10

The Multiverse Scenario

> *Alice laughed. 'There's no use trying' she said: 'One can't believe impossible things.' 'I daresay you haven't had much practice', said the Queen. 'When I was your age I always did it for half-an-hour a day. Why, sometimes I've believed as many as six impossible things before breakfast.'*
>
> Lewis Carroll, *Alice in Wonderland*, 1865

Among the recent physical theories that have attracted much attention both in scientific circles and in the public arena, the theory of the 'multiverse' stands out as a particularly interesting example of a higher speculation.[1] The basic claim of this theory—that there exists a multitude of other universes with which we have no contact and never will have contact—is not new in itself; but it is new that the claim has become part of scientific discourse and won acceptance in a not insignificant part of the community of theoretical physicists and cosmologists. What used to be a philosophical speculation is now claimed to be a new paradigm in cosmological physics, meant to replace the traditional ideal of explaining the universe and what is in it in a unique way from first principles. Perhaps, says one theorist, 'we are facing a deep change of paradigm that revolutionizes our understanding of nature and opens new fields of possible scientific thought'. Another theorist confirms that 'We are in the middle of a remarkable paradigm shift in particle physics'.[2] The new multiverse physics invites a different style of science where strict predictability and ordinary testability are abandoned or given low priority. Probabilistic reasoning based on the anthropic principle is an important part of the new style.

The universe-versus-multiverse debate is an interesting case of a contemporary controversy that concerns foundational issues. Part of the controversy is philosophical in nature insofar that it deals with the definition of science, but the participants are nonetheless the physicists themselves rather than professional philosophers. It opens a window on what might be thought to be a phenomenon of the past, namely, physicists acting as natural philosophers. At the same time, bandwagon effects and other sociological mechanisms are clearly at play. 'The smart money will remain with the multiverse and string theory', announces *New Scientist*, quoting the prominent string theorist Brian Greene of Columbia University as a convert to the new kind of physics: 'I have personally undergone a sort of transformation, where I am very warm to this possibility of there being many universes, and that we are in the one where we can survive.'[3] The multiverse style of doing physics has gained momentum, but it is too early to say if it will be the framework for tomorrow's theoretical cosmology. In spite of its undecided and peripheral status (as seen from the perspective of mainstream cosmology), it is worthwhile to examine it critically within a historical context.

10.1 EARLY IDEAS OF MANY WORLDS

Speculations concerning multiple worlds, conceived in either a spatial or temporal sense, can be traced back to the pre-Socratic philosophers, when such ideas were first discussed by Anaximander and Anaximenes. Epicurus, the Greek philosopher who lived about 300 BC and who is also known for his version of atomism, believed that 'there are infinite worlds both like and unlike this world of ours'. He argued as follows: 'For the atoms being infinite in number . . . have not been used up either on one world or on a limited number of worlds, nor on all the worlds which are alike, or on those which are different from these. So that there nowhere exists an obstacle to the infinite number of worlds.'[4] Much later, the fascinating idea of many worlds reappeared in a debate among scholars in the Middle Ages, who usually assumed the hypothetical other worlds to be identical or nearly identical to ours. One of the most prominent of the scholastic thinkers, the fourteenth-century Parisian philosopher and mathematician, Nicole Oresme, entertained ideas not only about worlds within worlds, but also about worlds that exist beyond our world and are concentric with it.[5] He considered the scenario a logical possibility, although he admitted that it could neither be proved by reason nor by evidence from experience. Medieval philosopher-theologians might conclude that the omnipotent God could have created a multitude of universes (since the notion was logically allowed), but they also concluded that God in his fathomless wisdom had chosen not to do so.

In the late renaissance, the notion of many worlds figured prominently in the cosmology of Giordano Bruno and since then the idea has been a standard ingredient in cosmological speculations. Bruno was convinced that the universe at large was infinite and that it contained an infinity of complete 'worlds' or solar systems, some of which he thought were entirely separated from our own world. A century later Leibniz suggested his famous hypothesis of 'possible worlds', with which he referred to the infinity of worlds that God could have created but had chosen not to actualize. Leibniz argued that God must have chosen this universe out of a multitude of other possibilities, 'for this existing world being contingent and an infinity of other worlds being equally possible, and holding, so to say, equal claim to existence with it, the cause of the world must needs have had regard or reference to all these possible worlds in order to fix upon one of them'.[6] In general he subscribed to the so-called principle of plenitude, the metaphysical idea that all that can exist actually does exist. Or, in an alternative formulation, what is not forbidden is compulsory.

The many possible worlds hypothesized by Leibniz were logically self-consistent but not as perfect as the existing one, the 'best of all possible worlds' (note that he did not refer to the Earth). Since Leibniz distinguished between possible worlds and the one and only real world, he cannot be considered a precursor of the multiverse. At any rate, when considering the early ideas of multiple worlds, such as were suggested in very different ways by Bruno and Leibniz, one should keep in mind that they were not, and were not meant to be, scientific contributions to astronomy. They were philosophical speculations, usually serving a moral and theological purpose. Yet they were commonly known and discussed, both in the contexts of theology and natural philosophy. One example among many is the famous Scottish philosopher David Hume, who in the posthumously published *Dialogues Concerning Natural Religion*, an attempt to undermine the generally accepted belief in natural theology, has one of his characters say:

> Many worlds might have been botched and bungled, throughout an eternity, ere this system was struck out; much labour lost; many fruitless trials made; and a slow and continued improvement carried on during infinite ages in the art of world-making. In such subjects, who can determine where the truth, nay, who can conjecture where the probability lies, amidst a great number of hypotheses which may be proposed, and a still greater which may be imagined.[7]

It is as if Hume anticipated the much later controversy over the multiverse. Another Enlightenment natural philosopher who speculated about the possibility of many worlds with different properties was Roger Boscovich, a contemporary of Hume, who was mentioned in Chapter 1.

Speculations about others worlds or dimensions were as common in the Victorian era as they were at the time of Leibniz and Hume. Some of them were mathematical pastimes, some were science fiction, and others again were associated with a spiritual meaning. Stewart and Tait's *Unseen Universe* of 1875, describing a world connected by bonds of etherial energy to the visible universe, belonged to the latter category (see Chapter 2). Louis-Auguste Blanqui, a French revolutionary activist and utopian communist, subscribed to the idea of an infinite and eternal universe consisting only of matter moving in space. He argued that, in a materially homogeneous and infinite universe, atoms must combine in identical structures and do so an infinite number of times. Therefore, at any given moment in time there would be exact replicas of any number of humans elsewhere in the universe, all of them performing the same actions and thinking the same thoughts. These doubles, he wrote, 'are of flesh and blood, or in pants and coats, in crinoline and chignon. These are not phantoms: they are the now eternalized'. Far from admitting that he was speculating, Blanqui claimed that his conclusions were 'a simple deduction from spectral analysis and from Laplace's cosmology'.[8] Replace 'spectral analysis' with 'string theory' and 'Laplace's' with 'inflationary', and we have a claim close to that of modern multiverse physicists.

The famous American astronomer Simon Newcomb, a professor of mathematics and astronomy at Johns Hopkins, was among the scientists who toyed with ideas of many universes, but without taking them very seriously. 'Right around us', he wrote, 'but in a direction which we cannot conceive, . . . there may exist not merely another universe, but any number of universes.'[9] Newcombe maintained that even if a fourth space dimension existed, the other universes or 'hyperspaces' associated with it would forever remain unknown to us and therefore not belong to the realm of true science.

Among the many pre-1900 speculations of multiple worlds, the one of greatest scientific impact was probably Boltzmann's idea of how the universe might locally escape the heat death predicted by the second law of thermodynamics. In the 1890s the Austrian pioneer of statistical physics argued that while the universe as a whole, implicitly supposed to be infinitely old, would be in an equilibrium state corresponding to maximum entropy, this might not be the case with all the parts of the universe. Basing his argument on the probabilistic notion of entropy he had introduced in 1877, in 1895 he developed a remarkable scenario of anti-entropic pockets in an infinite or perhaps just exceedingly large universe:

> If we assume the universe great enough we can make the probability of one relatively small part being in any given state (however far from the state of thermal equilibrium) as great as we please. We can also make the probability great that, though the universe is in thermal equilibrium, our world is in its present state. . . . Assuming the universe great enough, the probability that such a small part of it as our present world be in its present state, is no longer small. If this assumption were correct, our world would return more and more to thermal equilibrium, but because the whole universe is so great, it might be probable that at some future time some other world might deviate as far from thermal equilibrium as our world does at present.[10]

In Boltzmann's many-worlds scenario the 'worlds' were just different parts of the universe—he might have thought of different stellar systems or nebulae—not causally separated areas as in later multiverse ideas.

To jump ahead in time, relativistic cosmology changed the notion and way of thinking of many separate universes. Shortly after the introduction of the expanding universe, Eddington pointed out that the accelerated expansion of the closed Lemaître-Eddington universe with a positive cosmological constant would eventually lead to a situation with many distinct universes, although these were located in the same cosmic space: 'Objects separating faster than the velocity of light are cut off from any causal inference on one another, so that in time the universe will become virtually a number of disconnected universes no longer bearing any physical relation to one another.'[11] Here we have for the first time a scientifically sound prediction of a simple multiverse. Incidentally, in the same paper Eddington introduced the famous balloon analogy of a closed expanding universe, asking his audience to 'imagine the nebulæ to be embedded in the surface of a rubber balloon which is being inflated'.

As mentioned in Chapter 8, it is also from this period that we have the first relativistic models of a temporal multiverse, namely a cyclic universe of the kind contemplated by Richard Tolman in particular. In an investigation of inhomogeneous solutions of the cosmological field equations, Tolman was brought to consider also a different kind of multiverse, the spatial version. He observed that in such a universe, known as the Lemaître–Tolman model, there is the possibility that the universe can be open in one part of spacetime and closed elsewhere. Although inhomogeneous as a whole, the Lemaître–Tolman universe may contain independent homogeneous regions of different density and curvature. 'Some of these regions', he wrote, 'might be contracting rather than expanding and contain matter with a density and stage of evolutionary development quite different from those with which we are familiar.'[12]

Related ideas of what became known as bubble universes (the name seems to be due to Eddington) were proposed by a few astronomers and physicists in the 1960s, but without attracting much attention. The earlier mentioned Hoyle–Narlikar steady-state theory is an example. In the development of this cosmological theory the two physicists were led to consider separate and continually forming bubble universes of which our own was just one bubble among others. Hoyle even speculated that the empirically known physical constants, such as the mass ratio between the proton and the electron, might reflect the size of the particular bubble universe we inhabit and thus not be constant on the largest possible scale. 'The particular values we find for the dimensionless numbers of physics, or of some of these numbers, could conceivable belong to our locality', he said. 'If their values were different in other localities the full range of the properties of matter would be incomparably richer than it is usually supposed to be.'[13] Some forty years later a new generation of multiverse physicists would repeat Hoyle's speculation that the environment determines the physical laws and constants.

