is coming to be regarded as the standard cosmological model, called the concordance model. However, recent observations from the European Space Agency's X-ray observatory XMM-Newton cast doubt on the existence of dark energy at all.[48] And Blanchard and colleagues argue that the WMAP data can even be made consistent with $\Omega_{\rho 0} = 1$ and $\Omega_{\Lambda 0} = 0$, though there seem to be other problems with their model.[49] Yet other authors believe that the presence of hot intergalactic gas in superclusters could distort the microwave background spectrum and so seriously affect the WMAP model fits.[50] All one can say is that the situation is still very fluid!

## Summary

Having examined inflation now in some detail, we can see that it is far from the all-embracing solution to cosmology's problems that we were led to expect. The chief problems were in any case not of an empirical nature, but concerned the desire to extend the realm of scientific explanations from the consequences of physical laws operating on initial conditions to the initial conditions themselves. The attempt to remove the need for special initial conditions, and thereby to deny design, is rationalized via the indifference principle, and has led to a vast amount of theorizing, much of it quite ad hoc and contrived, to achieve the desired results.

It would seem, however, that inflation itself needs fine-tuning to work! When it is shown not to work, almost any modifications can be accepted to retrieve it. In the process, the connection with real particle physics is severed as arbitrary inflaton fields are postulated. Conflict with observation is removed, if need be, by abandoning the one characteristic prediction, namely flatness. As Earman and Mosterin point out, all this makes it extremely difficult to falsify the theory,[51] since it just adapts, chameleon like, to whatever the observational environment can throw at it. Inflation seems to have a life of its own, floating loose from the moorings of observation and experiment. It has not even been shown that inflation is probable from generic initial conditions. A suggested way round this is to postulate an infinite universe with lots of randomly chosen variants of an inflaton field, which are supposedly bound to give rise statistically to some inflating regions with life. But then we respond: (a) that was just what the original suggestion of regions of varying density did before inflation was invented, so nothing new is achieved; and (b) this means that all the problems associated with the multiverse hypothesis resurface, including that of measure (see next chapter).

It would seem that the scientific naturalist is driven, even if he is an inflationist, towards many universes, and to this topic we now return.

## Notes

1 Linde (1987), p. 61.
2 Penrose (1989b).
3 Rees (1997), p. 185.
4 Earman and Mosterin (1999), p. 17.
5 Ledermann and Schramm (1995), p. 160. However, GUTs do make some testable predictions, e.g. proton decay (see later).
6 Earman and Mosterin (1999), p. 15.
7 *Ibid.*, p. 17.
8 Guth himself recognizes this: 'The horizon problem is not a failure of the standard Big Bang theory in the strict sense, since it is neither an internal contradiction nor an inconsistency between theory and observation'—Guth (1997), p. 184.
9 In the flat case (curvature parameter $k = 0$) $\Omega$ is always 1; in the open case ($k = -1$) $\Omega$ starts from 1 and tends to 0 as both $t$ and $R$ tend to infinity; and in the closed case ($k = +1$) $\Omega$ starts from 1 and tends to infinity as $R$ tends to its maximum value (where $dR/dt = 0$), and then tends back to 1 as $R$ again tends to 0. These facts are all derivable from the Friedmann equation given in Appendix E; see note 19 of chapter 7 for FLRW terminology.
10 Earman and Mosterin (1999), p. 25.
11 *Ibid.*, p. 30.
12 Penrose (1986).
13 Penrose (1989b), p. 263.
14 Hawking and Page (1987).
15 Earman and Mosterin (1999), p. 34.
16 If $\alpha < \beta$, then $\Omega_P \in (1 - \alpha, 1 + \alpha) \rightarrow \Omega_P \in (1 - \beta, 1 + \beta)$. Note that the symbol '$\in$' here denotes 'belongs' to the interval, so that $\Omega_P \in (1 - \beta, 1 + \beta)$ is equivalent to $1 - \beta < \Omega_P < 1 + \beta$. It follows from the axioms of probability theory that $P[\Omega_P \in (1 - \beta, 1 + \beta)] \geq P[\Omega_P \in (1 - \alpha, 1 + \alpha)]$ (see Appendix A, theorem (T3)). As Earman and Mosterin note, for any reasonable prior, the inequality will be strict.
17 Guth (1981).
18 Linde (1982).
19 Albrecht and Steinhardt (1982).
20 Hawking (1988), p. 131.
21 Guth and Steinhardt (1984); McMullin (1993), p. 385; Leslie (1989), pp. 29-33.
22 Linde (1987).
23 Hawking (1988), p. 132.
24 McMullin (1993), p. 385.
25 Guth (1997), p. 277.
26 Shellard (2003), p. 764.
27 In Bartusiak (1986); quoted in Earman and Mosterin (1999), p. 36.
28 Guth (1997), pp. 238-239.

29 Barrow and Tipler (1986), p. 437.
30 Guth (1997), p. 238.
31 *Ibid.*, p. 238.
32 *Ibid.*, p. 53.
33 Krauss (1999).
34 Coles (1998).
35 Perlmutter *et al.* (1999); Hogan, Kirshner and Suntzeff (1999).
36 Krauss (1999), p. 36.
37 Martin Rees provides a simple, accessible explanation for this (Rees 2001, p. 192). Suppose a gas of normal matter in a tube expands by pushing outwards on a piston. The gas will cool, thereby losing energy. On the other hand, if a vacuum expands more energy would be created; hence the piston would need to be *pulled* out to achieve this, just as if it were working against a tension or negative pressure.
38 Krauss (1999), p. 37.
39 Weinberg (1989).
40 Redshift denotes the observed change in wavelength of light emitted from a receding source, and is commonly used by cosmologists to measure cosmological epoch. Light received from objects at redshift $z$ was emitted when the universe was $1/(1 + z)$ times its present size. It was by observing the redshifts of distant galaxies that Hubble discovered the cosmic expansion.
41 Remember $\Lambda$ and $\rho_\Lambda$ are constant, unlike the matter contributions which vary with time; $\Omega_\Lambda$, being $\rho_\Lambda$ divided by the critical density, does vary with time—hence the need for the suffix 0 in $\Omega_{\Lambda 0}$ to denote the present value.
42 Weinberg (1996).
43 Vilenkin (1995a, 1995b).
44 Perlmutter *et al.* (1999); Caldwell and Steinhardt (2000).
45 Bucher and Spergel (1999).
46 Melchiorri *et al.* (1999). See also de Bernardis *et al.* (2000).
47 Spergel *et al.* (2003).
48 Vauclair, Blanchard, *et al.* (2003).
49 Blanchard *et al.* (2003).
50 Myers, Shanks, *et al.* (2004).
51 Earman and Mosterin (1999), p. 39.

## Chapter 9

# The Realization of Infinitely Many Universes in Cosmology

'Can you do addition?' the White Queen asked. 'What's one and one and one and one and one and one and one and one and one and one?' 'I don't know,' said Alice. 'I lost count.'

(Lewis Carroll, *Through the Looking Glass*, combined volume with *Alice's Adventures in Wonderland*, Puffin1962, p. 321.)

### Introduction

In this chapter I show that, for certain classes of cosmological model which either postulate or give rise to a multiverse, only a measure zero subset of the set of possible universes above a given size can be physically realized. It follows that claims to explain the fine-tuning of our universe on the basis of these models by appeal to the existence of all possible universes fail.

We have seen in preceding chapters that there is a widespread consensus that modern cosmology has demonstrated that the universe which we inhabit is remarkably finely-tuned for life.[1] This fact has prompted renewed interest in theological arguments from design.[2] A counter-strategy often adopted by those who wish to deny design has been to postulate the existence of many universes in which the constants of nature, and/or the initial conditions, are chosen randomly for each. Whilst some authors seem to think that 'vastly many' universes will do the trick,[3] others are drawn to postulate an infinite ensemble 'characterized by all conceivable combinations of initial conditions and fundamental constants'.[4] Although I took issue with the claim in chapter 6, perhaps an infinite and exhaustive ensemble is in a sense simpler than some limited number after all. Be that as it may, we are then not supposed to be surprised to find ourselves in our particular member of the infinite ensemble of all possible universes, since we could only exist in a universe very like ours. The existence of all possible universes is taken to explain ours by the simple maxim, 'Everything that can happen will happen, somewhere sometime.'

We have already noted a number of criticisms of the multiverse hypothesis. These criticisms range from the scientific to the philosophical and metaphysical. For example, on the scientific side it would appear that physical parameters have to be special in order for there to be a multiverse in the first place, and that there would seem to be 'too much order', in a well-defined sense, in our universe. Philosophical criticisms include those such as the argument of Swinburne and others that the hypothesis (even of an exhaustive infinity of universes) is not simple, and is therefore of low prior probability, especially when compared with theism. A metaphysical criticism would be the non-observability, even in principle, of other universes.

Another criticism of a philosophical kind which we have encountered is that the hypothesis does not raise the probability that *this* universe is fine-tuned.[5] We have seen that a Bayesian analysis vindicates the view that the existence of many universes can explain the fine-tuning of this one, though the arguments adduced so far work to reduce the explanatory power of the hypothesis.

In this chapter I describe what I believe to be a flaw in two versions of the infinitely many universes hypothesis. The argument is straightforward, relying on a simple mathematical property of the real line, and relates to the question as to whether the models in question can indeed be exhaustive. It reduces further the explanatory power of these models.

## The Realization of Infinitely Many Universes

We have seen (see chapter 4) that there are a number of ways in which a multiverse, comprising an ensemble of infinitely many universes, might be conceived to arise. To recap, again utilizing George Gale's useful classification of what he terms multi-world theories (MWTs),[6] these are:

(1) 'Spatial MWTs', in which the many universes are envisaged as the simultaneous existence of infinitely many regions (sub-universes) in a single encompassing space. We have seen that a scenario in which infinitely many universes arise this way was suggested by George Ellis in the 1970s,[7] though a more popular scenario today is likely to be one in which the universes comprise bubble domains within an overall inflationary universe.

(2) 'Temporal MWTs', in which the many universes arise as consecutive 'bounces' of a single, oscillating 'closed' space-time. John Wheeler has speculated that the various constants of nature and initial conditions could be randomly recycled at each bounce.[8]

(3) 'Other-dimensional MWTs', in which the universes do not even belong to our space-time, but have become disconnected from it. Possible mechanisms for this include the infinitely multiple branching of worlds associated with Hugh Everett's many worlds interpretation of quantum mechanics, and the topological separation of 'baby' universes from ours at singularities, as discussed by Stephen Hawking[9] (though now discounted by him) and Alan Guth.[10]

My critique relates only to the first two of these categories. However, I also observed that McMullin makes the bold claim, tantalizing because he adduces no evidence, that MWTs based on Everett's branching worlds theory 'do not provide the range of alternative initial cosmic conditions or alternative physical laws that this version of an anthropic explanation of the initial parameter constraint would require.'[11] Further exploration of this point (and of the same point for 'baby' universes as well) would be welcome—indeed, as I noted in chapter 4, the burden of proof is surely with those advocating these models.

My critique of (1) and (2), then, arises from the following fundamental, yet trivial theorem: if the real line is divided into finite intervals of given minimum length, then there are at most countably infinitely many such intervals.[12] This result easily generalizes to higher dimensions, so that there are only countably infinitely many regions of finite size above a given volume in space. With this theorem as basis, the argument runs as follows:

(1) There is an uncountable infinity of possible universes above a given size M.

(2) There can be at most countably many non-overlapping regions of size M in a single space.

(3) Hence, the universes realized in multiverse cosmologies which postulate either a single 'containing' space or a single sequence of universes form a measure zero subset of the set of possible universes.

(4) Hence, the existence of a multiverse does not guarantee that there will be even one life-supporting universe.

Here (1) follows from the simple fact that 'size' is measured using the real number system; (2) is the fundamental theorem; and (3) follows from the fact that a countable subset of the real numbers, being the union of its individual points, is of measure zero.[13] Then (4) follows straightforwardly from (3).

It is clear from my expression of the 'fundamental theorem' that this argument applies directly to the Ellis-Brundrit type of simultaneously existing sub-universes of a single space, and to the bubble domains of inflationary cosmologies. Why then have I included Wheeler-type consecutive universes in (3) above? The situation is similar, because now only countably infinitely many universes above a given *duration* can be included in the sequence.

It should be noted that, once the regions are defined, we are not at liberty to redefine them, so that new regions represent other universe sizes, because the original realization is meant to represent individual universes with particular parameter choices.

The fact that a particular realization of a multiverse is of measure zero seriously undermines the existence of many universes as an explanation for fine-tuning. If the probability of any sub-universe being finely-tuned for life were strictly positive, then, we are told, the probability that an infinite ensemble would contain life-bearing sub-universes would be 1—this is the way the argument is usually formulated. Moreover, the number of life-bearing universes would then be infinite. This conclusion does, however, rely on the assumption that universe parameter sets are chosen randomly for each member of the ensemble, so that there is indeed a positive probability that any chosen universe will be life-supporting. If in fact all possible universes exist—if 'everything that can happen, does happen, somewhere sometime'—then there is no need to invoke probability at all. If all possible universes exist, those with parameters sufficiently fine-tuned for life, including our own, exist *ex hypothesi*. The proportion of them that are life-bearing is equal to the probability that an individual universe is life-bearing.

But if the set of realizable universes above a given size is of measure zero on the set of possible universes, then there is no guarantee that the realized set includes any life-bearing universes at all. For it to do so we require an additional hypothesis, for example that the realized set contains the same proportion of life-bearing universes as the set of all possible universes.

In the Wheeler case we are again in the position that only a countable sequence of universes of duration above a certain minimum can be realized. Here too the extra hypothesis is required, that this sequence includes a positive proportion of life-bearing universes.

We have seen (chapter 7) that the use of probability in this context is highly problematic. As for many of the usual fine-tuned parameters, it may be the case that the size or duration of a life-supporting universe must lie within a finite range (e.g. on the grounds that a too large universe may have expanded too fast for galaxies to form). We then have the problem of determining what the probability is that a parameter whose possible values lie in an infinite range actually fall in a finite range. If the infinite range is taken as the limit of a finite-range uniform distribution, as that range tends to infinity, then the answer will be zero.[14] However, the actual probability distribution to use is unknown, and choice of a uniform distribution arbitrary. It was considerations of this kind which led Neil Manson to the pessimistic conclusion that no inference, either to many universes or a designer, can be made from the fine-tuning of the universe.[15]

If the set of finely-tuned universes is of measure zero on the space of all possible universes, say because a particular parameter is of measure zero on its set of possible values, then the probability of any sub-universe being finely-tuned is zero. Thus the probability that any member of the infinite ensemble is life-bearing is zero. The number of life-bearing universes within the ensemble is then $0 \times \infty$, which is undefined. The appeal to infinitely many universes as an explanation for fine-tuning therefore fails.

This point about the set of fine-tuned universes being of measure zero, and therefore nullifying the explanatory power of an infinite cosmos, was overlooked in the seminal paper by Collins and Hawking,[16] to which I have drawn attention in earlier chapters. These authors showed that the set of asymptotically isotropic universes was of measure zero on the set of all spatially homogeneous universes. Deeming asymptotic anisotropy necessary for life, they went on to appeal to an infinite ensemble of universes to explain why we inhabit an asymptotically isotropic universe. But if the life-bearing universes form a set of measure zero, merely postulating an infinite ensemble is not enough to get us to an explanation for fine-tuning, a point originally noted by John Earman![17] Earman, discussing features supposedly varying across the sub-universes of the Ellis-Brundrit model, comments: 'But if the feature in question is unusual with a vengeance—measure zero—then the probability that it will be exhibited in some mini-world in the Ellis model is zero; ...' (though this statement might be a bit too strong—see below).

The argument of this chapter does not appeal to particular features, such as asymptotic isotropy, which are required to be fine-tuned. It appeals solely to the fact that only countably infinitely many universes above a given minimum size, out of a set of uncountably infinitely many possibilities, can be realized in a single space or sequence.

## Objections

In this section I imagine a sceptical interlocutor posing some objections to the argument presented in this chapter.

*Objection 1*: Are you not assuming that measure zero implies impossibility? The probability of choosing exactly ½ by random choice on the interval [0,1] is zero, but this does not mean that ½ does not exist!

*Response*: No, I am not assuming that measure zero entails impossibility. In fact it doesn't, as pointed out by Kingman and Taylor who note that, on a frequency interpretation of probability, an event $E$ of measure zero is such that $r(n)/n$ converges to zero as $n$ tends to infinity, where $r(n)$ is the number of times $E$ occurs in $n$ repetitions of the experiment: 'Thus $E$ is not necessarily the impossible event $\varnothing$ .'[18] Lawrence Sklar makes the same point in the context of statistical mechanics, referring to a set of points in phase space: 'That a set has probability zero in the standard measure hardly means that the world won't be found to have its total situation represented by a point in that set. After all, every phase point is the member of an infinity of sets of measure zero, such as the set of that point by itself.'[19]

Rather, what I say is, 'The number of life bearing universes ... is undefined'.[20] The point is that having infinitely many universes, rather than only 1, does not necessarily help, if the probability of a life-supporting choice of parameters is zero. The problem with one universe as a brute fact is that its parameters are so special, seemingly 'designed for life'. Infinitely many universes give an alternative explanation to design if the probability of life-supporting values for the parameters is positive. But if that probability is zero, we are not necessarily any further on.

In fact, this is exactly what Collins and Hawking found. For one particular requirement for life-bearing, namely asymptotic isotropy, the universes exhibiting this feature form a measure zero subset of the set of all possible universes. These authors then assumed without further warrant that the existence of infinitely many universes would explain the specialness of this one.

Let me repeat just to clarify this. Consider first the standard argument for a multiverse. Suppose the probability of life-supporting parameters is finite (i.e. non-zero and non-infinitesimal, though presumably small). Then if only one universe exists the probability that it will support life is negligible, being this small finite value. But if there are infinitely many universes the probability that at least one will support life is 1, given the further assumption of random choice.[21] Now consider what happens if the probability of life-supporting parameters is zero. If there is only one universe the probability that it will support life is zero. If there are finitely many, the probability is still zero (*pace* van Inwagen and Leslie) that any will be life-bearing. If there are infinitely many, we do not know what the probability is that any will be life-bearing—certainly none are guaranteed. Perhaps this moves us a bit further on, but we need a yet further assumption to get a definitive explanation for life-bearing universes.

*Objection 2*: If your argument is right it looks as though 'fine-tuning' plays no essential role in the argument. Suppose that there are finite upper and lower bounds on the values which constants can take in life-supporting universes, but no bounds on the values which these constants can take in universes in general. Then it looks as though the set of life-supporting universes will be of measure zero in the set of possible universes.

*Response*: This is just the point I was trying to make about fine-tuning arguments in general! It is indeed very difficult to quantify fine-tuning arguments for this sort of reason. The parameters might look incredibly fine-tuned, e.g. for the sake of argument initial expansion rate right to 1 part in $10^{55}$, and we are impressed by this. But any finite range would actually do, e.g. right to within a (large) factor, say a hundred million. The problem is that we don't know what probability distributions to take for these parameters.

It is for this reason that I have relied on plausibility arguments (cf. Salmon, as discussed in chapter 5), especially the perceptions of cosmologists themselves regarding the prior improbability of fine-tuning and the consequent need to find an explanation. However, one aspect of fine-tuning which genuinely seems to involve a probability (and thereby provide a counter to the arguments of Manson and McGrew *et al.*) is initial entropy. We have seen that Penrose[22] argues that the probability that a universe chosen at random possesses the order that ours does is

$$1 \text{ in } 10^{10^{123}}$$

*Objection 3*: Does not the argument show that a single infinite universe cannot exist (since a single universe can be divided into finite regions) and also that a single finite universe cannot exist (since the set of possible sizes is uncountably infinite)? Isn't the problem therefore more likely to lie with the mathematics than the argument for infinitely many universes?

*Response*: The claim is not that a measure zero set cannot exist (see response to objection 1), and certainly a single infinite universe and a single finite universe are both of measure zero. Rather, it is really a question of whether postulating infinitely many universes gets you much beyond the problems fine-tuning poses if there is only one universe. If all possible universes could be realized, this would guarantee one (indeed infinitely many) like ours. If only a limited subset can be realized there is no such guarantee.

*Objection 4*: Even if sound, your argument is not as significant as you claim, because you have chosen a very unusual version of many universes to focus on, namely an infinite space containing an infinite number of equal size finite regions.

*Response*: I would dispute that the version of the many worlds hypothesis chosen is unusual—it is basically sub-universes within a single space-time. Such a model is like that originally proposed by Ellis, and described in Ellis and Brundrit.[23] In the original proposal these were regions of a single all-embracing infinite, open universe. The regions had varying initial conditions and physical constants. Such universes could now be seen to arise as bubbles in some inflationary models. These universes are essentially finite non-overlapping regions, as is required for the main argument of this chapter to carry. The universes are not of equal size, only of finite size above a given minimum (which can be as small as you please—and I cannot really see why one should be worried at the exclusion of infinitesimally small universes). The argument of this chapter also applies to Wheeler-type sequential universes, so in fact it applies to two important classes of many-universe model.

For the two kinds of MWT considered in this chapter it seems to me that the only way out is to deny my first premise and argue that the number of distinct possible universes is not, after all, uncountably infinite. Indeed Max Tegmark seems to think that the number of possible universe configurations is finite.[24] From this he argues that there are infinitely many replicas of our universe, with infinitely many replicas of me, for example, some of which finish writing this book, others of which fall under a bus before doing so. John Barrow seems to think the same, and referring to inflationary models he says: 'And if our universe is infinite in extent then the number of alternatives that inflation can generate may be infinite as well. If it exhausts all the logical possibilities for variation that are available to it then any possibility that can exist will exist somewhere, not just once, but infinitely often'.[25]

This argument might hold if the number of universe configurations is indeed finite, as Tegmark claims, but if, for example, time is a continuous variable, then it seems to me that the claim is false. The time of an atomic decay, or the time at which I make a snap decision, which is also a quantum event according to Tegmark, are not constrained only to occur at discrete times. Indeed Tegmark seems to regard time as a continuous variable himself, since he goes on to discuss the alternative of mathematical structures in which it is discrete.

So it would seem that the argument carries for MWTs of types (1) and (2). Perhaps, however, we can say something about type (3), 'other-dimensional', MWTs as well. Even if one sets aside Gell-Mann's point that one doesn't have to accept the ontological reality of the universes in Everett's many worlds interpretation of quantum mechanics, as I remarked in chapter 4, the variation of physical parameters was an addition to Everett's original scheme. Indeed it would seem to be an arbitrary addition. Even then it is far from clear that this would *guarantee* the existence of all possible universes. For this one is virtually driven, beyond even Tegmark's 'ultimate ensemble' theory, to David Lewis's position of realism with regard to possible worlds, a rather different idea not dependent on quantum mechanics or any particular physical theories at all since all possible theories (physical and non-physical) are instantiated. Thus whilst the Everett scheme is not limited to countably many realized universes, it is not clear that it is exhaustive of the space of possible universes, and it is certainly anti-Ockhamite—arguably more so than what I would regard as the physically more plausible accounts of many universes which I have concentrated on in this chapter.[26]

## The Bayesian Analysis Revisited

Having to hand the investigations of this and the last two chapters, let us revisit the Bayesian analysis. We will change the notation a little for simplicity's sake. Let $E$ be the evidence of the fine-tuning of this universe. Let $H$ be the hypothesis of theism and let $H_i$ be the many worlds hypothesis, where $i = 1$ refers to spatial MWTs, $i = 2$ to temporal MWTs, and $i = 3$ to other-dimensional MWTs.

We have seen that a simple consequence of Bayes's theorem is:

$$\frac{P[H|E]}{P[H_i|E]} = \frac{P[E|H]}{P[E|H_i]} \cdot \frac{P[H]}{P[H_i]}$$

In chapter 6 I assigned numbers to the prior probabilities and likelihoods. The salient properties of the numbers actually chosen were:

$P[H_i] < P[H]$
$P[E|H_i] = 1$,
and $P[E|H] < 1$

which yielded, for this choice of parameters, $\frac{P[E|H_i]}{P[E|H]} < \frac{P[H]}{P[H_i]}$

This was essentially because, although theism did not guarantee the existence of this universe, it was still quite likely, given the intentions of a good God, whereas the prior probability of many universes was very much less than that of God on grounds of simplicity. It followed that $P[H|E] > P[H_i|E]$.

Let me summarize the findings of this chapter and chapter 7 (which I believe are unmodified by inflation as discussed in chapter 8):

(1) The existence of infinitely many universes depends critically on parameter choice. This reduces $P[H_i]$, at least for $i = 1$ and 2.

(2) The probability that any universe in an ensemble is fine-tuned for life is zero. This reduces $P[E|H_i]$ for $i = 1$, 2 and indeed 3, given that even the Everett scheme cannot guarantee the existence of all possible universes.

(3) Only a countable subset of possible universes can be realized for $H_1$ and $H_2$, thus reducing $P[E|H_i]$ for $i = 1$ and 2.

(4) The $H_i$ are untestable, thus reducing $P[H_i]$ for $i = 1$, 2 and 3. Arguably $P[H_3]$ is reduced the most here since, whilst one might just conceive of an influence from some universe which is part of the same space-time as ours, for an other-dimensional universe this would seem impossible.

(5) The $H_i$ are inconsistent with the amount of order in this universe, which is vastly greater than would be expected on any chance hypothesis. This substantially reduces $P[E|H_i]$ for each $i$. On any of the $H_i$, $P[E|H_i] << P[E'|\mathrm{H}_i]$ where $E'$ is the evidence of just sufficient order for us to exist in the cosmos.

From (1) to (5) above we are entitled to infer (for each $i$, in fact, though the conclusions look stronger for $i = 1$ and 2):

$P[H_i] << P[H]$,
$P[E|H_i] <<1$ and so $P[E|H_i] < P[E|H]$

Hence, for each $i$, both the likelihood ratio and the ratio of the priors favour $H$, and so:

$P[H|E] >> P[H_i|E]$

Of the alternatives, therefore, theism is substantially the best explanation for the fine-tuning of our universe.

## Conclusion

This chapter has shown that only a measure zero subset of possible universes can be realized by 'putting together' such universes in a single all-encompassing space-time. It follows that for two important multiverse cosmologies, namely a single space containing possible universes as sub-regions and a single sequence of universes, only a measure zero subset of possible universes will be realized. It follows that such cosmologies cannot guarantee the existence of even a single life-supporting universe. This conclusion would seem to be somewhat less assured in the case of 'other-dimensional MWTs', by which 'more' universes can be realized, though still plausible.

When taken in conjunction with the findings of the three previous chapters, the explanatory power of the multiverse hypothesis, at least in these two forms, is further reduced.[27]

## Notes

1 We have noted that the classic text is Barrow and Tipler (1986).
2 E.g. Swinburne (1990), but a number of others mentioned in chapter 3.
3 E.g. van Inwagen (1993), pp. 142-145; Leslie (1989), p. 6.
4 Carter (1974).
5 See Hacking (1987), White (2000).
6 Gale (1990).
7 Ellis and Brundrit (1979).
8 E.g. Wheeler (1973).
9 Hawking (1993), pp. 115-125.
10 Guth (1997), pp. 253-269.
11 See McMullin (1993), p. 380.
12 As we saw in note 25 to chapter 7, mathematicians distinguish rigorously between different 'degrees' of infinity. A countably infinite set such as the rationals can be put into one-to-one correspondence with the natural numbers 1, 2, 3, ... There are, however, uncountably infinitely many real numbers, and the natural numbers and the rationals each form a measure zero subset of the reals.
13 See Kingman and Taylor (1966), pp. 88-89, for the proof.
14 However, we saw in chapter 7 that this statement is made problematic by the need for normalization.
15 See Manson (2000). McGrew, McGrew and Vestrup (2001) reject the fine-tuning argument for the same reason. See also Collins (forthcoming), and the other papers from the same symposium, for more on this debate.
16 Collins and Hawking (1973).
17 Earman (1987).
18 Kingman and Taylor (1966), p. 269.
19 Sklar (1993), p. 182.
20 It would appear, however, that Earman has overlooked this point in the quotation I gave from Earman (1987).