Of course, philosophers had long been familiar with the notion of other universes, if usually taken in a metaphysical rather than physical meaning. 'There is nothing necessary about a physical universe', Lewis Feuer, a young American philosopher, pointed out in 1934. 'There is no formal contradiction in supposing that the physical relationships might be other than they are. One may legitimately speculate on the possible existence of regions where different laws obtain.'[14]

10.2 THE MODERN CONCEPT OF THE MULTIVERSE

Although the term 'multiverse' can be found in the early part of the twentieth century, and possibly earlier, in a scientific context it is quite new.[15] The first time it appeared in the title of a scientific publication seems to have been in 1998 (according to the Web of Science). However, the name itself is unimportant and there are other, broadly synonymous but less catchy names such as pluriverse, megaverse, and parallel worlds. More important is the meaning of the term, which in a general sense refers to 'worlds' with which we have no causal contact and possibly never will have contact. We cannot communicate with them, nor can we receive physical signals of any kind from them. In other words, we cannot establish their existence by direct empirical means.

There are different versions or levels of the multiverse and several ways to classify multiverse theories. Although some are more popular than others, none has won general recognition. According to a simple classification, which has some merit from the point of view of history of science, one can distinguish between (1) temporal multiverse models, (2) spatial multiverse models, and (3) models with other-dimensional universes. To these may be added (4) hierarchical or fractal universes.[16] The first class comprises the cyclic models dealt with in Chapter 8.

The simplest spatial multiverse is not very exotic as we only have to refer to our own universe, assuming that it is flat and infinite and satisfying the cosmological principle of uniformity. The classical Einstein–de Sitter universe of 1932, which expands critically as $R \sim t^{2/3}$, might be an example. In this model, where the expansion decelerates, one can in principle travel to arbitrarily distant regions, which is not possible in a universe with a growing expansion. As pointed out by Eddington, the universe does not have to be open to evolve into a multiverse, as does the closed and accelerating Lemaître–Eddington model. If the universe is both open and accelerating, as we now have strong reason to believe, there will be an infinity of causally disjoint regions or subuniverses. Not only are they inaccessible, but because there is an infinity of them one meets a number of conceptual problems that appear with a realized infinite ensemble. Still, this kind of multiverse is relatively uncontroversial. It constitutes the first level in the hierarchy of multiverse models proposed by the Swedish-born MIT physicist Max Tegmark, which includes universes increasingly more exotic and different from the one we know.[17] Whereas there is only one big bang in class I, in Tegmark's class II there are many big bangs, leading to a multitude of different universes governed by low-energy 'effective laws' with different dimensionality, particle content, constants of nature, etc. On the other hand, the truly fundamental laws are the same. Level III universes are essentially those associated with the Everett many-worlds interpretation of quantum mechanics, while the ultimate multiverse of level IV comprises an infinity of 'Platonic' universes governed not only by different laws of physics but also with different mathematical structures (see below).

Several historical roots can be identified for the idea of the modern multiverse such as emerged in the early years of the twenty-first century. For one thing, although ideas of many universes were not highly regarded, they had been discussed ever since the 1930s and were known to most cosmologists. Based on very different arguments, namely that anthropic coincidences could be explained on the basis of a 'world ensemble' hypothesis, Brandon Carter introduced in 1974 the modern formulation of the anthropic principle (see Chapter 9). His argument included the hypothesis of 'an ensemble of universes characterised by all conceivable combinations of initial conditions and fundamental constants'. Carter's anthropic principle came to play a very important role in later multiverse physics, but the connection was only established in the 1990s (although it was suggested earlier). Until then the multiverse and the anthropic principle were rarely seen as naturally connected. Of greater importance for the increased interest in the multiverse was the later recognition of what is known as the many-worlds interpretation of quantum mechanics. In fact, Carter thought that the latter interpretation supported the idea of a world ensemble: 'Although the idea that there may exist many universes, of which only one can be known to us, may at first sight seem philosophically undesirable, it does not really go very much further that the Everett [many-worlds] doctrine to which one is virtually forced by the internal logic of quantum theory.'[18]

In 1957 the young American mathematician and physicist Hugh Everett, at Princeton University, came out with a radically new 'relative state' interpretation, which challenged the orthodox Copenhagen interpretation due to Bohr, Heisenberg, Rosenfeld, and others. With Wheeler as his supervisor, he stated the new theory in the form of a PhD dissertation, and later the same year a much shorter version was published in *Reviews of Modern Physics*.[19] According to the Copenhagen view, a physical system described by a superposition of wave functions cannot be assigned reality before it is measured or observed. What happens at the moment of measurement is that the quantum state collapses to the one corresponding to the observed result. The other possible outcomes—and in general there are many of these—remain unrealized: reality is brought into existence by the collapse of the wave function caused by an observation. Everett's picture was entirely different, as he argued that the puzzles of quantum mechanics (such as Schrödinger's cat) could be explained by denying the collapse. Wave functions, he said, are real and continue to be described by the Schrödinger equation; they describe events that are real irrespective of observation and intervention of human consciousness. The post-measurement states that are unobserved are no less real than the measured one. Each outcome of a possible quantum event exists in a real world, if not in ours. In his published paper Everett faced the objection that no kind of such a 'splitting' process is known empirically:

> Arguments that the world picture presented by this theory is contradicted by experience, are like the criticism of the Copernican theory that the mobility of the earth as a real physical fact is incompatible with the common sense interpretation of nature because we feel no such motion. In both cases the argument fails when it is shown that the theory itself predicts that our experience will be what it in fact is.[20]

According to the Everett interpretation, by every subatomic process the world splits, branches, or multiplies, with our own bodies and brains being parts of the ceaseless multiplication. The other worlds are not 'failed' worlds, potential but non-realized worlds in some Leibnizian sense, they are every bit as real as the one we live in. Schrödinger's famous cat is not dead *or* alive, it is dead *and* alive, if not at the same place and time. Unfortunately the other worlds are strictly disconnected from ours. Everett showed in his work of 1957 that this strange picture, based on the postulate that all quantum possibilities are real, results in the very same experimental predictions as the

Copenhagen interpretation of quantum mechanics. Thus, from an instrumentalist point of view the two interpretations were equivalent.

The amazing alternative to understanding quantum mechanics that Everett proposed only became widely known in 1970, after it was described and popularized by Bryce DeWitt, a physicist at the University of North Carolina who at the time specialized in problems of quantum gravity.[21] For this reason it is also known as the Everett–DeWitt interpretation or sometimes the Everett–DeWitt–Wheeler interpretation. (There are differences between the versions of Everett and DeWitt, but these are unimportant in the present context.) DeWitt gave more emphasis to the splitting and the many 'maverick worlds' arising from the infinities of measurements:

> This [our] universe is constantly splitting into a stupendous number of branches, all resulting from the measurementlike interactions between its myriads of components. Moreover, every quantum transition taking place on every star, in every galaxy, in every remote corner of the universe is splitting our local world on earth into myriads of copies of itself.[22]

As he remarked with an understatement: 'The idea of 10^{100+} slightly imperfect copies of oneself constantly splitting into further copies, which ultimately become unrecognizable, is not easy to reconcile with common sense.' DeWitt also intimated that the many-worlds interpretation might have testable implications for big bang cosmology, but otherwise he did not relate the new picture of quantum mechanics to the universe as studied by astrophysicists and cosmologists. Nor did Everett in his works of 1957.

By the 1980s the many-worlds interpretation was receiving increasing attention, not least among physicists trying to describe the universe in terms of quantum theory. Although it was still a minority view, as it supposedly still is, it induced physicists and cosmologists to think about other worlds as something more than just a philosophical speculation. There is no doubt that the more sympathetic response to the many-worlds interpretation was a factor in the new multiverse cosmology that emerged shortly after the turn of the century. But it is unclear to what extent this was the case and it is also not very clear if the universes of the multiverse are to be thought of in the same way as the worlds of the Everett interpretation of quantum mechanics. In a series of works starting in the 1980s Viatcheslav Mukhanov argued that the multiple quantum worlds are all real, exhibiting all possible values of physical constants and other parameters. He maintained that all conceivable processes, including those violating the second law of thermodynamics, take place in reality. Not all proponents of the Everett interpretation are willing to go that far or even to admit the physical reality of the other worlds.

According to some enthusiasts of multiple worlds, the many-worlds interpretation is the *only* logical interpretation of quantum mechanics and the two are really just different sides of the same coin. 'The discovery of quantum mechanics', says Mukhanov, 'was in fact the discovery which gave a solid scientific basis to the "Multiverse versus Universe" debate.'[23] Tegmark too believes that the existence of many universes follows as a prediction of quantum mechanics: 'Accepting quantum mechanics to be universally true means that you should also believe in parallel universes.'[24] So does Tipler, who considers the many-worlds interpretation a misnomer, since it is the only possible interpretation: 'More precisely, if the other universes and the multiverse do not exist, then quantum mechanics is objectively false. This is not a question of physics. It is a question of mathematics.'[25] In spite of such bombastic statements, far from all physicists endorse the Everett interpretation. Nor do they agree that acceptance of quantum mechanics leads to the multiverse or that the two are intimately connected or connected at all. According to critics, the many-worlds interpretation has nothing to do with either the multiverse or the anthropic principle. Besides, many physicists see no reason to adopt the interpretation of Everett and DeWitt instead of the standard Copenhagen interpretation.

At about the same time that physicists warmed to hypotheses of many universes, philosophers discussed somewhat similar ideas. However, there was little connection between the two groups. In a book of 1981, the American philosopher Robert Nozick at Harvard University introduced the 'fecundity assumption', without referring to Carter's anthropic principle or the many-worlds interpretation of quantum mechanics. According to the principle of fecundity, the answer to the question 'why X rather than Y'—for example, why do we live in the universe X rather than in some other universe Y?—is that both X and Y exist but that we happen to experience X. All possibilities are realized and the actual world is merely the world we inhabit, because it makes our existence possible. 'The hypothesis of multiple independent worlds', Nozick said, 'enables us to avoid leaving something as a brute fact, in this case, that there is something.'[26] Nozick's principle of fecundity was a multiverse idea, but apparently it had no impact on the works of the cosmologists.