21 In fact, this probability tends to 1 as the number of universes $n$ tends to infinity. Thus by taking $n$ large enough, but still finite, the probability can be made as close to 1 as you please. In this sense 'vastly many' universes will do the trick.

22 Penrose (1989a), p. 344; Penrose (1989b), p. 260. Moreover, as noted in chapter 3 at note 48, this figure applies to a closed universe and decreases with increasing universe size: the probability is zero for an open universe.

23 Ellis and Brundrit (1979).

24 Tegmark (2003).

25 Barrow (2002), p. 282.

26 See Ellis, Kirchner and Stoeger (2003) for an important discussion of the realizability of multiverses recently published in the scientific literature.

27 I am grateful to two anonymous referees whose comments and objections to my argument were invaluable in helping me clarify my thoughts and revise the paper, Holder (2001b), on which this chapter is based.

# Chapter 10

# Conclusion

> None but a Christian can read one line of his physics so as to understand it rightly ... Your study of physics and other sciences is not worth a rush, if it be not God by them that you seek after.
>
> (Richard Baxter, *The Reformed Pastor.*)

I began by posing the challenge of the scientific naturalist, namely that all physical phenomena have an explanation from within science. We saw the mistake of arguments from design which seek to explain gaps in scientific knowledge by appeal to God. Rather, a viable argument from design must appeal to more general features of the universe such as the existence of order and the nature of the scientific laws which obtain. Very soon we saw that science is predicated on a belief in order in the universe, and in the epistemic value of elegance and simplicity in the evaluation of scientific theories. These considerations and the utility of the inductive method cannot be explained from within science and are already pointers to design.

I then set out the modern cosmological understanding of the origin and evolution of the universe. The Big Bang is well-established. It provides a very convincing story of the expansion of the universe through various distinct epochs. At the earliest times matter is split into its constituent elementary particles. Matter and anti-matter annihilate leaving a residue of 'normal' matter. Nuclear reactions occur, manufacturing some of the simplest of the chemical elements. Eventually matter and radiation become decoupled, with the remnant radiation observed today being highly confirmatory of the theory. Stars and galaxies form as gravitational instabilities in the expanding medium. The heaviest stars evolve the most rapidly and spew out the heavier chemical elements, which they have manufactured through nucleosynthesis, into the surrounding medium. Out of this enriched material planets form and, ultimately, life evolves. On our particular planet, at least, intelligent living beings emerge with the ability to explore and comprehend the mystery of it all. I pointed out, however, that whilst the physics of more recent eras is pretty secure, the further back one goes (albeit the times in question are *extremely* early!) the less certain becomes the physics. The GUT era is uncertain enough but, in view of the disassociation of theory from observation and experiment, in the Planck era (earlier than $10^{-43}$ seconds from the beginning) it is hard to see that physicists are doing ought else but metaphysics. Yet many scientists, like Richard Dawkins and Peter Atkins, supposedly eschew metaphysics!

It transpires that, in order for intelligent life to arise in the universe at some point in its history, a host of factors have to be 'just right' to within remarkable degrees of accuracy. Thus the initial conditions at the earliest time we can sensibly speak of, and the fundamental constants of nature, have to take the values they do to an astonishing precision. Without this precision the universe would be startlingly different, for example having a duration of months rather than billions of years, or lasting to eternity but entirely bland, devoid of interesting features such as galaxies, stars and planets, let alone life. I listed twelve of these seeming anthropic coincidences. Notable among those which have most impressed cosmologists was the discovery, by Fred Hoyle, that the conditions inside stars for the manufacture of the chemical elements, which are the building blocks of life, must be very tightly constrained. This discovery led Hoyle, an atheist, to write that a 'superintellect has monkeyed with physics'.[1]

All this 'fine-tuning' is *prima facie* evidence for design. However, there are alternative explanations on offer. Does the fine-tuning really call for explanation, seeing that some set of equally improbable conditions must obtain? I have argued that value does require explanation, and, what is more, an explanation is available, namely theism. Could there be a unique set of laws with precisely determined physical constants, so that the universe could not be other than it is? It does not look like it, but, even if this were the case, there is still the gigantic puzzle as to why the unique set of laws should be life-producing.

Some cosmologists have speculated that the origin of the universe in time can be circumvented. We analysed in some detail one particular attempt to do this, namely that of Jim Hartle and Stephen Hawking. Their model is extremely problematic, especially in its appeal to imaginary time, but even if it were successful, that would not invalidate the need for God as the explanation for why there is a universe, or indeed anything at all. Moreover, Hawking is mistaken in believing that the only rôle for God is at the beginning. The need for God's continuous upholding of the universe in existence, an important aspect of Christian doctrine, is not vitiated, and the idea of God interacting with the world he has made sits very comfortably with the picture of the universe painted by modern science.

We examined Edward Harrison's rather desperate-sounding idea that our universe was created by aliens in another universe. Besides suffering from severe technical problems and lacking in simplicity, this suggestion seems not to have any real advantages over other kinds of multiverse scenario (for discussion of which see below). Lee Smolin's alternative of 'natural selection' of universes is simpler in so far as it does not rely on aliens as intermediaries. However, this theory runs counter to established astrophysical understanding of star formation, and its major prediction that our universe should contain the maximum number of black holes compatible with our existence seems plain wrong. But perhaps there are better ways of making a multiverse—see below!

The theory of inflation may explain some of the parameter values but it too needs fine-tuning, and in any case, if it happens, it just raises the same kinds of question we have been considering but about the laws which govern the universe in the inflationary/GUT era. Among the problems identified with inflation are its willingness endlessly to adapt, even to the point of abandoning its most fundamental prediction, namely a flat universe; and the fact that the specialness of initial conditions in the standard Big Bang is merely replaced by the, arguably equally special, propensity of a region to inflate. Nowadays inflation is often taken to give rise to a multiverse, in which our universe is just one domain where symmetry breaking has gone in one particular direction.

We looked at the ways in which a multiverse, an ensemble of universes in which the parameters and initial conditions take many different values, might arise in general. Thus the universes which comprise the multiverse might be causally separated regions of the same space (as, for example, in inflationary schemes); or sequential universes in an oscillatory scheme; or universes in a distinct space-time altogether from ours (as in black hole creation models or in Everett's quantum branching model). In addition there is Max Tegmark's radical proposal that all structures that exist mathematically exist physically.

I trust I have shown that this multiverse hypothesis, in some form, is the only really viable alternative to design. If the parameters take on all possible values (although this is a theory-dependent claim I take issue with), then 'everything that can happen will happen somewhere sometime'. We are then not supposed to express surprise that we inhabit a member of the vast ensemble of universes conducive to our own existence, because we could not inhabit one that was not. This hypothesis is what the scientific naturalist is virtually compelled to go for. Yet it violates the very tenets of scientific naturalism!

I proposed a method for analysing the alternative explanations for fine-tuning which is basically the best contender for evaluating alternative scientific hypotheses, a procedure which ought to satisfy Richard Dawkins who claims that religions are explanatory competitors in the same market place as science. I showed how this method, Bayesian probability theory, is set up, and how it has coped with some objections raised against it. I discussed at some length the thorny problem of the assignment of prior probabilities in the theory.

I chose three alternatives to evaluate, namely design, the existence of one universe as a brute fact, and the existence of a multiverse. The whole point of the fine-tuning discussion is that a single universe, chosen in some sense randomly from an ensemble of candidate universes, is extremely unlikely to be life-bearing. Hence the single brute fact universe badly explains the evidence. Theism explains the evidence well, as fulfilling the intention of a good God to create intelligent creatures capable of a relationship with him, though it is always possible that God would not create a universe at all or else create a different, albeit beautiful and fruitful one. A multiverse explains the evidence even better, at any rate if all possible universes exist, because then ours automatically exists (this is contra the arguments of Hacking and White). When it comes to the prior probabilities, however, theism arguably fares best. The idea of God is simple compared with a complex physical universe, and much simpler than an infinitude of complex physical universes. This last is violently anti-Ockhamite. Moreover, God gains an edge over many universes on the grounds that some of the greatest philosophers have thought that God's existence follows by logic alone from the concept of God. No one has thought that about a physical universe, let alone many universes. Hence the Bayesian analysis shows that theism is preferable to the many universes hypothesis and *a fortiori* the single brute fact universe (incidentally vindicating my earlier claim that the fine-tuning demands explanation).

I went on to examine further the multiverse hypothesis, and found a number of problems with it in addition to its lack of simplicity. Thus it turns out that there must be constraints on physical parameters even to get many universes in the first place, undermining rather the explanatory power of the multiverse to explain constraints! Then, whilst it had been assumed for the multiverse hypothesis to work that there was a small but finite probability that a randomly chosen universe would be life-bearing, this probability is in fact zero. Moreover, any physical realization of an ensemble will exclude an infinity of possibilities. Then again, the hypothesis is untestable, which ought to undermine its credentials with scientific naturalists like Dawkins who make this complaint about religion! Also, the hypothesis is inconsistent with the amount of order found in this universe, and with the persistence of this order. Our universe is far more special than we would expect it to be, even if it were merely a random member of the subset of universes compatible with our existence.

I devoted a chapter to examining the theory of inflation in more detail, embracing some of the most recent developments in cosmology. It would appear that inflation is not the panacea to cosmological problems it is often portrayed to be. For a start, the problems are not of the normal kind which bring a scientific theory into question, such as—critically—conflict with observation. Rather, they are either introduced by the speculative GUTs invoked by inflation theory in the first place (the so-called 'monopole problem'); or they relate to initial conditions, which are usually regarded in science as given and not requiring explanation (the horizon and flatness problems). Even accepting that the latter are genuine problems, it is not clear that inflation really solves them!

Our more detailed look confirms some of the problems identified earlier with inflation. A further issue concerns the cosmological constant $\Lambda$, Einstein's 'biggest blunder' but now revived. There is increasing evidence that the universe is flat with the energy density consisting of three components: ordinary (baryonic) matter, dark matter, and dark energy (the last being the cosmological constant component). Unfortunately $\Lambda$ needs to be fine-tuned to a most remarkable degree, with the quantum vacuum component powering inflation almost but not quite cancelling the Einstein component. Calculations by Steven Weinberg throw doubt on whether the value of $\Lambda$ constrained by observations is consistent with $\Lambda$ being a random value compatible with our existence. Again, our universe looks as though it is too special!

Collins and Hawking had made the point about a life-bearing universe having zero probability when considering one particular feature required, namely asymptotic isotropy. I have shown that no physical realization of a multiverse, conceived as comprising infinitely many universes in a single containing space, can contain more than countably infinitely many universes above any given finite size. This further undermines the explanatory power of the multiverse hypothesis.

My criticisms do of course focus especially on what I regard as physically the most likely versions of a multiverse, in which the individual universes are conceived to exist simultaneously in a single containing space, or sequentially as successive Big Bang-Big Crunch bounces. The third type, in which separate universes exist by a branching process in distinct space-time realms, as in Everett's interpretation of quantum theory, may not be as constrained in terms of numbers of universes which can be realized. However, this is only so if the arbitrary assumption (which seems to be substantially lacking in justification) is added to Everett's original schema that all the parameters do take on all possible values, and if one also sets aside Gell-Mann's criticism that one should not in any case regard the universes as really subsisting. Besides, the theory is still extremely anti-Ockhamite, arguably even more so than the alternatives.

When all these further considerations are taken into account, both the prior probability and the likelihood of the multiverse hypothesis are reduced, arguably very dramatically. Hence theism is left a much clearer winner, and provides an explanation for the fine-tuning which ought better to commend itself to scientists than the multiverse hypothesis.

As with the evaluation of scientific theories, our weighing up the alternative explanations of the fine-tuning of the universe is probabilistic in nature. The point of the Bayesian analysis is that rational subjects ought normatively to hold beliefs which are consistent within the Bayesian schema. Of course the precise numbers we put into the equations were only illustrative, and designed to make the analysis simple. What really matters is only whether one number is much bigger than another or not. The plausibility arguments offered here justify such statements about relative magnitude, and a more qualitative treatment incorporating such statements would lead to just the same results.

If the probabilities do indeed fall out in the way they appear to in this book, then the chances are that there is in actual fact a Cosmic Designer. This Designer meant us to be here. Perhaps with Aquinas we can dare to say of the Designer, '... and this we call "God"'.[2] But the design argument gives us only limited information about God—that he exists, that he is glorious and powerful in so far as he could make such a magnificent universe, maybe a bit more. Having investigated in, I trust, a rational fashion, this version of the argument from design, would it not now be equally rational to investigate much more deeply what that Designer is like? That is of course another story, which will take us into the realms of Revelation, where we may hope to find

> ... the light of the knowledge of the glory of God in the face of Jesus Christ.
>
> (2 Corinthians 4:6, Authorized (King James) Version.)

## Notes

1 Hoyle (1981), p. 12.
2 St Thomas Aquinas, *Summa Theologiae*, 1a. 2, 3.

# Appendix A

# The Probability Calculus and Bayes's Theorem

Mathematicians usually define probability as a mapping from a set of sets onto the real numbers. However, as indicated in the main text, we shall find it more useful on the whole to take the philosophers' definition of the probability of a proposition. The two formulations are equivalent, with the philosophers' disjunctions and conjunctions of propositions replacing the mathematicians' unions and intersections of sets.

If $\mathbb{C}$ is a set of propositions, then, we define probability $P$ as a mapping from $\mathbb{C}$ onto the real numbers $\mathbb{R}$ with the following properties:

$P[A] \geq 0$ for all $A \in \mathbb{C}$ (A1)
$P[A] = 1$ if A is a necessary truth (A2)
$P[A \vee B] = P[A] + P[B]$ if $A \wedge B$ is necessarily false
i.e. if $A$ and $B$ are mutually exclusive.[1] (A3)

From these three basic axioms, with a little effort, one can derive the following important theorems of probability theory:

$P[\sim A] = 1 - P[A]$ (T1)
$P[A] = P[B]$ if $A \leftrightarrow B$ (T2)
if $A \rightarrow B$, then $P[A] \leq P[B]$ (T3)
for any $A$ and $B$, $P[A \vee B] = P[A] + P[B] - P[A \wedge B]$ (T4)

To progress further one needs the following additional axiom, which can be construed as defining conditional probability, written $P[A \mid B]$, and read as 'probability of $A$ given $B$':

$$P[A \mid B] = \frac{P[A \wedge B]}{P[B]} \text{ provided } P[B] \neq 0 \tag{A4}$$

It follows from (A4) that $P[A \wedge B] = P[A \mid B].P[B] = P[B \mid A].P[A]$, and hence, very simply, we have Bayes's theorem:

$$P[B \mid A] = \frac{P[A \mid B].P[B]}{P[A]} \tag{T5}$$

Since $P[A] = P[(A \wedge B) \vee (A \wedge \sim B)] = P[(A \wedge B] + P[(A \wedge \sim B)]$ it follows that

$$P[A] = P[A \mid B].P[B] + P[A \mid \sim B].P[\sim B]$$

i.e. what in chapter 5 I have called the 'total probability rule'.

Hence we derive the very useful alternative form of Bayes's theorem

$$P[B \mid A] = \frac{P[A \mid B]}{P[A \mid B].P[B] + P[A \mid \sim B].P[\sim B]}$$

By a simple extension of the above, if $P[B_1 \vee B_2 \ldots \vee B_n] = 1$ and the $B_j$ are mutually exclusive, then a third form of Bayes's theorem is

$$P[B_i \mid A] = \frac{P[A \mid B_i].P[B_i]}{\sum_{j=1}^{n} P[A \mid B_j].P[B_j]}$$

## The Axiom of Continuity

For most purposes the above axiomatization of probability is perfectly adequate. However, we also have occasion in this book to discuss probability in measure-theoretic terms. This entails extending axiom (A3), which leads to the additivity rule for finite disjunctions, so as to include an additivity rule for countably infinite disjunctions (which translates into the corresponding rule for infinite disjoint unions of sets on the mathematicians' definition of probability):

$$P[\vee_{i=1}^{\infty} A_i] = \sum_{i=1}^{\infty} P[A_i] \text{ if } A_j \wedge A_k \text{ is necessarily false for all } j \neq k \qquad \text{(A5)}$$

Suppose you wanted to choose an integer at random from the set of all integers. Then (A5) shows that each integer cannot have the same probability of selection. This is because the right hand side of (A5) would diverge to infinity if all the probabilities were equal and finite, but would be zero if they were all zero, whereas the left hand side—the probability that some integer is selected—is 1.

Similarly, if we cover the real line by dividing it into equal, non-overlapping intervals (closed at the left and open at the right, say), then a randomly chosen real number cannot be equally likely to lie in all the intervals so constructed. This is important for our discussion of the Principle of Maximum Entropy (PME) in chapter 5 (and Appendices B and E).

We have occasion, in the discussion of PME and elsewhere, to discuss continuous variables where sums are replaced by integrals. In this case subsets of possibilities under consideration may have measure zero (measure essentially having the properties of probability apart from the total of 1 for the whole space, as indicated in chapter 7). We then have to revise the meaning of zero probability. The probability of ½ being drawn from the interval [0,1] is zero, but we do not say that this is literally impossible, that it is necessarily false that ½ be drawn, or that ½ does not exist!

## Note

1 Here the logical symbol $\vee$ denotes the inclusive disjunction, i.e. $(P \vee Q)$ means (($P$ or $Q$) or both). The symbol $\wedge$ is the conjunction, so that $(P \wedge Q)$ means ($P$ and $Q$). The inclusivity of the disjunction becomes irrelevant when the propositions are mutually exclusive, as the hypotheses we wish to evaluate will be.

# Appendix B

# The Principle of Maximum Entropy

As noted in the text of chapter 5, Jaynes's Principle of Maximum Entropy (PME) is an attempt to get round the problems associated with the Principle of Indifference (PI). Indeed it could be regarded as trying to make the PI mathematically rigorous by providing criteria for assignment of prior probabilities when one has minimum information. The method is as follows.

Suppose a variable $X$ can take any of $n$ discrete values, $a_1, a_2, \ldots, a_n$.

Let $P[X = a_i] = p_i$.

Then, on Shannon's definition, entropy $E = -\sum_{j=1}^{n} p_i \log p_i$ (1)

This must be maximized subject only to the constraint $\sum_{j=1}^{n} p_i = 1$ (2)

The values of $p_i$ corresponding to maximum entropy in this case can be easily derived (using the mathematical device of Lagrange multipliers, for those who wish to know!). The result is

$p_i = P[X = a_i] = 1/n$ (3)

which is of course the well-known uniform distribution.

Seidenfeld points out how curiously over-powerful this technique is for extracting definiteness from minimum information.[1] Thus given a die about which we know nothing except that it has six sides, the Principle of Maximum Entropy tells us that we should assign probabilities of 1/6 to each possible outcome. The classical theory, on the other hand, tells us that we should do this only if the die is *fair*. But why should we *deduce* that the die is fair if we have no other information about it, seeing that it could be loaded in uncountably infinitely many ways?

Perhaps we could argue that in this case the PME is modelling our naïve notions of simplicity quite well (the reader is referred back to chapter 5 for our main discussion of simplicity). However, this is far from being universally the case. Very often maximum entropy distributions simply do not exist; in other cases they produce quite counter-intuitive results.

A particularly striking example of paradox, due to Shimony,[2] concerns an extension of the case above in which a variable $X$ can take any of $n$ discrete values. Suppose we acquire further evidence $e$, namely that the mean value of the $a_i$ is $\alpha$, i.e.:

$$\sum_{j=1}^{n} p_i a_i = \alpha \tag{4}$$

Then PME will treat (4) as a further constraint and maximize $E$ as given by equation (1) subject to both (2) and (4). This yields the following standard result for PME (again by using Lagrange multipliers):

$$p_i = P[X = a_i|e] = \frac{\exp(-\beta a_i)}{\sum_{j=1}^{n} \exp(-\beta a_j)} \tag{5}$$

where $\beta$ is a constant determined by $\alpha$.

Now in Bayesian terms, before $e$ is obtained one can have reasonable degrees of belief about what the result might be, i.e. about the possible values of the mean of the $a_i$. In other words one could assign a prior probability distribution to the value of $\alpha$, and hence of $\beta$. Moreover, PME specifies the prior probabilities $P[X = a_i]$ to be $1/n$ as in (3) above and the posterior probabilities to be as given by (5).

The standard probability theory relationship between the PME-derived $P[X = a_i]$ and $P[X = a_i|e]$, and the prior distribution for $\beta$, can now be used to derive what the last, i.e. the reasonable degree of belief for values of $\beta$, should be. The result is that $\beta = 0$ with virtual certainty! As Shimony notes, it is 'very surprising that a procedure which emphasizes honesty about one's ignorance should require one *a priori* to have virtual certainty concerning the outcome of an observation'.

In the above discussion PME was only applied to discrete probability distributions. But there is also the problem of adapting the method to continuous distributions. The quantity which Shannon defined as entropy in the continuous case, namely $-\int_{-\infty}^{\infty} f(x) \log f(x) dx$, where now $f(x)$ is the probability density, is not the limiting case of the discrete entropy, nor does it have the right properties of invariance under change of variable. Hence Jaynes was driven to advocate an alternative means of deriving prior probabilities in this case. This method is equally problematic!

Jaynes modifies the formula in the previous paragraph, giving information entropy $E$ as

$$E = -\int_{-\infty}^{\infty} f(x) \log[f(x)/\mu(x)] dx$$

where $\mu(x)$ is a measure necessary to make $E$ invariant under a change of variable. Jaynes argues that $E$ is maximized for $f(x) \propto \mu(x)$, so the problem now is to find a suitable expression for $\mu(x)$.

Developing an idea of Jeffreys,[3] Jaynes goes on to argue that the measure $\mu(x)$, and therefore the prior probability distribution $f(x)$, should possess certain invariance properties implicit in the problem being dealt with. For appropriate transformations $x'(x)$ one demands $\mu(x')dx' = \mu(x)dx$. This requirement is known as Jaynes's principle.

For example, if all we know is that a parameter $x$ can take any value on the real line (i.e. between $-\infty$ and $+\infty$), then Jaynes argues that the probability measure should be invariant under translation, i.e. under the transformation $x \rightarrow x' = x + l$ for all $l$.[4] Since $dx' = dx$ this implies $\mu(x + l) = \mu(x)$ for all $l$, and so $\mu(x)$ = constant (i.e. a uniform distribution, but see below).

Another important example we shall have cause to return to is the case of a parameter which can take all positive real values, i.e. which lies between 0 and $+\infty$. Jaynes assumes in this case that the measure should be invariant under change of scale, i.e. under the transformation $x \rightarrow x' = \lambda x$, for all real and positive $\lambda$. Jaynes's principle now implies $\mu(\lambda x)\lambda dx = \mu(x)dx$, and hence

$$\mu(x) \propto \frac{1}{x}$$

Now in both these cases the measure is non-normalizable. That is to say, the measure does not integrate to a finite value which could be used as a divisor so as to turn the measure into a probability distribution integrating to unity. This is in fundamental contradiction to the axioms of probability theory. Use of such 'improper' distributions, in which Jaynes persists, is a recipe for contradiction and paradox, as has indeed been demonstrated by Dawid, Stone and Zidek.[5] Seidenfeld has also demonstrated, for the simple example of finding the volume of a cube, that reversing the order in which data from two different methods is processed gives conflicting results.[6]

A particularly pertinent paradox, in view of the use of Jaynes's principle by some authors in the cosmological context, which we examine in chapter 7 (and Appendix E), is due to Milne.[7] Suppose we know that a parameter can take all positive real values and therefore has $\mu(x) \propto 1/x$. Not only is this measure non-normalizable over $(0, \infty)$; it is not even normalizable over the finite sub-interval $(0, a]$ for positive $a$. Suppose we now learn that $x$ lies in $(0, a]$ and wish to derive the probability that it lies within $(b, a]$ where $0 < b < a$. The easily derived answer for this conditional probability is

$$P[b < x \leq a \mid 0 < x \leq a] = 0,$$

for any $b$ in the interval $0 < b < a$.

This means that for any $b$ between 0 and $a$, we can be almost certain that $x$ is not greater than $b$. In other words, $x$ is arbitrarily close to 0! This is quite paradoxical and totally contrary to the claim that our derived distribution is that most compatible with ignorance. It rather belies the claim of Garrett and Coles that 'no paradox has ever been found in the *correct* application of Bayesian methods', when these authors insist that the assignment of prior probabilities using PME is a an inherent component of Bayesianism.[8] As we see in chapter 7 (and in detail in Appendix E), the problem with applications of the method to cosmology is that built-in singularities in the chosen measure translate into singularities at $\Omega = 0$ and $\Omega = 1$ in the cosmological density parameter, giving rise to the suspicion that these are merely an artifact of the method rather than a genuine solution to the flatness problem.

There is yet a further problem with the method, which, as we shall see, also impacts on its application to cosmology. This relates to the ambiguity arising from the transformations made in order to derive distributions for variables which are confined to other intervals than the whole real line or the positive reals.

Kirchner and Ellis[9] take as their starting point the validity of the non-normalizable distributions, derived above, for parameters lying in $(-\infty, \infty)$ and $(0, \infty)$. Noting that the $\mu(x) \propto 1/x$ measure is only valid for the *open* interval $(0, \infty)$, i.e. it is not valid if $x = 0$ is allowed, they proceed to derive a distribution for a parameter which can lie in the semi-open interval $[0, \infty)$, i.e. which allows $x = 0$.

If a parameter $v$ can lie in $[0, \infty)$, then we can write it as $v = w^2$ where $w$ is a new parameter in the range $(-\infty, \infty)$ and so, by Jaynes's principle, has measure $\mu_0(w) = \text{constant} = \kappa$, say. The measure for $v$, $\mu(v)$, is then given by

$$\mu(v)dv = \mu_0(w)dw$$

i.e. $\mu(v).2w\,dw = \kappa\,dw$

from which we obtain

$$\mu(v) \propto \frac{1}{\sqrt{v}}$$

If a parameter $s$ can only lie in a finite interval $[a, b]$ we can define another parameter $t$ by

$$s = a + \frac{b-a}{2}(1 + \sin t)$$

where now $t$ can lie in $(-\infty, \infty)$. This time, with Jaynes's principle dictating measure $\mu_0(t) = \kappa$ for $t$, the measure $\mu(s)$ for $s$ is given by

$$\mu(s).\frac{b-a}{2}\cos t\,dt = \kappa\,dt$$

from which we obtain

$$\mu(s) \propto \frac{1}{\sqrt{(b-s)(s-a)}}$$

This measure too is non-normalizable. It is also very different from what one might naïvely have expected in this case on the basis of 'minimum information', namely a uniform distribution over $[a, b]$, which at least has the merit of normalizability, and therefore conformity to the axioms of probability theory.[10]

Now in neither of the above cases is the transformation proposed unique. For example, to derive the measure for $v \in [0, \infty)$, why not define $w$ differently by writing $v = w^4$, still retaining $w \in (-\infty, \infty)$ and so $\mu_0(w) = \kappa$ ?[11] We then obtain

$$\mu(v).4w^3dw = \kappa\, dw$$

$$\text{i.e. } \mu(v) \propto \frac{1}{v^{3/4}}$$

And in the other case, instead of choosing $s$ to be a function of sin $t$, one could perfectly well (and with better reason, as explained below) choose it to be a function of tanh $t$,[12] where $t$ is still in the range $(-\infty, \infty)$:

$$s = a + \frac{b-a}{2}(1 + \tanh t)$$

Now we have

$$\mu(s).\frac{b-a}{2}(1 - \tanh^2 t)dt = \kappa\, dt$$

$$\text{i.e. } \mu(s) \propto \frac{1}{(b-s)(s-a)}$$

In other words we can find completely different, but equally valid, parametrizations which give completely different measures. Perhaps in the first of these cases $w^2$ is a simpler function than $w^4$. In the second case I certainly don't see that sin $t$ is any simpler than tanh $t$. Rather, sin $t$ is more complex (i) because it isn't defined in the limits $t \to \pm\infty$; and (ii) because it is not a one-to-one mapping. In contrast, as $t \to \pm\infty$, we have tanh $t \to \pm 1$ and tanh $t$ is a one-to-one, monotonically increasing function.