Although ideas of many universes were well known about 1980, the majority of physicists and cosmologists tended to consider them heterodox, weird, and speculative. The successful inflationary theory of the early universe proposed by Alan Guth in 1981 did much to change the situation, if not immediately. This first happened with the versions of 'chaotic' and 'eternal' inflation introduced by the Russian-born physicists Andrei Linde and Alexander Vilenkin a few years later. (Vilenkin was actually born in Ukraine, then part of the Soviet Union; he emigrated to the United States in 1976 and was followed by Linde in the late 1980s.) Linde, then at the Lebedev Physical Institute in Moscow, concluded early on that after the brief inflationary phase the universe became divided into an infinity of bubble- or subuniverses. At the Nuffield Workshop on the Very Early Universe that convened in Cambridge, England in the summer of 1982, he gave a brief description of the new bubble-universe scenario and also related it to the anthropic principle:

> In the scenario suggested above the universe contains an infinite number of mini-universes (bubbles) of different sizes, and in each of these universes the masses of particles, coupling constants etc. may be different due to the possibility of different symmetry breaking patterns inside different bubbles. This may give us a possible basis for some kind of Weak

> Anthropic Principle: There is an infinite number of causally unconnected mini-universes inside our universe, and life exists only in sufficiently suitable ones.[27]

Linde likened what he called the chaotic inflationary scenario to an infinite chain reaction with no end and possibly no beginning either. It followed as a consequence of the scenario that 'the universe is an eternally existing, self-reproducing entity, that it is divided into many mini-universes much larger than our observable portion, and that the laws of low-energy physics and even the dimensionality of space–time may be different in each of these mini-universes'.[28] Here we have the multiverse fully expounded. Moreover, in an important paper of 1986 he made it clear that he thought of the universe as a multiverse, or rather a tiny part of it, and, moreover, that he saw the idea associated with and supported by string theory:

> *All* types of mini-universes in which inflation is possible should be produced during the expansion of the universe, and it is unreasonable to expect that our domain is the only possible one or the best one. From this point of view, an enormously large number of possible types of compactification which exist, e.g. in the theory of superstrings should be considered not as a difficulty but as a virtue of these theories, since it increases the probability of the existence of mini-universes in which life of our type may appear. The old question why our universe is the only possible one is now replaced by the question in which theories the existence of mini-universes of our type is possible.[29]

In a book of 1987, celebrating the tercentenary of Newton's *Principia*, Linde repeated his idea of an anthropic multiverse. He concluded by stressing the difference between the new approach and the traditional one based on deductions from a fundamental theory: 'The line of thought advocated here is an alternative to the old assumption that in a "true" theory it must be possible to compute unambiguously all masses, coupling constants, etc. . . . This assumption is probably incorrect; in any case it is not necessary.'[30]

By 1990, then, there existed a variety of ideas of how multiple universes might be generated. Some of them were based on inflation theory, others on hypotheses of cyclic universes, and others again were motivated by the many-worlds interpretation of quantum mechanics.

According to the self-reproducing or eternal inflationary scenario, bubble universes will be produced constantly from regions of false vacuum and the universe as a whole, meaning the multiverse, will regenerate eternally. Vilenkin claims that inflationary cosmology, at least in the favoured eternal version, makes the multiverse 'essentially inevitable',[31] a claim supported by some other advocates of the multiverse. Guth, the primary originator of inflation theory, came to share the belief of Linde, Vilenkin, and others that inflation means multiplicity of universes. In *The Inflationary Universe*, a popular book that appeared in 1997, Guth wrote:

> If the ideas of eternal inflation are correct, then the big bang was not a singular act of creation, but was more like the biological process of cell division. . . . Given the plausibility of eternal inflation, I believe that soon any cosmological theory that does not lead to eternal

> reproduction of universes will be considered as unimaginable as a species of bacteria that cannot reproduce.[32]

As Guth and others have pointed out (or claimed), in a multiverse consisting of an infinity of universes anything that can happen will happen, and it will happen infinitely often. Anything is possible, unless it violates some absolute conservation law. According to the analysis of Guth and his collaborators, inflation will go on forever in the future, but it is probably not eternal in the past. In that case a primary big bang is still part of the picture, just as it is in cyclic theories with a limited number of past cycles.

The possibility of an infinite universe, whether connected with multiverse ideas or not, has caused concern among some modern cosmologists, as it did among philosophical cosmologists in the past. In a paper of 1979, Ellis and his collaborator G. B. Brundrit pointed out that in a low-density expanding universe it is highly probable that there exists an infinity of 'worlds' with an infinity of 'populations of beings identical in number and genetic structure with that on the Earth'.[33] Although we will never be able to observe these other worlds or populations, we can be 'reasonably confident' of their existence. As a way out of the dilemma, they mentioned the possibility that the cosmological principle might not hold true for the universe at large. The same problem, but now in the context of inflationary cosmology, was examined several years later by Vilenkin and Jaume Garriga of the Autonomous University of Barcelona. Apart from its basis in inflation, the conclusion of Garriga and Vilenkin was largely the same, namely that there is an infinite number of 'unquestionably real' cosmic regions with histories identical to ours.[34] The kind of universe considered by Ellis and Brundrit, an open and uniform one, was what Tegmark later called a level I universe. By counting the number of quantum states that a Hubble volume can have, Tegmark concluded again that in some far away galaxy there will exist identical copies of you and me. In fact, there will be an infinite number of such copies, the closest one (don't worry) some $(10^{10})^{29}$ m away.[35]

The problem of an infinite universe, either in a spatial and material sense or in a temporal sense, has been considered more seriously by Ellis and his two colleagues U. Kirchner and William Stoeger, who argue forcefully against an actually existing infinite set of anything: electrons, universes, or time units. The objections against such actual or realized infinities are old and of a conceptual and logical rather than scientific nature. David Hilbert was only one of many who objected: in a lecture of 1925, he concluded that 'the infinite is nowhere to be found in reality; it neither exists in nature, nor does it provide a basis for rational thought'.[36] Finding the situation in modern cosmology, with its apparent justification of an infinity or worlds, to be 'distinctly uncomfortable', Ellis and his coauthors suggest that a cosmologically flat space is probably an abstraction that does not hold physically.[37] Most other cosmologists seem to be undisturbed by the infinity problem and consider it to be of no scientific relevance.

One should not believe that the ghost of infinity is something discovered by modern cosmologists. On the contrary, it is hard to think of an older problem. It has been discussed since the time of Aristotle, the consensus view being that actual infinities cannot exist. In many cases the rejection of real or physical infinities was theologically based, namely that infinity is a quality that belongs to God alone. For example, this was one of the reasons the brilliant mathematician (and devout Catholic) Augustin Cauchy gave for rejecting the possibility of an actual infinity. Later in the nineteenth century the question was re-examined in an original way by the German mathematician Georg Cantor in his theory of transfinite numbers. It also became part of the controversy over the heat death, which was generally seen as a realistic scenario of the future only if the universe was of finite size. One of the standard objections to the heat death was to postulate an infinite universe to which the law of entropy increase presumably did not apply. During the period of controversy, roughly 1870–1910, the possibility of actual infinities was scrutinized by many scientists, philosophers and theologians. The Catholic philosopher Constantin Gutberlet spoke for most of them when he concluded that 'it is absolutely impossible that the number of celestial bodies or atoms can be infinite'.[38] The concern of Ellis and his colleagues can to some extent be seen as a continuation of this nineteenth-century historical tradition.

But let me return to the multiverse of the modern period. Since the beginning of the twenty-first century there has been a marked change in the interest in and attitude to the multiverse scenario. Some eminent physicists have 'converted' from the idea of a single universe to the possibility of many universes, and more find it at least worthwhile to discuss the multiverse. Part of the reason has been the increased focus on the cosmological constant as a source of the dark energy that followed the discovery of the accelerated universe.

Another very important reason, apart from the inflation model, is that theoretical advances in string theory (or M-theory) have inspired confidence in the multiverse. As mentioned, the idea of relating the multiverse to concepts of string theory was suggested by Linde in 1986, but it only appeared in detailed form several years later. Similarly, the connection between string theory and the anthropic principle was largely ignored in the two last decades of the twentieth century, when string theorists tended to shun anthropic ideas. As the Dutch theorist A. N. Schellekens observed, 'The number of string papers before 2000 containing the "A-word" can be counted on the fingers of one hand.'[39] The situation only began to change with a paper of 2000 in which two string theorists, Raphael Bousso at Stanford University and Joseph Polchinski at the University of California, Santa Barbara, demonstrated mathematically that a very large number of string vacuum states might explain the size of the cosmological constant without direct appeal to fine-tuning.[40] The Bousso–Polchinski theory indicated a way to create new bubble universes somewhat similar to that of eternal inflation, but based on the fundamental string theory.

String theorists have traditionally hoped that the theory, when sufficiently developed and understood, would result in a unique compactification or in a 'vacuum selection principle' from which the one and only vacuum state describing the universe would emerge (see further Chapter 11). It now seems that this ambitious hope has to be abandoned for good. Apparently there is no unique way in which string theory can predict all the constants of nature by compactifying the six extra dimensions that are additional to the ordinary four dimensions of space-time. Each of these compactifications corresponds to a distinct vacuum state of space–time with a particular set of physical parameters, interactions, and types of particles. Such a vacuum is taken to represent a possible low-energy world with its own laws and constants of physics. This theory of a 'landscape' of universes has since 2002 been promoted and developed by many physicists, in particular by Leonard Susskind of Stanford University, one of the founding fathers of string theory.[41] Susskind's popular book *The Cosmic Landscape* appeared in 2006, significantly subtitled *String Theory and the Illusion of Intelligent Design*.

Like most advocates of the multiverse, Susskind believes that the anthropic principle plays an important and legitimate role in cosmology, but in a version that does not in any way indicate a benevolent creator. It is a general feeling among physicists that the multiverse is intimately connected with anthropic reasoning. Some believe that if it can be proved that the landscape follows from string theory, the anthropic principle will become an almost inevitable part of physics. 'The combination of inflationary cosmology and the landscape of string theory gives the anthropic principle a scientifically viable framework', Guth says.[42]

Linde has spelled out the connection from the landscape to the anthropic principle as follows:

> If this scenario [the landscape] is correct, then physics alone cannot provide a complete explanation for all properties of our part of the Universe. . . . According to this scenario, we find ourselves inside a 4-dimensional domain with our kind of physical laws, not because domains with different dimensionality and with alternative properties are impossible or improbable, but simply because our kind of life cannot exist in other domains.[43]

In another comment Linde has summarized the twin ideas of the multiverse and the anthropic principle, at the same time indicating the controversy these ideas have brought with them: 'In some other universe, people there will see different laws of physics. They will not see our universe. They will only see theirs. They will look around and say, "Here is our universe, and we must construct a theory that uniquely predicts that our universe must be the way we see it, because otherwise it is not a complete physics." Well, this would be a wrong track because they are in that universe by chance.'[44]

The string landscape provides the possibility of an enormous number of universes, and eternal inflation provides a mechanism for generating them. To describe the very large but discrete set of states, the word 'discretuum' has been coined. The number of different vacuum states or possible universes that come out of string theory is a staggering 10^{500} or more.[45] Sometimes the figure 10^{1000} is quoted, but what matters is that the number of universes is huge beyond comprehension. Since no reasons have been found that any of the vacua are preferred over others, it is assumed that each of the vacua is *a priori* a valid candidate for a universe. The many universes are claimed to really exist or to be parts of the 'populated' landscape. However, it is not obvious what such a reality claim implies, just as it is not obvious what the reality of the many worlds in the Everett theory means. Susskind explains: 'What physicists . . . mean by the term *exists* is that the object in question can exist *theoretically*. In other words, the object exists as a solution to the equations of the theory. By that criterion perfectly cut diamonds a hundred miles in diameter exist. So do planets made of pure gold. They may or may not actually be found somewhere, but they are possible objects consistent with the Laws of Physics.'[46] Apart from being a modern reincarnation of the principle of plenitude, this is an unorthodox and problematic notion of existence which assumedly is not shared by the majority of physicists.

The meaning and scientific relevance of the string landscape remain highly controversial, and it is not even certain that the landscape exists as more than the possibility of a multitude of stable or metastable vacuum states. In 2004 three theorists at the Santa Cruz Institute for Particle Physics concluded that 'the possibility that the real world is described by one of these states appears somewhat dim'.[47] They pointed out that whereas some parameters can be tightly constrained by anthropic arguments, other parameters cannot. For example, life is believed to be consistent with a lower limit of 10^{16} years for the proton's lifetime, whereas it is known experimentally that the lifetime is greater than 10^{32} years. For this and other reasons the three physicists hesitated in accepting the 'new paradigm for scientific explanation', that is, the anthropic-multiverse paradigm.