One reaction to the problem I have just identified is to say that in each case the new measure I have produced still has singularities at the same points and is non-normalizable. With some heavy mathematics one might be able to prove a general theorem along these lines. But even if this is true it is hardly an adequate response, especially when Kirchner and Ellis argue that 'improper measures can be used as priors in Bayes theorem because the normalization factor cancels'.[13] Since my alternative measures tend to infinity at different rates at the singularities it may well be that the normalization factor *doesn't* cancel out.

## Notes

1 Seidenfeld (1979), p. 425.
2 See Shimony (1985).
3 See Jeffreys (1961), pp. 119-125.
4 Writing this in probability terms, the requirement is that a variable $X$ which can take any value on the real line should satisfy $P[x < X < x + dx] = P[x + l < X + l < x + l + d(x + l)]$ for any $l$. Since $d(x + l) = dx$ this leads to a uniform distribution, as in the text.
5 See Dawid, Stone and Zidek (1973).
6 Seidenfeld (1979), p. 422.
7 Milne (1983).
8 Garrett and Coles (1993), p. 30.
9 Kirchner and Ellis (2003).
10 Swinburne argues that the Principle of Indifference can be used by making the simplest choice of probability distribution, and nowhere does he discuss Jaynes's attempt to be more rigorous. Swinburne chooses the uniform distribution for a parameter $T$ constrained to lie in an interval $[a, b]$, arguing that, for example, a uniform distribution of $T^2$ over $[a^2, b^2]$ is more complex. See Swinburne (2001), pp. 116-118. This approach is still problematic, if for no other reason than that we are often hard-pressed to distinguish, if one parameter is a function of another, which of the two is the simpler. It does, however, have the important merit, as pointed out in the text, of normalizability.
11 Of course there are plenty of other possibilities, e.g. $v = w^6$, $v = w^8$, etc., or, to use a different tack, $v = \cosh t - 1$, where $\cosh t$ is the hyperbolic function $\cosh t = \frac{1}{2}(e^t + e^{-t})$.
12 $\tanh t$ is the hyperbolic function analogous to the trigonometric function $\tan t$, and is defined in terms of the two other hyperbolic functions $\sinh t$ and $\cosh t$ by $\tanh t = \sinh t/\cosh t$, where $\sinh t = \frac{1}{2}(e^t - e^{-t})$ and $\cosh t = \frac{1}{2}(e^t + e^{-t})$ (as in the previous note).
13 Kirchner and Ellis (2003), p. 1201.

# Appendix C

# The Ravens Paradox

I pointed out in the text of chapter 5 that Bayes's theorem can be deployed to resolve some outstanding paradoxes of induction, and notably Carl Hempel's 'ravens paradox'. In a nutshell the paradox is that the hypothesis 'All ravens are black' is confirmed not only by observations of ravens which turn out to be black, but by non-black objects which turn out not to be ravens. This is because the hypotheses 'All ravens are black' and 'All non-black objects are not ravens' are logically equivalent.

Let $H$ be the hypothesis 'All ravens are black'.

Let $E$ be the evidence that, given that $a$ is randomly selected from the set of ravens, $a$ turns out to be black.

Let $E'$ be the evidence that, given that $b$ is randomly selected from the set of non-black objects, $b$ turns out to be a non-raven.

Then Bayes's theorem states:

$$P[H|E] = \frac{P[E|H].P[H]}{P[E|H].P[H] + P[E|\sim H].P[\sim H]}$$

omitting for convenience conditioning on background evidence $K$.

Since $P[E|H] = 1$, this reduces to

$$P[H|E] = \frac{P[H]}{P[H] + P[E|\sim H].P[\sim H]}$$

Similarly we have

$$P[H|E'] = \frac{P[H]}{P[H] + P[E'|\sim H].P[\sim H]}$$

It follows that $P[H|E] > P[H|E']$ iff $P[E|\sim H] < P[E'|\sim H]$

Suppose $\exists$ $r$ ravens and $N - r$ non-ravens
Suppose $k$ ravens are black, $r - k$ ravens are non-black
Then $\sim H$ is true iff $k < r$

Suppose $m$ of the $N - r$ non-ravens are non-black.

Then $P[E|\sim H] = \dfrac{k}{r}$

and $P[E'|\sim H] = \dfrac{m}{r-k+m}$

$P[E|\sim H] < P[E'|\sim H]$ is true iff

$$\frac{k}{r} < \frac{m}{r-k+m}$$

which is true iff $k < m$.

That is to say, provided the number of black ravens is less than the number of non-black non-ravens the hypothesis will be better confirmed by looking at ravens than by looking at non-black objects.

Even greater clarity is obtained if we add to each side of the inequality $k < m$ the quantity $r - k$. Then sampling from ravens is more productive than sampling from non-black objects if

$$r < m + r - k$$

i.e. if, quite simply, the number of ravens is less than the total number of non-black objects. But we know that, in our universe, $r \ll m + r - k$.

My resolution of the ravens paradox is essentially the same as that of Earman.[1] Earman puts the fact that *a* and *b* are drawn from the sets of ravens and non-black objects into the background knowledge *K* and then calculates $P[H|$(*a* is a raven) $\wedge$ (*a* is black) $\wedge K]$ and $P[H|$(*b* is not a raven) $\wedge$ (*b* is not black) $\wedge K]$. This improves on earlier attempts at resolving the paradox by Suppes and Horwich. Suppes uses samples from the universe as a whole and mistakenly draws conclusions about drawing from the set of ravens or the set of non-black objects. Horwich comes closer to a resolution but conditions on evidence '*a* is drawn from the set of ravens and *a* is black' and '*b* is drawn from the set of non-black objects and is not a raven'. These are not quite what is required, namely 'given that *a* is drawn from the set of ravens it turns out to be black' and its equivalent for non-black objects. Horwich inaccurately assumes that the probabilities of his versions of evidence given the hypothesis are 1: this is only so on my definition of the evidence (and on Earman's with his revised *K*).

Other attempts at resolution of the ravens paradox seem to require further assumptions. Thus Howson and Urbach need to add arguments about the initial probability distribution of the percentage of ravens which are black,[2] and Mackie that *a priori* observation of blackness and ravenhood are independent.[3] To repeat, my solution here seems simpler in that no such further assumptions are required.

Earman shows how incorporation of background knowledge can help resolve further raven-related problems. In Good's example we are supposed to know that we are in one of two bird universes: universe $U_1$ has 100 black ravens, no white ravens and one million other birds; universe $U_2$ has 1000 black ravens, 1 white raven and one million other birds. Picking a bird at random from the universe and finding it to be a black raven actually disconfirms the hypothesis 'all ravens are black', because such a bird is more likely to have come from universe $U_2$. Appropriate application of Bayes's theorem demonstrates this.

Good's example is interesting since it shows a violation of the general condition (known as Nicod's condition) that an instance of 'an R is a B' confirms the hypothesis 'All Rs are Bs'. Another example, due to Rosenkrantz, postulates three party goers each leaving the party with a hat. Given that they were the only guests who arrived with hats, the hypothesis 'each leaves with the wrong hat' is disconfirmed by the observation that A has B's hat and B has A's hat. The point is, though, that Bayes's theorem can accommodate these examples when background knowledge is taken into account.

## Notes

1 Earman (1992), pp. 69-73. Earman also discusses the solutions of Suppes and Horwich referred to in the text.
2 Howson and Urbach (1993), pp. 127-128.
3 Mackie (1963); discussed in Howson and Urbach (1993), pp. 166-167.

Appendix D

# The Self-Sampling Assumption and the Doomsday Argument

## Introduction

As noted in chapter 7, the Doomsday Argument purports to show that, from simply observing one's own location in time within the human race, one should raise one's expectation of an early demise to our species. In this appendix I briefly examine two counter-arguments to this. The first, which appeals to Bostrom's Self-Sampling Assumption and thereby to the possible existence of extra-terrestrial civilizations, reveals a peculiar interdependence between civilizations, but is still found wanting when this is removed. The second, which utilizes the fact of my own existence, and has a more direct parallel with multiverse explanations of cosmic fine-tuning offered in this book, especially in chapter 6, is deemed satisfactory. It is shown how issues of human identity impact the arguments.

## Extra-Terrestrials and the Longevity of the Human Species

The Doomsday Argument, originated by Brandon Carter[1] and elaborated by John Leslie,[2] asserts, then, that I am more likely to find myself where I do in the sequence of all human beings who exist if there are relatively few rather than many humans to follow me. Hence, by Bayes's theorem, the prior probability of few humans in total ever existing, based on estimates of annihilation by weapons of mass destruction and the like, is enhanced relative to the prior probability of many.

Let's just see how this works. For simplicity we limit ourselves to two mutually exclusive possibilities: either our universe will eventually contain 200 billion persons—call this hypothesis $A$, or it will contain 200 trillion persons—hypothesis $B$. Let $P[A]$ be the prior probability of a small universe based on estimates as to whether the human population will annihilate itself in a nuclear holocaust or the like, and $P[B]$ be the corresponding probability that the universe is long-lasting. Let $E$ be the evidence that a random member of the universe is within the first 200 billion persons. Then the likelihoods are:

$$P[E|A] = 1$$

and

$$P[E|B] = \frac{200 \times 10^9}{200 \times 10^{12}} = 10^{-3}$$

Bayes's theorem (in the useful form for making comparisons, as given in chapter 5) yields

$$\frac{P[A|E]}{P[B|E]} = \frac{P[E|A]}{P[E|B]} \cdot \frac{P[A]}{P[B]}$$

$$= 10^3 . \frac{P[A]}{P[B]}$$

i.e. the prior probability of a short-lived universe is enhanced relative to a long-lived universe, which is the Doomsday result.

In discussing the Doomsday Argument in his book *Anthropic Bias*[3] Nick Bostrom provides a counter to the argument by suggesting that 'outsiders', non-human civilizations, should be taken into account. Bostrom posits the following concrete problem, which I paraphrase, making the argument as clear as possible by tidying up what I see as the loose expression of it by Bostrom himself.

The alternatives are a generalization of those in the example above. $A$ and $B$ are now two alternative possible *multiverses*. Each contains a million 'small' civilizations with 200 billion persons and a million 'large' civilizations with 200 trillion persons. If multiverse $A$ is realized, then our civilization is one of the small civilizations; if multiverse $B$ obtains, then our civilization is one of the large ones. The aim is to calculate the probability that the human civilization is small, in other words that multiverse $A$ obtains, given that an individual drawn randomly from the whole ensemble is among the first 200 billion members of his species and that he is human.

The first step, says Bostrom, is the same as above, namely to estimate the empirical prior probability, $P$[the human civilization is small], taking account of factors such as nanotech warfare which might annihilate the human species before it gets large.

Now in my terminology the human civilization is small iff $A$, i.e. 'the human civilization is small' means the same thing as multiverse $A$ being the one which exists. Hence $P$[the human civilization is small] = $P[A]$ by theorem (T2) of Appendix A.

Bostrom's second step is, in my terminology, to calculate $P[H|A]$ where $H$ is the hypothesis 'X is a human', on the assumption, namely the Self Sampling Assumption (SSA), that 'X' is a random individual drawn from all individuals in the ensemble. This is simply the proportion that the human population comprises of the whole ensemble of civilizations:

$$P[H|A] = \frac{200 \times 10^9}{200 \times 10^9 \times 10^6 + 200 \times 10^{12} \times 10^6}$$

$$\approx 10^{-9}$$

Similarly

$$P[H|B] = \frac{200 \times 10^{12}}{200 \times 10^9 \times 10^6 + 200 \times 10^{12} \times 10^6}$$

$$\approx 10^{-6}$$

Next we take account of the Doomsday Argument. Let $E$ be the evidence that 'X is among the first 200 billion members of his species'.

Then $P[E| A \wedge H] = 1$

and $P[E|B \wedge H] = 10^{-3}$

Bayes's theorem now tells us that

$$\frac{P[A|E \wedge H]}{P[B|E \wedge H]} = \frac{P[E|A \wedge H]}{P[E|B \wedge H]} \cdot \frac{P[A|H]}{P[B|H]}$$

$$= \frac{P[E|A \wedge H]}{P[E|B \wedge H]} \cdot \frac{P[H|A]}{P[H|B]} \cdot \frac{P[A]}{P[B]}$$

Putting in the numbers derived above, we obtain:

$$\frac{P[A|E \wedge H]}{P[B|E \wedge H]} \approx \frac{1}{10^{-3}} \cdot \frac{10^{-9}}{10^{-6}} \cdot \frac{P[A]}{P[B]}$$

i.e.

$$\frac{P[A|E \wedge H]}{P[B|E \wedge H]} \approx \frac{P[A]}{P[B]}$$

What this equation tells us is that the existence of 'outsiders', civilizations other than the human one, nullifies the Doomsday Argument. And it doesn't matter how many other civilizations there are, since the above logic can be generalized as follows.

Suppose $\exists x$ 'small' civilizations with $m$ inhabitants each and $y$ 'large' civilizations with $n$ inhabitants each (all we really need to assume here is that $m < n$). $A$ is now the multiverse in which the human civilization is one of the small civilizations and $B$ that in which the human civilization is large.