The universes generated by eternal inflation have a common causal origin and share the same space–time, for which reason they do not form a completely disconnected multiverse. The multitude of other 'domain universes' are not accessible to observers located in our universe but are nonetheless connected, as a leaf on an oak tree is connected to all the other leaves of the tree. (However, while the leaves are largely of the same shape and size, the universes may differ widely.) This distinguishes this kind of multiverse from the more radical notion of a multiverse made up of strictly disjoint universes as proposed by Tegmark and others. It is only in the first case that regular properties across the ensemble of universes can be expected. In the absence of such regularity it seems hard or perhaps impossible to say anything about the universes on a scientific basis. As Ellis and others have argued, there is a great deal of difference between the two kinds of multiverse. The hypothesis of domain universes can be ruled out if it turns out that there never was an inflationary era in the history of the cosmos. There is no similar way to rule out the hypothesis of strictly separate universes.

Although the domain or bubble universes making up the multiverse are separate, they need not always have been entirely separate. According to some physicists, including string theorist Laura Mersini-Houghton of the University of North Carolina at Chapel Hill, there is the possibility that neighbouring universes may interact gravitationally. Perhaps our universe collided with another one shortly after the big bang, or perhaps one or more other universes exert a gravitational pull on large lumps of matter in our universe. The recent proposal of a 'dark flow', a phenomenon based on observations of the motion of galactic clusters, is seen by some theorists as a signature of the impact of another universe. Mersini-Houghton and her collaborator Richard Holman at the Carnegie Mellon University consider the dark flow to be evidence for a particular model of the landscape universe.[48] Generally, many physicists believe that cosmological observations (rather than laboratory experiments) may provide the first tests of 'new physics' such as the string landscape.

Multiverse physics, in its widest sense, leads to a surprising and entirely new conception of laws of nature and the relationship between law-bound and contingent phenomena. Physicists are used to thinking, and have reasons to think, that the fundamental laws, whether we know them or not, are the unique and first principles from which natural phenomena can in principle be calculated. This is the Einsteinian view of physics. But according to multiverse thinking there is nothing particularly elevated about the laws that govern *our* universe. They may be merely local and anthropically allowed by-laws, that is, consistent with life as we know it. From the grander perspective of the multiverse they are contingent and so are the values of at least some of the physical parameters. According to Martin Rees: 'The entire history of our universe could be just an episode in the infinite universe; what we call the laws of nature (or some of them) may be just parochial by-laws in our cosmic patch.'[49]

In principle, then, Newton's law of gravitation does not have a status any more dignified than that we assign to the 'law' that the inner planets are small and have no or few moons. Rather than accepting that the environment is determined by the laws of nature, multiverse physicists suggest that the laws are determined by the environment. This is a most radical suggestion. The idea that some physical quantities are in this sense environmentally selected and thus to be explained by means of anthropic reasoning appear in several works of modern physics, if not necessarily in connection with the multiverse hypothesis.[50]

10.3 AN ULTIMATE THEORY OF EVERYTHING?

The legendary 'theory of everything', a term that may first have turned up in the scientific literature as late as 1985,[51] is a putative theory that fully explains all natural phenomena within a unified framework of all fundamental but particular physical theories, that is, theories with a limited domain. Reflecting a significant reductionistic bias, it is taken for granted that the theory of everything (TOE) belongs to physics and not to any other science—to speak of a 'botanical theory of everything' presumably does not make sense outside botany. Of course, the very notion of a theory of everything is problematic, as a theory, in the ordinary meaning of the term, must necessarily rest on some assumptions concerning entities and concepts, these assumptions being physical, mathematical, or philosophical. It would seem that there will always be some properties that are inexplicable. In spite of such general arguments against the existence of a theory of everything, physicists have happily pursued the goal of an ultimate theory, if mostly in a somewhat less ambitious version than a truly final theory.[52]

The dream of being able to represent all fundamental knowledge about nature by a single theoretical system, or perhaps even by a single master equation, is reflected in the history of unification that started with Newton and took pace with Maxwell and his generation. We have met several attempts at establishing a unified physical framework in this book, from the vortex theory of the 1870s to Heisenberg's 'world equation' of the 1950s. However, the modern and more successful attempts at unification only occurred a little later, starting with the unified quantum theory of electromagnetic and weak interactions established by Steven Weinberg, Abdus Salam, and others about 1970. The electroweak theory was an important milestone in the unification programme, and another one was its extension to an electronuclear 'grand unified theory' some years later (Sheldon Glashow, Howard Georgi, Weinberg, and others).[53] Yet, impressive as these theories are, they are far from qualifying as theories of everything. Not only do they contain several free parameters, more seriously they do not incorporate the gravitational force. A theory of everything must, as a minimum, unify the grand unified quantum field theories with the general theory of relativity.

The most discussed and developed version of such a unified theory, and consequently the best candidate for a theory of everything in the traditional sense, is the theory of superstrings or M-theory (see Chapter 11). As we have seen, recent developments in string theory have led to the idea of a string landscape which, in conjunction with eternal inflation, has been interpreted as a theory of multiple universes. However, theories of the multiverse are not usually seen as candidates for a theory of everything, although they may turn out to be consequences of such a theory.

In a series of works starting in 1998, Max Tegmark has developed a most ambitious theory of everything with strong links to the multiverse. His idea of a mathematical multiverse is not really a theory in the traditional sense, but should rather be considered a framework for a future theory or a meta-theory, or perhaps as a philosophical claim for a meta-theory (Fig. 10.1). The basis of Tegmark's theory (which I shall nonetheless call it) is not the hypothesis of multiple universes, which is presented as a consequence of the theory and which did not appear explicitly in his first communication of 1998, written before the inflation-landscape multiverse was introduced. In this work Tegmark discussed in general terms the nature of a theory of everything and in particular the relation between what exists mathematically and what exists physically.

Tegmark's basic postulate is that the world is purely mathematical and that in the strongest possible sense, namely that physical reality *is* a mathematical structure and nothing but. This ontological claim he later called the mathematical universe hypothesis or MUH. He realizes of course that this is an unconventional view but dismisses the alternative—that the world is not completely mathematical—as 'somewhat of a resignation' when it comes to predictive power.[54] The standard view is that mathematics is

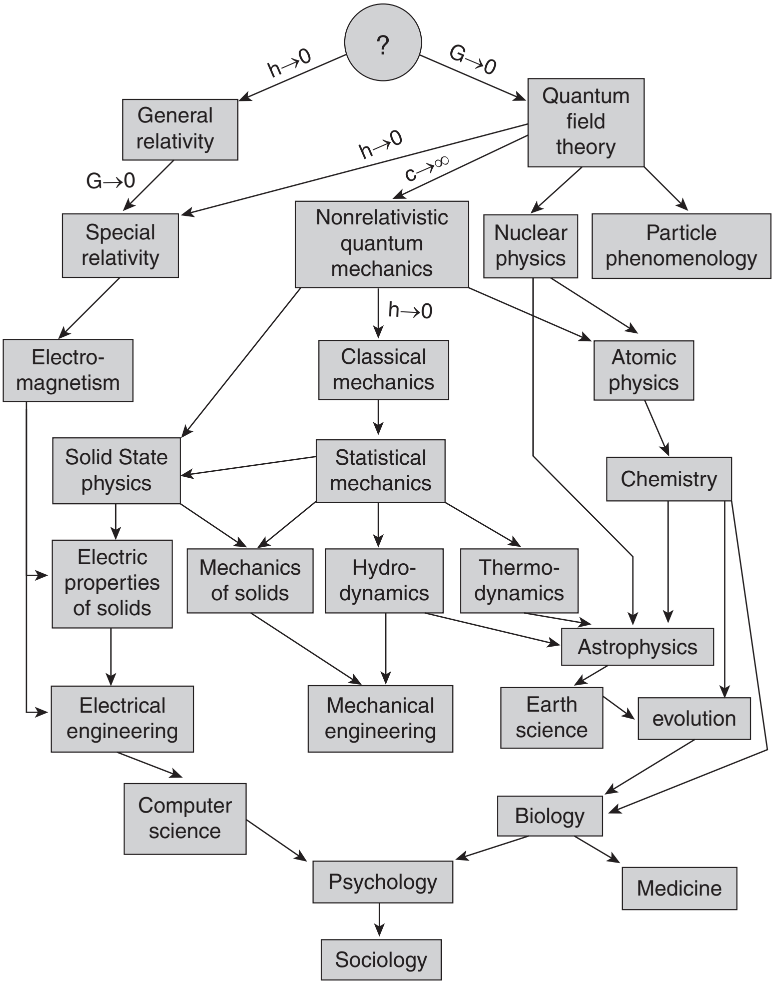

Fig. 10.1. Max Tegmark's illustration of the mathematical theory of everything from which all other theories are derivable. The degree of fundamentality is highest at the top and lowest at the bottom.
Source: Max Tegmark, 2008 'The mathematical universe' *Foundations of Physics* **38** (2008), 101–150.

merely a tool that describes and can be useful in understanding aspects of the physical world, but this is a view far from Tegmark's. His view, 'a form of radical Platonism' that he considers a candidate for a theory of everything, is that *everything* that exists mathematically is also endowed with physical existence. One's immediate response to such a claim is presumably that it is either nonsense or a freewheeling philosophical speculation that may or may not be intellectually interesting.[55] Tegmark argues, however, that it qualifies as a scientific theory because it makes non-trivial statistical predictions. Moreover, he suggests that it is superior to views that deny the mathematical nature of the world or only accept that some mathematical structures have physical existence.

Feynman found it 'quite amazing that it is possible to predict what will happen by mathematics, which is simply following rules which really have nothing to do with the original thing'.[56] At the same time Eugene Wigner, reflecting on the same amazing fact, famously problematized what he called 'the unreasonable effectiveness of mathematics in the natural sciences'. According to Tegmark, the problem raised by Feynman and Wigner (and many others) receives a natural explanation within a theory according to which the world is a mathematical structure. Within such a theory, 'our successful theories are not mathematics approximating physics, but mathematics approximating mathematics'.[57]

In later works Tegmark has developed these ideas and related them to the multiverse. As Geoffrey Chew advocated 'nuclear democracy' in the 1960s, so Tegmark advocates 'mathematical democracy' in the early twenty-first century. The general idea of reducing physical reality to mathematics is not new, of course, but it may never before have appeared in such an extreme form as in Tegmark's theory of everything. Many years earlier James Jeans described God as a pure mathematician, arguing that reality was basically mathematical. 'All the concrete details of the [physical] nature', he said, 'the apples, the pears and bananas, the ether and atoms and electrons, are mere clothing that we ourselves drape over our mathematical symbols—they do not belong to Nature, but to the parables by which we try to make Nature comprehensible.'[58] Tegmark argues similarly, but in much greater detail, that in an ultimate theory all human 'baggage'—the words and concepts we use to make sense of the equations and to relate symbols to measurements—will disappear, leaving only the bare mathematics. Not only is this baggage (or Jeans' 'clothing') redundant, so is the entire empirical domain. The theory of everything of the twenty-first century differs from Laplace's omniscient demon, but it expresses the same dream and the same kind of unrestricted hubris. 'All properties of all parallel universes . . . could in principle be derived by an infinitely intelligent mathematician.'[59]

In Tegmark's later expositions of his mathematical universe he argues that the commonly accepted assumption of an external physical reality independent of humans *implies* the mathematical universe hypothesis. Moreover, the multiverse is seen as following from the hypothesis because, if the mathematics is immensely richer than what we know from the physics of our universe, the majority of mathematical structures must be realized in other universes. *Ex hypothesis* there cannot be mathematical structures without physical existence. But can the mathematical universe hypothesis ever be tested? According to Tegmark it can, at least in the weak sense that there is evidence in favour of it. One piece of evidence is held to be the increasing mathematization of physics and the uncovering of new mathematical regularities in nature. 'I know of no other compelling explanation for this trend than the physical world really is mathematical.'[60]

While Tegmark argues that physics is in essence mathematical, other scientists have suggested that mathematics originates in the physical multiverse rather than the other way around. Inspired by computer and information science they speculate that the true theory of everything, and indeed reality itself, must be understood in computational terms, say as a universal quantum computer that can simulate everything.[61]

One may suspect that the mathematical universe with its infinity of structures and corresponding worlds is so rich that it amounts to an anything-goes universe. But this is not quite the case for any of the classes of the multiverse. There may well be universes with tartan elephants, if such creatures are mathematically allowed (as they presumably are), but none of the kinds of multiverse imply that all *imaginable* universes or objects exist. One can easily imagine a flat-space universe where the circumference of a circle differs from $2\pi r$ (at least I can), but no such mathematical universe exists. Most multiverse models, including the string landscape, do not even claim to represent all *possible* universes but only a tiny subset of them. The reason is that they rely on a number of assumptions, such that the universes are described by quantum mechanics and have only one time dimension. Although 10^{500} universes are a lot, the number is infinitesimal compared to the number of possible universes. Not even the mathematical universe includes all imaginable universes, 'only' those which can be mathematically defined.

In his argument for a mathematical universe Tegmark naturally draws upon the ideas of other physicists who have suggested a greater role for mathematics in physics than the one ordinarily accepted. For example, in an important paper of 1931 in which he predicted the existence of the positron and the magnetic monopole on the basis of quantum mechanics and relativity theory, Dirac offered the following advice, quoted by Tegmark:

> The most powerful method of advance that can be suggested at present is to employ all the resources of pure mathematics in attempts to perfect and generalize the mathematical formalism that forms the existing basis of theoretical physics, and after each search in this direction, to try to interpret the new mathematical features in terms of physical entities.[62]

Even more relevant, but less well known, is Dirac's 1939 address mentioned in Chapter 7, with its suggestion that 'the whole of the description of the universe has its mathematical counterpart'. In this work Dirac questioned the traditional separation in physical theories between laws of nature and contingent initial conditions. This idea reappears in multiverse physics, where there is no fundamental difference between the two parts. As Tegmark expresses it: 'A TOE with a landscape and inflation reclassifies many of the remaining "laws" as initial conditions, since they can differ from one post-inflationary region to another, but since inflation generically makes each such region infinite, it can fool us into misinterpreting these environmental properties as fundamental laws.'[63]

Tegmark's multiverse theory is not the only modern theory of everything that relies on the notion of physical reality being essentially mathematical. Frank Tipler entertained somewhat similar ideas in an ambitious paper of 2005 in which he suggested that the standard model of elementary particles conjoined with a theory of quantum gravity is, in a sense, the correct theory of everything. The TOE already exists! While Tegmark equates mathematical and physical reality, Tipler regards physical reality to be a subset of a much larger mathematical reality. His Pythagorean–Platonic universe rests on the assumption that 'physical reality is not "real" ultimately; only number—the integers comprising the true ultimate reality—is actually real'.[64] Tipler, too, operates with a multiverse consisting of an indefinite number of universes. In the multiverse fashion he explains the values of the free parameters of the standard model by appealing to a claim that 'all possible values of the constants are obtained in some universe of the multiverse at some time'.[65]

According to Tipler, 'The multiverse is forced upon us by observation'.[66] By this he means that since, in his view, quantum mechanics leads necessarily to a multiverse, and since observations tell us that quantum mechanics is true, then observations also tell us that there is a multitude of other universes. There are an awful lot of them, but not quite as many as in Tegmark's mathematical multiverse. The multiverse argued by Tipler does not involve all logically possible universes, but only those that are consistent with the fundamental laws of physics as we know them today. Moreover, his theory of everything differs from many other proposals of unified cosmophysics by not involving ideas such as superstring theory and cosmic inflation. These ideas he does not believe in. First and foremost, what distinguishes Tipler's ideas from most other theories of everything is the crucial and controversial role he assigns to intelligent life, a topic which will be taken up in Chapter 12.

Whether associated with string theory or some other theoretical framework, ideas of theories of everything are controversial and not generally taken very seriously. Some scientists consider them to be innocent pastimes, mere mathematical games, while for others they represent an unhealthy and speculative trend in theoretical physics.

Many physicists specializing in condensed matter physics and related fields object to the arrogant reductionism of particle physics and the entire philosophy underlying the notion of a theory of everything. They argue that the quest for an ultimate theory in terms of elementary particles and fields is fundamentally misguided because there is no deductive link between such a theory, should it exist, and most phenomena of real physics. These phenomena are emergent, that is, they depend on organizing principles and collectives states that cannot be reduced to simpler states. Following up on earlier criticism of this kind by the eminent solid-state theorist Philip Anderson, Robert Laughlin, a Nobel laureate at Stanford University, has attacked what he considers the dominant fundamentalism of theoretical physics. In a paper co-authored by David Pines of the Los Alamos National Laboratory he criticized the 'imperative of reductionism', which 'requires us never to use experiment, as its objective is to construct a deductive path from the ultimate equations to the experiment without cheating'. In sharp contrast to the ideas of Tegmark and Tipler, the two physicists concluded:

> Rather than a Theory of Everything we appear to face a hierarchy of Theories of Things, each emerging from its parent and evolving into its children as the energy scale is lowered. The end of reductionism is, however, not the end of science, or even the end of theoretical physics. How do proteins work their wonders? Why do magnetic insulators superconduct? Why is ^{3}He superfluid? . . . The list is endless, and it does not include the most important questions of all, namely those raised by discoveries yet to come. The central task of theoretical physics in our time is no longer to write down the ultimate equations but rather to catalogue and understand emergent behavior in its many guises, including potentially life itself.[67]

While Laughlin and Pine spoke of theoretical physics being in 'the midst of a paradigm change', particle and string theorists such as Gross and Polchinski would have nothing of it. They denied that the fundamental laws of nature are emergent phenomena or that complexity is to be epistemically preferred over simplicity. 'To me, the history of science seems to be a steady progression toward simpler and more unified laws', Polchinski commented in the *New York Times*. 'I expect to see this continue and to contribute to it. Things may take many surprising twists and turns, but we reductionists are still quite happily and busily reducing.'[68]

10.4 WORLDS, UNOBSERVED AND UNOBSERVABLE

The increasing popularity of multiverse cosmology and anthropic arguments has caused a great deal of debate in the physics community, although it is a debate that the large majority of physicists and astronomers probably tend to find irrelevant or may even be unaware of. The overarching question is whether multiverse cosmology is a science or not. Have physicists in this case unknowingly crossed the border between science and philosophy, or perhaps between science and theology? Almost all physicists agree that a scientific theory has to speak out about nature in the sense that it must be empirically testable, but they do not always agree what testability means or how important this criterion is relative to other criteria. In this section I consider some of the arguments for and against the multiverse as a scientific proposal.

The eminent astrophysicist Dennis Sciama, a former student of Dirac and for a period an enthusiastic advocate of the steady-state theory, was an early convert to the multiverse. In the late 1980s he suggested that the existence of many worlds was necessary not only to explain the fine-tuning of natural constants but also to explain why the possibility of many other universes did not, apparently, correspond to the physical realities of these possibilities. During the 1989 Venice conference he argued strongly in favour of a multiverse consisting of many universes, each governed by its own fundamental theory. He did not need either inflation or string theory to reach the desired conclusion, but only the doctrine that 'everything which is not forbidden is compulsory', that is, the principle of plenitude.[69] In an essay of 1993, well before the controversy had gained momentum, Sciama considered some of the potential objections against the hypothesis of many worlds:[70]

(i) The hypothesis is much too extravagant and bizarre to be credible.
(ii) It violates the well-established tradition in theoretical physics to explain phenomena deductively from a fundamental theory.
(iii) The multiverse hypothesis has no real predictive power.
(iv) It is unscientific to postulate the existence of other universes, many of which are unobservable even in principle.

The objections listed by Sciama are among those that entered the controversy over the multiverse that only started in earnest after his death in 1999.

With regard to the first point, although the multiverse is certainly bizarre, this cannot in itself be a valid argument against the hypothesis. Since Copernicus claimed that the Earth rotates about its axis and further whirls around the Sun (a most bizarre theory by the standards of the time), scientists have learned that weird consequences of a theory do not necessarily imply that the theory is false. Besides, there are other theories that can compete with the multiverse in weirdness, the Everett interpretation of quantum mechanics being one of them and the wormholes of general relativity perhaps another. There are even physicists who apparently consider weirdness a sign of health rather than a problem. As Mukhanov says about the many-worlds interpretation, it is 'crazy enough to be true'.[71] Nonetheless, arguments based on epistemic or ontological weirdness do play a role and often contribute to the overall assessment of a theory, as they did in the case of the steady-state theory in the 1950s.

The stupendous number of parallel universes may seem to be wasteful and hence to violate the principle of simplicity accepted by most physicists. However, as a response to this objection it may be enough to recall that principles of simplicity and economy are notoriously ambiguous and offer little practical guidance for choosing between theories. Moreover, it can be and has been argued that the multiverse does not really run counter to Ockham's famous razor and in an explanatory sense is in fact a simpler concept than a single universe.[72]

The distinguished astrophysicist Martin Rees, a supporter of the multiverse, has on several occasions argued that there are good reasons to believe in the many unobservable universes or at least to take the hypothesis seriously. His 'slippery slope' argument is: 'From a reluctance to deny that galaxies with redshift 10 are proper objects of scientific enquiry, you are led towards taking seriously quite separate spacetimes, perhaps governed by quite different laws.'[73] With this he means that we have no problem in accepting that galaxies that have crossed the visible horizon are still real parts of the universe. They are unobservable, but it would take a naïve empiricist view to deny their existence. Nor have we serious problems with conceiving galaxies passing beyond the horizon corresponding to an infinite redshift; they disappear, but remain real. From this there is but a small step to accept the existence of galaxies that disappear at an ever-increasing rate, although these are and forever will be unobservable in principle. We may now compare these causally disjoint regions, held to be real, with other disjoint regions that emerge from the big bang according to the eternal inflation scenario. Rees's point is that if we have confidence in the reality of the first class of regions, why not believe in the reality of the second class as well?