With $H$ still the hypothesis that a random member of the ensemble is human and $E$ the evidence that $X$ is among the first $m$ members of his species, we have

$$P[H|A] = \frac{m}{xm + yn}$$

and

$$P[H|B] = \frac{n}{xm + yn}$$

In addition $P[E|A \wedge H] = 1$

and $P[E|B \wedge H] = \frac{m}{n}$

Bayes's theorem yields

$$\frac{P[A|E \wedge H]}{P[B|E \wedge H]} = \frac{P[E|A \wedge H]}{P[E|B \wedge H]} \cdot \frac{P[H|A]}{P[H|B]} \cdot \frac{P[A]}{P[B]}$$

as before. Putting in the new numbers, we now obtain:

$$\frac{P[A|E \wedge H]}{P[B|E \wedge H]} = \frac{n}{m} \cdot \frac{m}{xm + yn} \cdot \frac{xm + yn}{n} \cdot \frac{P[A]}{P[B]}$$

i.e.

$$\frac{P[A|E \wedge H]}{P[B|E \wedge H]} = \frac{P[A]}{P[B]}$$

The upshot is that the Doomsday Argument is nullified as before—indeed the equation is exact.

The argument presented above would seem to carry by unimpeachable logic, yet there is something strange about it. How can the long-livedness of our human civilization depend on the existence and size of other civilizations, however many or few?[4] The argument is suggesting that we need to take into account the probability that any individual in the ensemble is human, which is different for $A$ and $B$, and when we do so this cancels the Doomsday effect, namely that if a random human is early it is much more likely that our civilization will be short-lived.

In the choice Bostrom presents us with, namely that between multiverse $A$ and multiverse $B$, it is in fact not merely the interdependence of civilizations which is curious but the bizarre nature of that interdependence. Thus, suppose we learn we are in multiverse $A$, i.e. that our civilization is small. It follows that at least one civilization other than our own is different from what it would have been had we learnt that our civilization were large (i.e. that multiverse $B$ obtained). For, given $A$, $\exists$ our civilization, $x - 1$ other small civilizations and $y$ large civilizations. On the other hand, given $B$, $\exists$ $x$ small civilizations, our large civilization, and $y - 1$ other large civilizations.

Perhaps it is easiest to see this point if we take the simplest possible case, that there is one small civilization and one large civilization (i.e. $x = y = 1$). If the human civilization is small then the other civilization is large and vice versa. It is as if the two civilizations were locked together like quantum particles in the famous EPR (Einstein-Podolsky-Rosen) experiment. If we discover one particle to be 'spin up' then the other is instantaneously in the 'spin down' state, and vice versa. This is highly counter-intuitive. Indeed surely the short-livedness of our universe would suggest that other universes too were short-lived. A random sample of one is admittedly small, but it is all we have to go on.

Of course this is begging the question of the *actual* interdependence of different civilizations. In some multiverse scenarios they are taken to be completely independent universes, having no causal contact with our own. In other scenarios, there is indeed some kind of dependence, as in the Everett model in which they are branches separating off from a parent universe through quantum splitting. Whether there is ever such a direct correlation with size, however, is highly questionable.

Perhaps one way round this problem is to redefine the alternatives $A$ and $B$ yet again, as follows:

$A$: $x$ small civilizations with $m$ inhabitants each, plus the human universe as small, plus $y$ large civilizations of $n$ inhabitants each.

$B$: $x$ small civilizations with $m$ inhabitants each, plus $y$ large civilizations of $n$ inhabitants each, plus the human universe as large.

In this case there is no necessary dependence of the universes on each other. The algebra runs like this, with $H$ and $E$ defined just as before:

$$P[H|A] = \frac{m}{xm + m + yn}$$

and

$$P[H|B] = \frac{n}{xm + yn + n}$$

As before $P[E|A \wedge H] = 1$

and $P[E|B \wedge H] = \frac{m}{n}$

Bayes's theorem yields the same formula as earlier:

$$\frac{P[A|E \wedge H]}{P[B|E \wedge H]} = \frac{P[E|A \wedge H]}{P[E|B \wedge H]} \cdot \frac{P[H|A]}{P[H|B]} \cdot \frac{P[A]}{P[B]}$$

Putting in the latest numbers, we obtain:

$$\frac{P[A|E \wedge H]}{P[B|E \wedge H]} = \frac{n}{m} \cdot \frac{m}{xm + m + yn} \cdot \frac{xm + yn + n}{n} \frac{P[A]}{P[B]}$$

i.e.

$$\frac{P[A|E \wedge H]}{P[B|E \wedge H]} = \frac{xm + yn + n}{xm + yn + m} \cdot \frac{P[A]}{P[B]}$$

Note that we do not now have the neat cancellation. This much messier formula shows that there is a dependence on the precise values of $x$, $y$, $m$ and $n$. Taking some examples to correspond as closely as we can to the above we find:

(1) $x = y = 10^6$; $m = 200 \times 10^9$, $n = 200 \times 10^{12}$

In this case $\frac{P[A|E \wedge H]}{P[B|E \wedge H]} \approx \frac{P[A]}{P[B]}$, i.e. very little different from the original example.

(2) $x = y = 1$; $m = 200 \times 10^9$, $n = 200 \times 10^{12}$

Now $\frac{P[A|E \wedge H]}{P[B|E \wedge H]} \approx 2\frac{P[A]}{P[B]}$, i.e. there is a small 'Doomsday factor' of 2.

(3) If we take $x = y = 0$; $m = 2 \times 10^9$, $n = 2 \times 10^{12}$, then of course we obtain the unadulterated Doomsday result:

$$\frac{P[A|E \wedge H]}{P[B|E \wedge H]} = 10^3 \frac{P[A]}{P[B]}$$

We have seen that the final result depends on the precise values of $x$, $y$, $m$ and $n$, though in fact the 'Doomsday factor' rapidly declines once there is at least one other universe of each kind in the ensemble. The upshot is that this refined analysis has not made a great deal of difference.

Ultimately it seems that the crux lies in whether one takes 'outsiders' into account at all. The mathematics of the original Doomsday Argument still seems valid when they are not. Thus if we make X a random individual drawn from the human civilization, and $E$ the evidence that X is early, the Doomsday Argument is simply this, with the Bostrom's original definitions of $A$ and $B$:

$P[E|A] = 1$

and $P[E|B] = 10^{-3}$

Bayes's theorem yields

$$\frac{P[A|E]}{P[B|E]} = \frac{P[E|A]}{P[E|B]} \cdot \frac{P[A]}{P[B]}$$

$$= 10^3 \frac{P[A]}{P[B]}$$

All we have done here of course is omit the dependence on $H$, the hypothesis that X is drawn randomly from the whole ensemble and turns out to be human. Is it only a matter of taste whether we do so or not, or can anything else be said?

We who are doing these calculations are of course human. There is an element of self-selection. It seems hard to imagine myself as a random member of this gigantic ensemble. How can I know anything about the ensemble in the first place? How can I know whether $A$ or $B$ obtains, or the crucial interdependence of civilizations? The choice offered between $A$ and $B$ seems highly artificial.

I think we can in fact go farther. It is not just hard but impossible to imagine myself as a random member of the ensemble. 'I' simply cannot be non-human since 'being human' is an essential part of *me*. Similarly, if X is human he is human necessarily. He cannot, as it were, wake up and find he is a Martian or a dolphin. The idea of taking X or, more obviously, 'I' as a random member of the whole ensemble is exposed as fallacious.

## Possible Humans

It does seem legitimate, however, to imagine myself as a random member of the human race (though see below, since even this claim can be disputed). Suppose I then find that I am within the first 200 billion humans, say. I can postulate that there might be either around 200 billion humans in total, or 200 trillion (I could of course expand the range of possibilities, and do a slightly more elaborate calculation, as indeed has been done in the literature). If I am within the first 200 billion humans, that weights the overall number of humans towards 200 billion rather than 200 trillion.

Or does it? It seems to me that there is a far better (indeed decisive) refutation of the Doomsday Argument, though curiously it is one Bostrom rejects—even though it relies, less controversially one would have thought, on only selecting from human populations.

The Self Indication Assumption (SIA)[5] says that, in assigning my prior probabilities I ought to take into account my own existence. A universe with 200 trillion humans gives me $10^3$ times the probability of existing that a universe with only 200 billion humans does. This factor of $10^3$ will cancel the Doomsday factor which rightly says that, given I exist and if I am 'early', I am $10^3$ times more likely to be in the smaller universe. This can be seen in a rigorous way using Bayes's theorem, as before.[6]

Let $A$ be the hypothesis that the universe is short-lived containing $m$ humans and $B$ be the hypothesis that the universe is long-lived containing $n$ humans ($n > m$).

Suppose there are $N$ possible humans altogether ($N > n > m$).[7] Suppose further that X is a human randomly chosen from the space of possible humans.

Let $H$ be the hypothesis that X exists and $E$ the evidence that X is early, i.e. within the first $m$ humans. Then we have, analogously to earlier equations:

$$\frac{P[A|H \wedge E]}{P[B|H \wedge E]} = \frac{P[E|H \wedge A]}{P[E|H \wedge B]} \cdot \frac{P[H|A]}{P[H|B]} \cdot \frac{P[A]}{P[B]}$$

$$= \frac{n}{m} \cdot \frac{m/N}{n/N} \cdot \frac{P[A]}{P[B]}$$

$$= \frac{P[A]}{P[B]}$$

the Doomsday and SIA factors cancelling, as predicted above.

It seems to me that the fundamental difference between this and the case of 'outsiders' is that existence is not a necessary attribute of *me*.[8] I did not have to exist. I may or may not have existed. However, exist or not, I could not be other than human.

As intimated above, the claim that I can even be regarded as a random member of the human race has also been challenged, notably by Garrett and Coles in a paper we have considered elsewhere in this book, but also by George Sowers.[9] Thus 'I' cannot come at a totally random point in the sequence of humans, because my parents had to precede me, their parents had to precede them, and so on. According to Saul Kripke, I had the origin I did of necessity, with the particular sperm and egg from the particular parents that I had coming together; otherwise I would not be me.[10] Perhaps, then, it would be more accurate to think of X as a random member of the human race, as we have just done, than to think specifically of me. Then it is true that if X exists he is bound to be early in the 200 billion person universe, and early with probability $10^{-3}$ in the 200 trillion person universe. But he is also $10^3$ times more likely to exist given the bigger universe. And so we have the cancellation required to defeat the Doomsday Argument.

The problem now is rather different, but analogous to one we met in chapter 6. There we were not in a position to observe an abstract 'fine-tuned universe', only the particular one we inhabit. Now we are not in a position somehow to select a random member of the human race: we can only choose particular humans from our world who have necessary identifying origins.

Suppose, on the other hand, that my real identity were as a disembodied soul, and my body, genetic make-up, and so on, were not essential to me. We can imagine souls waiting around in heaven for bodies to come along. Then I could imagine myself as a random member of the human race. And then the anti-Doomsday argument would carry through with me instead of X. I am not commending this view of human identity, and neither do those philosophers or physicists who support the Doomsday Argument, but it seems that something like it is required for the Doomsday Argument to get off the ground in the first place. It is of course equally the case that this assumption also contains within it the seeds of the above refutation.[11]

## SIA and Fine-Tuning

Yet another oddity is that both Bostrom and Leslie reject the appeal to SIA, though both believe a multiverse can be invoked to explain the fine-tuning of our universe.[12] However, it seems to me that the clearest way of understanding the multiverse argument (see chapter 6) is in terms of universe selection rather than observer selection (i.e. favouring Sciama, Vilenkin and others, rather than Bostrom's SSA). As such, the argument closely parallels SIA: essentially, the more universes that are instantiated, the more chance there is that ours exists. We can see this by generalizing the argument of chapter 6 as follows.

Suppose there are $N$ possible universes. Suppose our universe is one of $m$ fine-tuned universes permitting life. Let $H_1$ be the hypothesis that only one universe exists and $H_2$ the hypothesis that all possible universes exist. Let $E_1$ be the evidence that a fine-tuned universe exists and $E_2$ the evidence that our universe exists. Then Bayes's theorem gives:

$$\frac{P[H_2|E_i]}{P[H_1|E_i]} = \frac{P[E_i|H_2]}{P[E_i|H_1]}.\frac{P[H_2]}{P[H_1]}, \text{ for } i = 1, 2$$

which yields

$$\frac{P[H_2|E_1]}{P[H_1|E_1]} = \frac{N}{m}.\frac{P[H_2]}{P[H_1]}$$

and

$$\frac{P[H_2|E_2]}{P[H_1|E_2]} = N.\frac{P[H_2]}{P[H_1]}$$

which is how the many universe hypothesis in its various forms explains fine-tuning, though of course, as always, one still has to argue about the priors.[13] Here it would seem that the enhancement factor $N/m$ or $N$ is analogous to the SIA factor $m/n$ which cancelled the Doomsday factor $n/m$ above. In the case of universes, however, there seems no analogy to the Doomsday factor itself, which would require some kind of indexical information about our place in the sequence of universes.

In conclusion it would seem that there is nothing to fear from the Doomsday Argument after all, not because we can appeal to hypothetical aliens to help us, but because we ought properly to take into account our own existence. Moreover, we have shown up the weakness of SSA in multiverse arguments in comparison with the more straightforward appeal to random selection of universes.

## Notes

1 Carter (1983).
2 E.g. Leslie (1990b, 1996). Leslie was responsible in particular for noting the importance of prior probabilities and hence the correct use of Bayes's theorem to derive a shift in probability towards our race's early extinction.
3 Bostrom (2002), pp. 112-114.

4 A puzzling feature noted by Olum, p. 7 in Olum (2000). Bostrom (2002) seems to acknowledge this point (p. 120) but argues that it is not causally disconnected regions affecting each other but only our beliefs about them. But if my beliefs don't reflect the way things really *are*, then it sounds like I have a pretty shaky epistemology.
5 Bostrom (2002), pp. 122-126.
6 This point has been well made by Olum (2000), and by Bartha and Hitchcock (1999).
7 Of course, as is usually acknowledged in the literature, there are complications if $N$ could be infinite. These may or may not be soluble using non-standard analysis (see the doubts I expressed on this for our analysis of chapter 6, in note 8 thereto).
8 An important distinction which Aquinas drew between humans and God is that God 'is his own existence' whereas humans are not, in other words God is necessary but humans only contingent. See *Summa Theologiae,* 1a. 3, 4.
9 Garrett and Coles (1993), pp. 39-44; Sowers (2002).
10 Kripke (1981), pp. 110-115.
11 The idea of pre-existent immortal souls is Platonic rather than Christian, though, as we saw in chapter 6, some philosophers, notably Richard Swinburne, are body-mind dualists (not of course in this Platonic sense). The advantage of dualism theologically is that it makes it easy to see how a person survives after death if there is an immaterial, but essential, part which survives the body's destruction. On the other hand, Christians affirm the resurrection of the body: it is through bodies that human beings function, both now and in the 'new heaven and new earth' to come (Revelation 21:1). Clearly I cannot develop a position on either side of this debate in this book, though it is certainly interesting how it impacts on such apparently remote questions as the Doomsday Argument, many universes, and cosmological design.
12 Note that, in contrast to Bostrom, Leslie retains a belief in the Doomsday Argument because he rejects the need to consider outsiders.
13 More accurately $H_1$ here is the hypothesis that just one universe exists as a random selection from the set of possible universes. Thus for present purposes I have ignored the further hypothesis that there is a single universe *designed* to be fine-tuned, which is of course my favoured view and argued for in the main text.