The slippery slope argument may be more seductive than compelling, especially because it does not recognize the drastic difference between earlier observed regions of the universe and the infinity of disjoint regions. It is an argument that does not convince Paul Davies: 'As one slips down that slope, more and more must be accepted on faith, and less and less is open to scientific verification.'[74]

There is another kind of argument that is not specific to the multiverse, namely, that if a theory can explain phenomena that cannot otherwise be explained, then this theory is likely to be true. Linde offers the following version of the argument:

> We don't have any other alternative explanation for the dark energy; we don't have any alternative explanation for the smallness of the mass of the electron; we don't have any alternative explanation for many properties of particles.... These are experimental facts, and these facts fit one theory: the multiverse theory. They do not fit any other theory so far. I'm not saying these properties necessarily imply the multiverse theory is right, but you asked me if there is any experimental evidence, and the answer is yes. It was Conan Doyle who said, 'When you have eliminated the impossible, whatever remains, however improbable, must be the truth.'[75]

It is quite remarkable that Linde considers unexplained facts such as the proton–electron mass ratio to be 'experimental evidence' in favour of the multiverse. This is about the same logic that Boscovich adopted in the eighteenth century, when he suggested that phenomena such as cohesion and chemical affinity amounted to evidence for his theory of matter. Again, by the same logic Eddington's fundamental theory of the 1930s should have been readily accepted as true by his contemporaries since it was solidly supported by experimental evidence that other theories could not account for.

Yet another defence of the existence of a multitude of unobservable universes relies on historical analogy. There have been, so the argument goes, other cases in the history of science of predictions of unobservable entities and phenomena, and we have confidence in some of them. A theory cannot be considered scientific if *all* its predictions concern unobservable entities, but if some of them are observable and testable things are different. It is not a valid objection against a theory that it makes untestable predictions, for almost all scientific theories do that. Newton's theory of gravity predicts how the moon of some distant planet beyond the horizon revolves around the planet, but since the planet can never be observed the prediction is untestable. Yet we do not dismiss Newton's law because the prediction cannot be tested. Nor did scientists in the late eighteenth century question the scientific nature of the law of gravity because it, in conjunction with the emission theory of light, predicted the existence of invisible 'dark stars', a kind of classical black hole.[76] What matters is that a theory must make *some* testable predictions, as Newton's does abundantly, and it is on the basis of these testable predictions that it will be judged.

A well-established theory with empirical successes may include predictions which cannot be tested, and in such a situation one can argue that we have reason to believe in them in spite of their hypothetical nature. This is a very common argument in support of the multiverse scenario. We believe in quarks and gluons because they are predicted by the reliable quantum theory of strong interactions, and we believe in properties of black holes because they are predicted by the reliable theory of general relativity. As Tegmark phrases it:

> Because Einstein's theory of General Relativity has successfully predicted many things that we *can* observe, we also take seriously its predictions of things we cannot observe, e.g., that space continues inside black hole event horizons and that (contrary to early misconceptions) nothing funny happens right at the horizon. Likewise, successful predictions of the theories of cosmological inflation and unitary quantum mechanics have made some scientists take more seriously their other predictions, including various types of parallel universes.[77]

The argument presupposes that the physics behind the multiverse hypothesis, mainly eternal inflation and string theory, has the same credibility and epistemic authority as the theory of relativity, which may well be questioned. At any rate, historical analogies only carry limited epistemic force.[78] Without singling out any particular theory, Rees imagines a highly successful physical theory of the future that explains, for example, why there are three families of leptons and why the proton is about 1836 times as massive as the electron. 'If the same theory, applied to the very beginning of our universe, were to predict many big bangs, then we would have as much reason to believe in separate universes as we now have for believing inferences from primordial nucleosynthesis about the first few minutes of cosmic history.'[79]

Whereas critics of the multiverse claim that predictions of many universes escape testing, proponents of the idea argue that it is testable, albeit not in the ordinary sense. A multiverse theory may of course be trivially falsifiable if it is specific enough, say that it predicts that all universes are devoid of water. More generally, a multiverse theory can be ruled out if it predicts that none of the universes in its ensemble have properties observed in our world. Unfortunately, real multiverse theories are anything but specific and cannot be tested in this way. It is generally agreed that theories of the universe cannot result in definite predictions of the kind known from other parts of physics. Nonetheless, proponents of the multiverse insist that testable predictions are possible, but that the predictions will appear in the form of probability distributions. For example, it should be possible to determine what fraction of an immense and possibly infinite number of universes includes a cosmological constant of a size within a certain range.

The problem of how to define and compute probabilities in multiverse physics, that is, to calculate from a multiverse theory the probability that we should observe (in our universe, of course) a given value for some physical property, is known as the 'measure problem'. This problem is a hot topic in current research, but in spite of much work it has not led to a solution. It involves comparison of one infinity with another, which in general leads to an undefined expression. Aurétien Barrau, a French physicist and advocate of the multiverse, admits that 'except in some favourable cases, . . . it is hard to refute explicitly a model in the multiverse'.[80] Physicists seem to agree that although it is possible to derive some probability predictions from a multiverse theory, this can be done only if certain strict conditions are satisfied. These conditions do not hold if the laws of physics vary from universe to universe, in which case no predictions of any kind appear to be possible.

The strongest and most articulate critic of the multiverse is possibly George Ellis, who in several works has not only raised technical objections to the theory but also questioned its scientific nature. Is the multiverse a scientific concept, a reality which follows nearly inevitably from fundamental physics? Or is it an interesting speculation whose proper place is in philosophy departments and science fiction literature? Whereas Susskind and Linde supports the first claim, Ellis is more in favour of the second one, maintaining that the existence of a multiverse 'remains a matter of faith rather than proof'. In an illuminating discussion with Bernard Carr, he stresses that the very nature of science is at stake in the current discussion about the multiverse:

> Its advocates propose weakening the nature of scientific proof in order to claim that the multiverse hypothesis provides a scientific explanation. This is a dangerous tactic. . . . There has been an increasing tendency in theoretical physics and cosmology to say it does not matter whether a proposal is testable. . . . [But] can one maintain one has a genuine scientific theory when direct and indeed indirect tests of the theory are impossible? If one claims this, one is altering the meaning of science. One should be very careful before so doing. There are many other theories waiting in the wings, hoping for a weakening of what is meant by 'science'. Those proposing this weakening in the case of cosmology should be aware of the flood of alternative scientific theories whose advocates will then state that they too can claim the mantle of scientific respectability.[81]

That is, if multiverse cosmology is admitted as a science, how can scientists reject pseudosciences such as astrology, intelligent design, and crystal healing on methodological grounds?

The current cosmophysical debate, in some measure reminiscent of the debate in the 1930s, is in part about the legitimate standards of physical science and the role of speculations. Both parties accept that speculative proposals have an important part in science, and in cosmology in particular, but they disagree whether the multiverse proposal is speculative or not, and if the multiverse is admitted as a speculation, whether it is a scientific or philosophical speculation. The critics argue that in the strong sense of an ensemble of totally disconnected universes, the multiverse theory definitely belongs to the latter class. Protagonists of the mutiverse are more inclined to accept even this extreme idea as a scientific speculation. Admitting that the multiverse is 'highly speculative', Rees maintains that the existence or non-existence of other universes is nonetheless a scientific question. As seen from his perspective it belongs to science, not metaphysics. Characteristically, he appeals to the traditional standard of demarcation, namely that the multiverse hypothesis results in 'some claims about other universes [which] may be refutable, as any good hypothesis in science should be'.[82]

Many physicists with a career in the more traditional approaches to particle physics have their misgivings about string theory in general and the landscape scenario in particular (see also Chapter 11). As one example, consider Burton Richter, an eminent particle physicist, Nobel laureate, and former director of SLAC, the Stanford Linear Accelerator Center. Jointly with the Brookhaven physicist Samuel Ting, in 1976 Richter received the Nobel Prize for the work that led to the discovery of the J/Ψ meson and which was an important part of the so-called November revolution in particle physics. Richter followed the development in multiverse physics with a mixture of wonder and disgust. This was not his kind of physics, if physics at all. In 2006, 30 years after having been awarded the Nobel Prize, he offered the following advice to the 'landscape gardeners':

> Calculate the probabilities of alternative universes, and if ours does not come out with a large probability while all others with content far from ours come out with negligible probability, you have made no useful contribution to physics. It is not that the landscape model is necessarily wrong, but rather that if a huge number of universes with different properties are possible and equally probable, the landscape can make no real contribution other than a philosophic one. That is metaphysics, not physics.[83]

10.5 BETWEEN SCIENCE AND PHILOSOPHY

Directly or indirectly, many of the questions discussed in the multiverse controversy are of a philosophical nature, not least when it comes to the proper standards of science on which the multiverse scenarios should be evaluated. Interestingly, the questions are discussed mostly within the scientific community, whereas philosophers so far have shown little interest in them. In a sense there is nothing new in the present situation. Cosmology has always been a field where metaphysical and other philosophical considerations have played a role. In spite of the great progress that has occurred during the last century, parts of cosmology may still be more philosophical than scientific in nature. The two fields cannot be easily and cleanly separated. This became clear during the steady-state controversy in the 1950s, and it appears no less clearly in the current controversy over the multiverse.

One of the problems is the infinite number of universes in some multiverse theories, or more generally the appearance of realized infinities in cosmology, as mentioned previously. When such infinities turn up, they inevitably raise problems of a philosophical nature that cannot be solved by scientific methods alone. Another issue concerns the relationship between prediction and explanation, two qualities which are highly regarded by practically all physicists. Indeed, most will agree that a theory must be able to predict as well as explain parts of nature, a theory which neither predicts nor explain just does not qualify as science. However, the two qualities do not always go easily together. There are theories that have great explanatory power but rate poorly when it comes to testable and specific predictions. As Ellis and other critics have argued, multiverse theories are extreme in this respect since they offer no specific predictions and yet are able to explain about everything. A theory which operates with 10^{500} or 10^{1000} universes can accommodate almost any observation; and should the observational result be revised, it will have no problem with explaining that either. As Ellis objects, 'The existence of universes with giraffes is certainly predicted by many multiverse proposals, but universes where giraffes do not exist are also predicted'.[84]

Ellis recognizes of course that accepted norms of science are not static and what has passed as legitimate science has changed over time and from one science to another. Nonetheless he insists that there is a core feature of science that must be retained at all cost, namely that scientific theories are empirically testable. Leave this criterion, and you have left science. Lee Smolin is no less adamant in his advocacy of falsifiability as a *sine qua non* of science. Referring to the lack of testability of the string landscape, he deplores that 'some of its proponents, rather than admitting that, are seeking leave to change the rules so that their theory will not need to pass the usual tests we impose on scientific ideas'.[85] On the other hand, physicists sympathetic to the multiverse call attention to the methodological changes that have occurred throughout the history of science, and they are more willing to accept softened versions of the principle of testability. Only very few will dispense with it altogether.