Appendix E

# The Principle of Maximum Entropy Applied to Cosmology

As noted in chapter 7, some authors have attempted to solve the flatness problem in cosmology through the application of Jaynes's Principle of Maximum Entropy. Since we are dealing with continuous random variables, it is the invariance principle as applied to these which is required, as discussed in Appendix B. We examine in some detail the key papers of Evrard and Coles,[1] and Kirchner and Ellis,[2] both pairs of authors aiming to show that $\Omega_0$ ( $\rho/\rho_c$ evaluated at the present time) should be infinitesimally close to unity.

The evolution of the universe is described classically by the Friedmann equation:[3]

$$\left(\frac{dR}{dt}\right)^2 + kc^2 = \frac{8}{3}\pi G\rho R^2$$

Here $R$ is the cosmic scale parameter,[4] $\rho$ the matter density, $k$ the curvature parameter, $G$ the gravitational constant, and $c$ the speed of light. For much of the universe's history we can regard the universe as pressureless, in which case the law of conservation of mass tells us that the quantity $\rho R^3$ is constant (such a universe is called a 'dust' universe by cosmologists). We define another scale parameter

$$\chi = \frac{4\pi G\rho R^3}{3c^2}$$

Evrard and Coles now write the observable cosmological parameters $\Omega$ and $H$ in terms of the non-observable parameters $R$ and $\chi$ :[5]

$$\Omega = \frac{\rho}{\rho_c} = -\frac{2R.d^2R/dt^2}{dR/dt} = 2\left(2 \mp R/\chi\right)^{-1}$$

and

$$H = \frac{1}{R}\frac{dR}{dt} = \left(\frac{c}{\chi}\right)\frac{\sqrt{2 \mp R/\chi}}{\left(R/\chi\right)^{3/2}}$$

where the $\mp$ corresponds to the two cases $k = \pm 1$.

Next comes the application of Jaynes's principle of invariance which supposedly applies to continuous distributions. Because $R$ and $\chi$ are scale factors it is argued that we should seek a measure $\mu$ such that $\mu d\chi dR$ is invariant under transformations $R' = \alpha R$ and $\chi' = \beta\chi$ where $\alpha$ and $\beta$ are constants. The unique measure so defined is

$$\mu(\chi, R) \propto \frac{1}{\chi R}$$

By substituting from the above equations for $\Omega$ and $H$, and (an important technical point for the mathematically minded) factoring in the determinant of the Jacobian matrix, it is possible to transform this into a measure for $\Omega$ and $H$. The result is

$$\mu(\Omega, H) \propto \frac{1}{H\Omega|\Omega - 1|}$$

Now the first thing to notice about this measure is that it is non-normalizable and hence can only lead to an improper prior probability. We have already noted that improper priors violate the axioms of probability theory and lead to paradoxes. Evrard and Coles argue that one can get round the problem by bringing in additional information, such as the ages of cosmic objects, which would rule out high values of $H$ and $\Omega$. Also appeal could be made to anthropic selection effects.

The problem with this is that this additional information looks very *a posteriori* and $\mu$ is supposed to be a prior measure, before information of that kind is introduced. If we are going to introduce anthropic considerations we might as well revert to design! In any case Evrard and Coles take this suggestion no further.

The key move of Evrard and Coles is now to point to the fact that the measure in $\Omega$ has singularities at $\Omega = 0$ and $\Omega = 1$.[6] Furthermore these singularities are the two 'fixed points' in the evolution of $\Omega$. Models with $\Omega = 1$ remain in that state forever. Models with $\Omega < 1$ (expanding forever models) evolve to a state with $\Omega = 0$. Models with $\Omega > 1$ (recollapsing models) are transitory. Evrard and Coles believe that, in the absence of further information, we should infer that the system is in one of the two fixed states. They also argue that, on this 'least informative measure', any value of $\Omega$ not exactly equal to 1 is actually infinitely far from this value. Flat (uniform) distributions for $\Omega$ are therefore highly deceptive.

We have seen that a value of $\Omega_0$ ($\Omega$ today) close to 1, say $1 \pm 0.5$, implies that $\Omega_P$ ($\Omega$ at the Planck time) needed to be very close to 1 indeed, something like $1 \pm 10^{-60}$. The broad (uniform) measure makes this extremely improbable but the so-called minimum information measure would not imply that the range at earlier and earlier times became arbitrarily improbable. On the contrary the probability associated with the range for $\Omega_0$ is preserved as one goes back in time.

Whilst this all seems very ingenious, there has to be a nagging doubt. We have seen before how paradoxes arise from the insistence on invariance under multiplicative transformations. Milne[7] showed that, for any variable constrained to lie on the positive 'half' of the real line, or a finite sub-interval thereof, scale invariance leads to the paradoxical conclusion that the number is almost certainly 0, remarkably like the conclusion Evrard and Coles come to in the present case, but surely incompatible with what these authors describe as 'the least informative, least-prejudiced measure'. It seems to me that it is a case of 'What you put in is what you get out'.

Kirchner and Ellis make a further, rather technical but quite fundamental, criticism of Evrard and Coles, and then go on to derive a measure of their own. Their criticism of Evrard and Coles is that the parameters $R$ and $\chi$ specify not only the model but also the time during the evolution of the model. Since $\chi$ is constant but $R$ is time-dependent the measure $\mu(\chi, R)$ defined above is not a measure over models, which is what is required, but a measure over an ensemble of possible states of models. This has the unfortunate consequence of assigning different probabilities to the same set of universe models at different times, whereas what we require is time-independent probabilities for models.

Kirchner and Ellis argue that one needs a measure over the constants of motion of the dust models. Starting from the more comprehensive version of the Friedmann equation, which includes the cosmological constant term, namely

$$\left(\frac{dR}{dt}\right)^2 + kc^2 = \frac{8}{3}\pi G\rho R^2 + \frac{1}{3}\Lambda R^2$$

Kirchner and Ellis[8] point out that the constants of motion for dust models are $\chi$ and the cosmological constant $\Lambda$, together with the curvature constant $k$. They then provide a complete classification of models for the two cases of open ($k = -1$) and closed ($k = +1$) universes.

Kirchner and Ellis find that there is a single class of open big bang universe and two classes of closed big bang universe for which the parameters take values in the ranges $0 \leq \chi < \infty$ and $-\infty < \Lambda < \infty$. It follows from Jaynes's principle, taking the derivation I gave in Appendix B, and for the moment ignoring the qualifications expressed there, that the measure in $\chi$ and $\Lambda$ for these open and closed big bang universes is

$$\mu_{ocbb}(\chi, \Lambda) \propto \frac{1}{\sqrt{\chi}} \tag{1}$$

Kirchner and Ellis also find two classes of model, namely closed 'bounce' models, for which the parameters take more restricted values, $\Lambda$ lying in the range $0 < \Lambda < \infty$ and $\chi$ lying in the range $0 \leq \chi \leq c/3\sqrt{\Lambda}$.

We noted in Appendix B how Jaynes's principle can be used to transform a variable confined to a limited range. Utilizing this method, we can parametrize $\chi$ by

$$\chi = \frac{c}{6\sqrt{\Lambda}}[1 - \sin z]$$

where the new variable $z$ can take all real values (and so have uniform measure), and hence we can obtain the measure for the bounce universes

$$\mu_{bounce}(\chi, \Lambda) \propto \frac{1}{\sqrt{\chi}} \cdot \frac{1}{\sqrt{\frac{1}{3}c - \chi\sqrt{\Lambda}}} \cdot \frac{1}{\Lambda^{3/4}} \tag{2}$$

Like Evrard and Coles, Kirchner and Ellis next note that $\chi$ and $\Lambda$ are not observables. We can see how $\Lambda$ makes an effective contribution to the overall energy density by rewriting the Friedmann equation as

$$\left(\frac{dR}{dt}\right)^2 + kc^2 = \frac{8}{3}\pi G \rho_u R^2$$

where total energy density $\rho_u = \rho + \rho_\Lambda$ and $\rho_\Lambda = \Lambda/8\pi G$. The three parameters which uniquely identify a model universe and its age are then the Hubble parameter $H$ and the density parameters $\Omega_\rho$ and $\Omega_\Lambda$ defined by

$\Omega_\rho = \rho/\rho_c$ as before, and $\Omega_\Lambda = \rho_\Lambda/\rho_c$

Kirchner and Ellis then go on to calculate the measure for the current values $\Omega_{\rho 0}$ and $\Omega_{\Lambda 0}$ given the observed value of $H_0$. There are some complications which we skip over for the moment, for example in some models $H = H_0$ is never reached, and in others it is reached twice, so that in the latter case two different points in the ($\Omega_{\rho 0}, \Omega_{\Lambda 0}$) plane correspond to the same model.

First we write $\chi$ and $\Lambda$ in terms of $\Omega_{\rho 0}$ and $\Omega_{\Lambda 0}$:

$$\begin{pmatrix} \chi \\ \Lambda \end{pmatrix} = \begin{pmatrix} \Omega_{\rho 0} c / 2H_0 |\Omega_0 - 1|^{3/2} \\ 3H_0^2 \Omega_{\Lambda 0} \end{pmatrix}$$

where $\Omega_0 = \Omega_{\rho 0} + \Omega_{\Lambda 0}$. Then, factoring in the determinant of the Jacobian matrix, for the open and closed big bang models we obtain:

$$\mu_{ocbb}\left(\Omega_{\rho 0},\Omega_{\Lambda 0}\right) \propto \sqrt{\frac{\Omega_{\rho 0}}{|\Omega_0 - 1|^{3/2}}} \cdot \left|\frac{1}{\Omega_{\rho 0}} - \frac{3/2}{\Omega_0 - 1}\right| \tag{3}$$

The important point to notice is that there is a non-integrable divergence along the line $\Omega_{\rho 0} + \Omega_{\Lambda 0} = 1$.

For closed bounce models, the extra factor in (2) above implies

$$\mu_{bounce}\left(\Omega_{\rho 0},\Omega_{\Lambda 0}\right) \propto \left(2\sqrt{3} - 9\Omega_{\rho 0}\sqrt{\frac{\Omega_{\Lambda 0}}{\left(\Omega_0 - 1\right)^3}}\right)^{-\frac{1}{2}} \Omega_{\Lambda 0}{}^{-\frac{3}{4}}\mu_{ocbb} \tag{4}$$

although this bounce solution only exists for

$$\frac{\Omega_{\Lambda 0}\Omega^2_{\rho 0}}{\left(\Omega_0 - 1\right)^3} \le \frac{4}{27} \tag{5}$$

Having established all this mathematical apparatus we are now in a position to see what conclusions Kirchner and Ellis draw, and to criticize them.

Kirchner and Ellis are rightly worried that the minimum information measure for $\Lambda$ for the open and closed big bang models (equation (1)) does not favour small, non-zero values compatible with observation. They correctly note that only the *a priori* probability allows us to decide whether our universe is likely or not. However, rather than follow this logic to its conclusion, and infer that our universe is not likely, they prefer to speculate about $\Lambda$ being restricted by some unknown and unspecified theory. This is wilfully to ignore the alternative, namely that it was chosen (designed) so that life could evolve.[9] Note also that the measure for the bounce models has a non-integrable divergency for $\Lambda \to \infty$.

Kirchner and Ellis then specialize to the case of fixed $\Lambda$ and take up the point that the measure for open and closed big bang models is integrable for $\Omega_0 \to 0$ and $\Omega_0 \to \infty$ but diverges for $\Omega_0 \to 1$. They then conclude, like Evrard and Coles, that all such models have $\Omega_0$ infinitesimally close to 1, so that the flatness problem is solved, but they remain worried that $\Lambda$ has to be treated differently. It would seem to me that the case of the bounce models is rather different, since if one fixes $\Lambda$ then $\Omega_0$ cannot be allowed to tend to one in view of inequality (5) above.

Of course, the treatment of Kirchner and Ellis, like that of Evrard and Coles, is also subject to the criticism that is endemic to the use of Jaynes's principle, namely that diverging measures lead to paradoxical conclusions. Their results too are a case of 'What you put in is what you get out.' As noted in Appendix B, the measures derived from Jaynes's principle are not unique; rather, there is an inherent ambiguity, for example in deriving the measure for a parameter restricted to a finite interval on the real line. Kirchner and Ellis themselves recognize that problems arise when they note that, because the measures for the open and two types of closed universes diverge, the ratio of the prior probabilities for these alternatives becomes ambiguous so that we cannot say if any is more probable than another.

A further point to note is that imposing a value of $H_0$ automatically excludes from consideration those models which never reach this value. These might be *a priori* probable.

Thus I am extremely sceptical of the conclusions of both Evrard and Coles and Kirchner and Ellis. However, if for a moment we assume that these authors are right, what does this imply? Well, it would seem that there is then no need to invoke inflation or many universes, or even design, to explain the value of this one particular parameter. However, we can still ask van Inwagen's question, 'Even if $\Omega_P$ must lie in a narrow range of necessity, why is it that this narrow range is the only range conducive to life?' We still have to account for the surprising connection between anthropic potentiality and the laws of physics as we understand them, a connection which on the face of it would seem no more likely than that writing the digits of $\pi$ on a grid, and colouring the squares by some arbitrary rule, would produce a painting of the Mona Lisa. Moreover, many other anthropic coincidences remain unexplained.

## Notes

1 Evrard and Coles (1995).
2 Kirchner and Ellis (2003).
3 Derived by applying Einstein's field equations of general relativity to an idealized universe which is perfectly homogeneous and isotropic. Here the cosmological constant $\Lambda$, which Einstein introduced to give static universe solutions, is omitted, but, as we shall see, Kirchner and Ellis include it. We consider the possibility of non-zero $\Lambda$ in more detail in chapter 8.
4 $R$, written more fully as $R(t)$, is a function which measures how the distance between any two particles (or galaxies) in the above idealized homogeneous and isotropic universe changes with time $t$.
5 $H$ is the Hubble parameter which measures the rate of expansion of the universe.
6 It is thus very far from the broad distribution expected by Garrett and Coles (1993), p. 35.
7 Milne (1983). See Appendix B.
8 Kirchner and Ellis actually use slightly different notation and units from those here, which I have retained for clarity and ease of comparison with Evrard and Coles.
9 Perhaps it is a case of reluctance in a scientific paper to acknowledge the design option. Yet Ellis is a theist who advocates design (see for example Ellis (1996), which is very sympathetic to my thesis in this book). He is the recipient of the 2004 Templeton Prize for Progress in Religion, following in the footsteps of earlier winners Polkinghorne, Peacocke, Davies and Barbour whom I mention elsewhere. Some of the problems to do with measure have been recognized, however, in the more recent Ellis, Kirchner and Stoeger (2003).

# Glossary

*Note that italicized items within definitions cross-refer to their own, separate entries.*

**Logical Symbols**

$\rightarrow$ material implication: $A \rightarrow B$ is equivalent to 'if $A$ then $B$'
$\leftrightarrow$ biconditional: $A \leftrightarrow B$ is equivalent to '$A$ if and only if $B$'
iff short for 'if and only if', i.e. same as $\leftrightarrow$
$\wedge$ and (conjunction)
$\vee$ or (disjunction: $A \vee B$ means '$A$ or $B$ or both')
$\sim$ not
$\exists$ there exists

**Mathematical Symbols**

$\rightarrow$ tends to, e.g. $1/x \rightarrow 0$ as $x \rightarrow \infty$
$\sum$ sum; $\sum_{i=1}^{n}$ means sum over the index $i$ going from 1 up to $n$
$\infty$ infinity
$\propto$ is proportional to
$\sim$ is of the order of/approximately equal to
$\approx$ is approximately equal to
$\lesssim$ is less than or approximately equal to
$\gtrsim$ is greater than or approximately equal to
$>>$ is much greater than
$\in$ is a member of: $a \in A$ means that $a$ is an element or member of the set $A$
$P[A]$ probability of $A$
$P[A|B]$ probability of $A$ given $B$
$(a, b)$ open interval on the real line, i.e. all $x$ such that $a < x < b$
$[a, b]$ closed interval, i.e. all $x$ such that $a \leq x \leq b$
$[a, b)$ half open interval, i.e. all $x$ such that $a \leq x < b$

**Symbols for Cosmological Quantities**

$\rho$ mean density of energy in the universe: subdivided into ordinary (*baryonic*) matter, *dark matter*, and *dark energy* components
$\rho_c$ critical density: if $\rho = \rho_c$ the universe is just '*open*'

$R$ scale factor describing the expansion of the universe
$\chi$ constant of motion in *dust universe*
$k$ curvature parameter: $k = -1, 0, +1$ corresponds to *open*, just open, and *closed* universes respectively
$\Omega$ ratio of mean density to critical density: $\Omega = \rho/\rho_c$
$\Omega_0$ present-day value of $\Omega$
$\Lambda$ cosmological constant: repulsive force originally included in field equations of general relativity by Einstein, now associated with *dark energy* and powering of *inflation*
$H$ Hubble parameter: measures the rate of expansion of the universe
$z$ redshift: light from a receding object (galaxy) is shifted towards the red end of the electromagnetic spectrum; radiation received from objects at redshift $z$ was emitted when the universe was a fraction $1/(1 + z)$ of its present size

### Symbols Denoting Physical Constants

$G$ the gravitational constant
$c$ the speed of light
$h$ *Planck's constant*
$\hbar$ $h/2\pi$

### Units

K degrees absolute, i.e. above absolute zero which is $-273°$ Celsius and the minimum possible temperature.
eV electron volt, the energy gained by an electron falling through a potential of 1 volt. 1 GeV (giga electron volt) is $10^9$ eV and is equivalent to a temperature of about $10^{13}$ K.

### Technical Terms in Particle Physics and Cosmology

*Anthropic Principle.* This states that the properties we observe in the universe must be compatible with the fact that we exist. Varieties include *Weak*, *Strong*, and *Participatory Anthropic Principles* (*WAP*, *SAP* and *PAP*).

*Anti-matter.* To each ordinary particle there corresponds an anti-particle with the same mass but opposite electric charge, e.g. the anti-particles of the proton and electron are the antiproton and the positron respectively.

*Baryon.* Subspecies of *hadron* consisting of 3 *quarks*.

*Boson.* Particle with intrinsic *spin* a whole number in units of $\hbar$.

*Brane.* Generalization of *string* to higher dimensions. A *p*-brane has *p* dimensions, and so, for example, a 1-brane is a string and a 2-brane is a membrane.

*Chaotic cosmology.* Cosmological model of Charles Misner which purported to show that the evolution of the universe was not dependent on initial conditions.

*Closed universe.* Universe which eventually recollapses to a 'big crunch'.

*Concordance model.* Name for the currently popular cosmological model consistent with *inflation*, for which $\Omega_0 = 1$, breaking down into *baryonic matter*, *dark matter* and *dark energy* components 0.05, 0.25, 0.7 respectively.

*Copenhagen interpretation.* Interpretation of quantum mechanics whereby measurement of a quantity collapses the *wave function* into a definite state.

*Coupling constants.* Constants measuring the strengths of the *fundamental forces* of nature.

*Dark matter.* Non-*baryonic* matter of unknown identity which is deemed to exist because of its gravitational pull on visible matter.

*Dark energy.* Vacuum energy giving rise to the *cosmological constant* (see definition of $\Lambda$) and so contributing to the overall energy density of the universe—note that the vacuum is a sea of activity in quantum theory.

*Decoherence.* When the interaction with its environment is taken into account the states of a macroscopic object 'decohere' into one definite, classical state.

*Dust universe.* Cosmological model in which pressure is taken to be zero, a good approximation for most of the history of the universe.

*Fermion.* Particle with intrinsic *spin* an odd multiple of $\frac{1}{2}\hbar$.

*Fundamental forces.* The four fundamental forces of nature are: gravity acting between any two masses, electromagnetism affecting charged particles, the weak nuclear force giving rise to radioactive decay, and the strong nuclear force binding *quarks* together in atomic nuclei.

*Gluon.* Particle which carries the strong nuclear force.

*Grand Unified Theory (GUT).* Generic name for speculative theories which seek to unite the electroweak and strong forces.

*Hadron.* Particle which experiences the strong nuclear force.

*Indifference principle.* Name introduced by Ernan McMullin for the principle invoked by chaotic cosmology and inflationary theory according to which the state of the universe today should not depend on initial conditions. Roger Penrose argues that the principle is invalid. Cf. *Principle of Indifference* in probability theory.

*Inflation.* Postulated very short period of rapid, exponential expansion of the universe occurring between $t \sim 10^{-35}$ secs and $t \sim 10^{-32}$ secs from the origin. Invoked to explain some of the anthropic coincidences.

*Inflaton.* Name given to fields which drive *inflation*. In contrast to the familiar electric and magnetic fields, these fields are scalar, i.e. have magnitude but no direction.

*Lepton.* Light particle which experiences the weak, but not the strong, nuclear force.

*Loop quantum gravity.* Alternative *TOE* to *string theory* whereby space-time is granular.

*M-theory.* Theory which unites the five versions of *superstring* theory.

*Magnetic monopoles.* Isolated magnetic north (or south) poles, predicted by *GUTs* to arise as topological defects, misalignments of regions of space due to *phase transitions* proceeding at different rates.

*Many worlds interpretation (MWI).* Interpretation of quantum theory whereby all the outcomes of a quantum measurement are realized but in different, parallel universes.

*Microwave background radiation.* Relic radiation field suffusing the universe, originating from the hot Big Bang but now having cooled to 2.7 K with the universe's expansion.

*No-boundary universe.* Idea of Jim Hartle and Stephen Hawking that the universe is finite but not bounded in imaginary time.

*Open universe.* Universe which expands for ever.

*Participatory Anthropic Principle (PAP).* Highly controversial and speculative claim that 'Observers are necessary to bring the Universe into being' (Barrow and Tipler, following Wheeler).

*Phase transition.* Change of state (like water to ice) brought about by '*spontaneous symmetry breaking*' in the early universe.

*Planck length.* About $10^{-33}$ cm. Size of the universe when quantum gravity becomes important. Size of a typical *string* in *string theory.*

*Planck mass.* About $10^{-5}$ gm. Typical mass of a particle in *string theory.* About $10^{28}$ times the mass of a proton.

*Planck energy.* About $10^{19}$ GeV. Energy at which the strength of gravity between fundamental particles becomes comparable to the other forces. Typical energy of a vibrating *string* in *string theory.*

*Planck time/era.* About $10^{-43}$ secs. Time light takes to travel one Planck length. Age of the universe when quantum gravity becomes important.

*Planck's constant.* Denoted by $h$, with $\hbar = h/2\pi$. Ubiquitous in quantum theory. For example the energy of a photon of frequency $\nu$ is $h\nu$, and quantum mechanical *spin* is a multiple of $\hbar$. $\hbar$ occurs in the formulae for *Planck energy*, *mass*, *length* and *time.*

*Quantum chromodynamics (QCD).* Theory of the strong nuclear force which binds *quarks* to form atomic nuclei.

*Quantum electrodynamics (QED).* Theory of the electromagnetic field consistent with both special relativity and quantum theory.

*Quark.* Elementary constituent of *hadrons*: *quarks* combine in threes to make *baryons* and in twos to make mesons.

*Quintessence.* More general form of *dark energy* which is allowed to vary with time.

*Spin.* Quantum mechanical equivalent of angular momentum in classical physics.

*Spontaneous symmetry breaking.* Process whereby the fundamental forces become distinct from one another at different stages of the early evolution of the universe.

*Standard model.* Theory of particle physics whereby the electromagnetic and weak nuclear forces are combined and the strong force is described by *quantum chromodynamics (QCD)*, cf. the standard model of cosmology which is the Big Bang theory combined with the standard model of particle physics.

*String.* Hypothetical one-dimensional object whose vibrations give rise to the different species of elementary particle.

*String theory.* The theory which attempts to unite quantum theory and gravity by postulating that matter consists of *strings*.

*Strong Anthropic Principle* (*SAP*). Controversial claim that 'The Universe must have those properties which allow life to develop within it at some stage in its history' (Barrow and Tipler, following Carter).

*Superstring theory.* Theory which incorporates *supersymmetry* into *string theory*.

*Supersymmetry.* Principle which relates each *fermion* to a corresponding *boson*.

*Theory of Everything* (*TOE*). Name for hypothetical theory uniting all the forces of nature, in particular making gravity and quantum theory consistent. Candidates include *string theory* and *loop quantum gravity*.

*Wave function.* Describes the state of a system in quantum theory—in fact a superposition of states until observation causes wave-function collapse.

*Weak Anthropic Principle* (*WAP*). Uncontroversial claim that 'What we can expect to observe must be restricted by the conditions necessary for our presence as observers' (Carter).

## Technical Terms from Probability Theory

*Classical probability.* Assignment of probability to 'equally likely outcomes' decided by considerations of symmetry.

*Conditional probability.* Probability of $A$ given $B$, written $P[A|B]$.

*Confirmation.* Evidence $E$ confirms hypothesis H if the *posterior probability* of $H$ given $E$ is greater than the *prior probability*, i.e. if $P[H|E] > \mathrm{P}[H]$.

*Countability.* In mathematics a set is countably infinite if its elements can be put into one-to-one correspondence with the natural numbers 1, 2, 3, ... It transpires that the fractions are countable but the reals (which include numbers such as $\pi$ not expressible as fractions) are uncountably infinite.

*Epistemic probability.* Probability based on evidence.

*Explanatory power.* Probability of evidence $E$ given hypothesis $H$ divided by the *prior probability* of $H$, i.e. $P[E|H]/P[H]$.

*Likelihood.* Probability of evidence $E$ given hypothesis $H$, written $P[E|H]$.

*Logical probability.* Assignment of probability on the basis of a supposed logical relationship between hypothesis and evidence. This is also known as 'objective probability'.

*Measure.* Mathematical function $\mu$ having the property of *countable* additivity of exclusive disjunctions: $\mu[\vee_{i=1}^{\infty} A_i] = \sum_{i=1}^{\infty} \mu[A_i]$ if $A_j \wedge A_k$ is necessarily false for all $j \neq k$. More usually in mathematics the definition is framed in terms of disjoint unions of sets. Probability is a special case in which the measure of the whole space is equal to unity.

*Personal probability.* This utilizes the probability calculus to express the relationships between a particular agent's beliefs. It is also known as 'subjective probability'.

*Physical probability.* Measures the extent to which one event physically causes another.

*Posterior probability.* Probability of a hypothesis $H$ having taken into account specific evidence E as well as background knowledge, written $P[H|E]$.

*Principle of Indifference (PI).* If there is no reason to prefer one hypothesis over another, give all competing hypotheses equal probability. Cf. *indifference principle* in cosmology.

*Principle of Maximum Entropy (PME).* Ostensibly objective way of assigning prior probabilities when possessing only minimum information.

*Prior probability.* Probability of a hypothesis $H$ on the basis of background knowledge (such as the rules of logic) only, written $P[H]$.

*Relative frequency.* This relates probability to the proportion of times a particular outcome occurs over many trials.

*Statistical probability.* Probability defined by the *relative frequency* approach.

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