Among the antagonists of the multiverse and anthropic reasoning are also Steinhardt and Turok, who argue that their own model of an infinite cyclic universe is methodologically superior to the inflationary multiverse. 'Science should remain based on the principle that statements have meaning only if they can be verified or refuted', they say, concluding that the multiverse fails miserably on this count. The two theorists note with regret the trend towards accepting anthropic reasoning, which 'seems likely to us to drag a beautiful science towards the darkest depths of metaphysics'.[86] The Steinhardt–Turok cyclic universe is itself a kind of (temporal) multiverse, but in a sense very different from the one currently discussed in the universe–multiverse debate.

In a situation where the very standards of science are at stake one might expect the scientists to appeal to philosophical notions and demarcation criteria of science. Although this has happened in the modern cosmological debate, it is only on rare occasions and without much effect. Generally speaking, physicists have little respect for or are plainly uninterested in the opinion of philosophers (not to mention sociologists and theologians). They see it as part of their job to expand the domain of physics at the expense of philosophy and other branches of knowledge, to turn vague philosophical doctrines into precise and operational scientific concepts. And they believe they have succeeded in doing so on many occasions. For example, the semiphilosophical anthropic principle has now moved into physics and thus, because it is no longer philosophical, become scientifically acceptable. This kind of imperialist rhetoric is far from new, but it is particularly common in the modern debate over string theory and the multiverse.

About the only philosopher of science who is widely known among physicists is Karl Popper, famous for his falsificationist criterion of science which he stated in his classic work *The Logic of Scientific Discovery* of 1958. (The book first appeared in German in 1934, as *Logik der Forschung*, but without being much noticed.[87]) Whether or not they make reference to Popper's philosophy, many physicists (including Ellis and Smolin) feel that testability and falsifiability are indispensable for a scientific theory. Mario Livio, a physicist who is to some extent sympathetic to the multiverse and anthropic explanations, has emphasized that a theory that cannot be tested even in principle can hardly be counted as scientific. It 'goes against the principles of the scientific method, and in particular it violates the basic concept that every scientific theory should be falsifiable', he says.[88] As mentioned, Rees is another advocate of the multiverse who has defended its scientific nature by arguing that it does lead to falsifiable claims. But not all physicists have the same reverence for the falsifiability criterion.

As early as 1989, during the Venice conference on the anthropic principle, Carter discussed the principle and its implications in relation to Popperian philosophy of science, which he criticized in a general way for its 'negativist' attitude.[89] Carter objected to Popper's 'refutability principle', with which term he referred to the one-sided emphasis on refutation of predictions at the expense of confirmation. Still, although he rejected the 'folklore version of the Popper principle', he maintained that the anthropic principle was falsifiable and thus not in direct conflict with Popper's criterion of science. Other physicists advocating the anthropic principle and the multiverse have been more openly hostile to philosophers in general and Popperianism in particular. After all, have philosophers any right to dictate to the physicists the norms of science and hence to decide whether their theories belong to science or not?

Provoked by the charges against the multiverse of being unfalsifiable, Barrau insists that science can only be defined by the scientists themselves: 'If scientists need to change the borders of their own field of research, it would be hard to justify a philosophical prescription preventing them from doing so.'[90] Indeed, the multiverse controversy has highlighted the fundamental question of the very definition of science and the demarcation criteria that distinguishes science from non-science. Perhaps philosophers have no 'right' to decide which criteria are valid, but do the scientific experts have such a right? What if the experts disagree? Should the question then be decided by a vote? Or by a court of justice? Inspired by the multiverse controversy, the American physicist Robert Ehrlich argues that 'decisions as to what constitutes a legitimate scientific theory are simply too important to be left to the practitioners of that field, who obviously have vested interests in it, such as a desire to keep the funding coming'.[91]

Susskind is another multiverse advocate who has little patience with armchair philosophy and philosophical demarcation criteria. As to Popper's falsificationism he has no confidence at all, only scorn:

> Throughout my long experience as a scientist I have heard unfalsifiability hurled at so many important ideas that I am inclined to think that no idea can have great merit unless it has drawn this criticism. . . . Good scientific methodology is not an abstract set of rules dictated by philosophers. It is conditioned by, and determined by, the science itself and the science who create the science. . . . Let's not put the cart before the horse. Science is the horse that pulls the cart of philosophy.[92]

The multiverse theory clearly has problems with testability, as usually understood, and even greater problems with falsifiability. And so what?—is the response of some multiverse physicists. They either argue that science needs no formal norms except those that scientists agree upon, or they point to other criteria that may overrule the one of testability. An acceptable physical theory has to lead to statements that can be compared with observations and experiments, but it is generally agreed that there are other factors at play than mere empirical testing. We can have good reasons for believing in a theory even though it does not lead to directly testable consequences. Almost all physicists agree that a satisfactory theory, in addition to being testable, must also be simple and internally consistent, it must show explanatory power, and it must connect to the rest of science. Where the waters divide is when it comes to the priority given to these criteria. Is empirical testability absolutely necessary? And, if this is granted, how should testability be understood?

It is quite clear that some of the multiverse physicists have no respect at all for philosophers of science in general and for the 'Popperazi' in particular, to use Susskind's nickname for the modern followers of Popper. 'As for rigid philosophical rules', he says, 'it would be the height of stupidity to dismiss a possibility [such as the string multiverse] just because it breaks some philosopher's dictum about falsifiability'.[93] On the other side, Smolin and Ellis subscribe to Popperian standards of science, falsificationism included, if not in quite the dogmatic sense of Bondi, according to whom 'There is no more to science than its method, and there is no more to its method than Popper has said' (see Chapter 5). Given the abstract nature of Tegmark's theory of the mathematical universe one might expect him to side with Susskind, but this is not the case. He refers positively to Popper's criterion of falsifiability, arguing that both the multiverse and the mathematical universe theory of everything satisfy the criterion. On the other hand, Tegmark also seems to agree with Carter's point that science is not so much about proving theories wrong as it is about accumulating positive evidence for theories. 'What we do in science isn't falsifying, but "truthifying"—building up the weight of evidence', he says.[94] Tegmark's 'truthifying' is commonly known as verification or confirmation.

As pointed out by Michael Heller, a Polish cosmologist, philosopher, and Catholic priest, multiverse physicists often refer to Popperian falsifiability in ways that are vague and scarcely legitimate.[95] Most likely, few of them have ever read Popper or looked into the philosophical literature concerned with falsificationism. Whereas Popper held, to express it briefly, that it is a necessary condition for a scientific theory that it must be falsifiable in principle, of course he never claimed that it is a sufficient condition. There are evidently falsifiable statements that do not qualify as scientific. A new theory of gravitation from which it follows that planets necessarily move in circular orbits (such as was thought in pre-Keplerian astronomy) is certainly falsifiable, but this alone does not make it scientific.[96] Likewise, Tegmark's appeal to Popperian falsifiability presupposes that because a theory leads to consequences that can be proved wrong by observation, and indeed are wrong, it is of a scientific nature. But this is plainly a misrepresentation of what falsifiability means.

As philosophy is involved in the debate over the multiverse, so is religion, if mostly indirectly and between the lines. It is common among supporters of the multiverse to conceive it as an alternative to a divinely created world and to demarcate the theory from ideas of natural theology. The multiverse appeals to the anthropic principle, but without any trace of intelligent design. 'If there is only one universe', Bernard Carr says, 'you might have to have a fine-tuner. If you don't want God, you'd better have a multiverse.'[97] Richard Swinburne, the eminent theistic philosopher, agrees that the multiverse is as contrary to Christian belief as the anthropic principle. 'To postulate a trillion trillion other universes, rather than one God in order to explain the orderliness of our universe, seems the height of irrationality,' he comments.[98]

On the other hand, there is no one-to-one correspondence between the multiverse and belief in a divine creator. Several physicists with a dislike of the multiverse idea have called attention to what they conceive as the religious or quasi-religious elements it contains. To Ellis, belief in the multiverse is essentially based in 'faith' (if not religious faith), and Paul Davies find multiverse explanations to be 'reminiscent of theological discussion'. To his mind, they are effectively reintroducing divine explanations in cosmology: 'Far from doing away with a transcendent Creator, the multiverse theory actually injects that very concept at almost every level of its logical structure. Gods and worlds, creators and creatures, lie embedded in each other, forming an infinite regress in unbounded space.'[99]

The views of Don Page, a theoretical physicist at the University of Alberta and former collaborator with Stephen Hawking, may illustrate that the multiverse does not necessarily contradict Christian belief. By his own account a conservative Christian, Page believes that the divinely created universe has a purpose, and that whether there is a single universe or a lot of them. 'I do believe the Universe was providentially created by God', he says, and 'I also strongly suspect that the Universe is a multiverse, with different parts having different values of the physical parameters'.[100] Page finds the multiverse theory simpler, more elegant, and with greater explanatory force than the single-universe theory, and he sees no reason why God should not have decided to create a multiverse instead of a universe. At a symposium in 2008 Page gave a presentation entitled 'Does God love the multiverse?' in which he argued that the multiverse is not an alternative to design by God. He tended to answer his question affirmatively.

It has even been suggested that multiverse physics and intelligent design share some methodological ground, a suggestion nearly all advocates of the multiverse will vehemently deny. Yet, one of the standard arguments for dismissing creationism and intelligent design is that they cannot be tested and provide no room for falsification. This was essentially the argument of the US Supreme Court when it decided in 1986 that scientific creationism is religious and not scientific in nature. In this case the opponents of creationism, including a large number of American physicists, emphasized that 'An explanatory principle that by its very nature cannot be tested is outside the realm of science'.[101] But, so it has been argued, intelligent design is hardly less testable than many multiverse theories. To dismiss intelligent design on the ground that it is untestable, and yet accept the multiverse as an interesting scientific hypothesis, may come suspiciously close to applying double standards.[102] As seen from the perspective of some creationists, and also by some non-creationists, their cause has received unintended methodological support from multiverse physics.

Notes for Chapter 10

1. Kragh 2009d is a historically oriented introduction to the subject.

2. Barrau 2007. Schellekens 2008, p. 1. Kuhnian metaphors such as 'revolution' and 'paradigm' abound in the literature on superstrings and multiverse physics, but almost never with references to Kuhn's philosophy of science.

3. Ananthaswamy 2009. A few years earlier, Greene expressed his reservations with respect to anthropic multiverse ideas, which he felt were too easy. 'Maybe', he said in an interview, 'you just needed five more years of hard work and you would have answered those unresolved questions, rather than just chalking them up to, "That's just how it is".' *Scientific American Special Edition* **15**, issue 3 (2005), 50–55.

4. Quoted in Crowe 1999, p. 3.

5. Grant 2007, p. 228.

6. Quoted in Crowe 1999, p. 28. The source is *Théodicée* from 1710, one of Leibniz's most important works.

7. Hume 1980, p. 36.

8. Blanqui 1872, p. 47.

9. Newcomb 1906, p. 164. On the interest in hyperspaces and other universes, see Bork 1964.

10. Boltzmann 1895, p. 415. For more than a century Boltzmann's argument has attracted the interest of physicists and philosophers alike. For a recent review, see Ćirković 2003a.

11. Eddington 1931b, p. 415.

12. Tolman 1934b, p. 175. Reprinted in *General Relativity and Gravitation* **29** (1997), 935–43. The Lemaître–Tolman model is also known as the Tolman–Bondi model because Bondi investigated it in 1947.

13. Hoyle 1965b, p. 131.

14. Feuer 1934, p. 346.

15. The American novelist and historian Henry Adams used the term 'multiverse' a couple of times in his autobiographical *The Education of Henry Adams* first published in 1918. Writing in the third person, he said: 'The child born in 1900 would, then, be born into a new world which would not be a unity but a multiple. Adams tried to imagine it . . . He could not deny that the law of the new multiverse explained much that had been most obscure. . . .' The first time 'multiverse' appeared in a scientific journal (the *Irish Astronomical Journal*) may have been in 1982, but then in relation to Adams. See Jaki 1982.

16. Gale 1990. See also the historical review in Trimble 2009.

17. Tegmark 2003.

18. Carter 1990, p. 131 and p. 133 (first published in Longair 1974, pp. 291–98).

19. The article in *Reviews of Modern Physics* (Everett 1957) is reproduced in Wheeler and Zurek 1983, pp. 315–23. On Everett's life and work, see Byrne 2007.

20. Everett 1957, p. 460.

21. DeWitt 1970. DeWitt's work on quantum gravity led him to suggest that quantum mechanics applies to the entire universe at all times, such as Everett had earlier proposed. According to the Copenhagen interpretation, only an open system interacting with a classically describable measuring device (an observer) can be treated quantum mechanically, for which reason there can be no quantum mechanics of the universe. In 1967 DeWitt proposed a wave equation for the universe, known as the Wheeler–DeWitt equation, and expressed the hope that mathematical consistency alone would lead to a unique wave function.

22. DeWitt 1970, p. 33.

23. Mukhanov 2007, p. 270.

24. Tegmark 2007, p. 23, a tribute to Everett's theory on the occasion of its 50th anniversary.

25. Tipler 2007, p. 95. See also Tipler 1994, pp. 483–88. In the early 1950s, David Bohm's causal interpretation of quantum mechanics was rejected as metaphysical nonsense by leading quantum theorists, including Pauli, Heisenberg, and Rosenfeld. According to them, there was only one interpretation, namely the Copenhagen interpretation. In a letter to Rosenfeld of 16 April 1958, Heisenberg said: 'I agree with you that the expression *Copenhagen interpretation* is not really fortunate, in so far that one could think that there are also other interpretations, such as claimed by Bohm, for example. Of course, we both agree that these other interpretations are nonsense . . .' Quoted in Pauli 1996, pp. 342–43.

26. Nozick 1981, p. 129. The fecundity assumption is related to the principle of plenitude, but the latter refers only to the realization of possibilities in the actual world we live in. Whereas Nozick did not mention the anthropic principle, he did refer to Wheeler's speculations of many universes with different laws of physics.

27. Linde, 'Nonsingular regenerating inflationary universe', reprint of July 1982. Accessible online as http://www.stanford.edu/%7Ealinde/1982.pdf.

28. Linde 1990, p. 29.

29. Linde 1986, p. 399.

30. Linde 1987, p. 628. In the same volume, Hawking made use of the weak anthropic principle to explain why we live in an expanding rather than a contracting universe.

31. Vilenkin 2007, p. 163.

32. Guth 1997, pp. 251–52. See also the self-creating universe scenario in Gott and Li 1998.

33. Ellis and Brundrit 1979, p. 38. This is pretty much the same conclusion that Blanqui reached back in 1872, although in his case on a purely speculative basis (see above).

34. Garriga and Vilenkin 2001.

35. Tegmark 2003. The contention, made or implied by Ellis, Tegmark, Guth, and others, that in an infinite universe with an infinity of things there will be objects with any combination of those things, is wrong. Infinity alone is obviously not a sufficient condition for these combinations to occur.

36. Hilbert 1925, p. 190. Hilbert referred both to quantum theory (the impossibility of infinitely small quantities) and cosmology (the impossibility of infinitely large quantities).

37. Ellis, Kirchner, and Stoeger 2004.

38. Quoted in Kragh 2008, p. 84, where further information on the controversy can be found.

39. Schellekens 2008, p. 8.

40. Bousso and Polchinski 2000. This paper did not refer to the 'A-word'.

41. Susskind 2006. See also Bousso and Polchinski 2004 and Carroll 2006. A comprehensive review appears in Douglas and Kachru 2007. The landscape multiverse hypothesis was quickly taken up by journalists and disseminated to the public. See, for example, Overbye 2002.

42. Guth and Kaiser 2005, p. 888.

43. Linde 2007, p. 134.

44. Quoted in Folger 2008.

45. For an explanation of the number 10^{500} that does not require expert knowledge of string theory, see Conlon 2006.

46. Susskind 2006, p. 177.

47. Banks, Dine, and Gorbatev 2004, p. 2.

48. Mersini-Houghton and Holman 2009. See also Gefter 2009.

49. Rees 2007, p. 66.

50. For example Jaffe, Jenkins, and Kinchi 2009, who prefer to speak of environmental constraint rather than selection.

51. Schwarz 1985, p. v: 'Superstring theory . . . could be a "theory of everything"'. Ellis 1986 and Rújula 1986 also referred to the possibility of a theory of everything, both of them in connection with the new theory of superstrings.

52. On the final theory, see Weinberg 1992, especially pp. 211–40. See also Taylor 1993, who concludes that any theory of everything contains the seeds of its own destruction.

53. For a historical perspective on different views on unity and disunity in the period, see Cat 1998.

54. Tegmark 1998, p. 2.

55. A critique of Tegmark's Platonic multiverse hypothesis appears in Heller 2009, pp. 107–13. Heller concludes that the hypothesis may at best 'serve as an inspiration for science fiction novelists'. It should be noted that the mathematical universe hypothesis is not Platonic in the real or authentic sense, according to which the mathematical objects (which alone are real) do not exist in any physical universe but in some transcendent non-spatial and non-temporal world.

56. Feynman 1992 (originally published 1965), p. 171.

57. Tegmark 2003, p. 50. Wigner 1960. On a different and more modern perspective on the mathematics-physics relationship, see Jaffe and Quinn 1993. See also the original analysis in Steiner 1998.

58. Jeans 1934, p. 356.

59. Tegmark 2008, p. 125.

60. Ibid., p. 141.

61. Inspired by the ideas of David Deutsch and others, Karthik 2004 speculates that we live in a level III multiverse which self-replicates an infinite number of times. What is traditionally called a theory of everything (TOE) is for him merely a theory of something (TOS). Deutsch, a physicist at the University of Oxford, has long promoted his own ideas of the multiverse, the theory of everything, simulated worlds, physical eschatology, and the like. See e.g. Deutsch 1997.

62. Dirac 1931, p. 60. On Dirac's view on the relation between mathematics and physics, see Kragh 1990 and Bueno 2005. Dirac's scientific practice was not consistent with the praise of the power of pure mathematics, as he expressed it in 1939 and on some other occasions. He basically conceived mathematics as 'only a tool' (Dirac 1958, p. viii) and emphasized physical ideas at the expense of mathematical formalism.

63. Tegmark 2008, p. 117.

64. Tipler 2005, p. 905.

65. Ibid., p. 960.

66. Tipler 2007, p. 15.

67. Laughlin and Pines 2000, p. 31. Laughlin received the 1998 Nobel Prize for his co-discovery of the fractional quantum Hall effect. On Anderson's early criticism of reductionistic particle physics, see Anderson 1972 and Cat 1998.

68. Quoted in Johnson 2001.

69. Sciama 1993b, p. 108. Like many other protagonists of the multiverse, Sciama felt a need to legitimate the scientific nature of the hypothesis. He argued that, 'by making a testable prediction, the hypothesis that there exist many disjoint universes is a physical hypothesis'. In his case, the prediction was that the Penrose–Hawking singularity theorem was wrong.

70. Sciama 1993a.

71. Mukhanov 2007, p. 272.

72. For example Sciama 1993b, p. 108 and Tegmark 2007, p. 123. Victor Stenger, a physicist, science writer, and advocate of atheism, has argued that 'The cosmology of many universes is more economical if it provides an explanation for the origin of our universe that does not require the highly nonparsimonious introduction of a supernatural element that has not heretofore been required to explain any observations'. (Stenger 1995, p. 236). Roush 2003 defends the opposite view.

73. Rees 2007, p. 63 and similarly in Rees 2003b.

74. Davies 2003.

75. Interview with Linde in Folger 2008. What philosophers of science sometimes call the Sherlock Holmes strategy refers to a passage in one of Conan Doyle's most famous short stories, *Silver Blaze*. It goes without saying that the strategy is questionable. How can one know that all alternative explanations have been eliminated?

76. The invisible dark stars of very high density discussed by John Michell, Laplace, and others were not, strictly speaking, undetectable. It was realized that in principle their existence might be revealed by their gravitational perturbations on visible stars or planets. On the history of the idea of dark stars and its relation to black holes, see Israel 1987.

77. Tegmark 2008, p. 124, and very similar in Livio and Rees 2005.

78. The use and misuse of historical analogies can be followed through most of history of science. In a discussion of the methods of cosmology, Thomas Gold warned against relying on such analogies: 'The most valuable lesson to be learnt from the history of scientific progress is how misleading and strangling such analogies have been, and how success has come to those who ignored them' (Gold 1956, p. 1722). Gold's argument was directed against Dingle's critique of the steady-state theory and other modern models of the universe.

79. Rees 2003b, p. 385.

80. Barrau 2007.

81. Carr and Ellis 2008, 2.33.

82. Rees 2003b, p. 388.

83. Richter 2006, p. 9.

84. Carr and Ellis 2008, p. 2.35.

85. Smolin 2006, p. 170.

86. Steinhardt and Turok 2004.

87. However, *Logik der Forschung* was noticed by Einstein, who read it soon after it appeared. He liked it very much, so as he told Popper in a letter of 15 June 1935: 'Your book has pleased me in many ways. Rejection of the "inductive method" from an epistemological standpoint. Also the falsifiability as determining property of a theory of reality.' Quoted in Van Dongen 2002, p. 39.

88. Livio 2000, p. 187.

89. Carter 1993.

90. Barrau 2007.

91. Ehrlich 2006, p. 86.

92. Susskind and Smolin 2004.

93. Susskind 2006, p. 196.

94. Quoted in Matthews 2008.

95. Heller 2009, pp. 88–89.

96. This example was used by McVittie against Bondi's frequent claims that the steady-state theory, being easily falsifiable, was more scientific than the relativistic rival models of the universe. See Kragh 1990, p. 250.

97. Quoted in Folger 2008.

98. Swinburne 1996, p. 68. Weinberg (2007, p. 39) has called attention to an article in the *New York Times* in which Christoph Schönborn, archbishop of Vienna, grouped together 'neo-Darwinism and the multiverse hypothesis in cosmology' and attacked them for trying 'to avoid the overwhelming evidence for purpose and design found in modern science'. The source is *New York Times* of 7 July 2005, p. A23.

99. Davies 2003.

100. Page 2007, p. 412. See also the interview in Lightman and Brawer 1990, where Page expressed his sympathy for a multiverse. While in favour of the multiverse, he rejects Tegmark's mathematical (level IV) multiverse because it involves contradictions.

101. The documents from the 1986 court case can be found online as http://www.talkorigins.org/faqs/edwards-v-aguillard/amicus1.html.

102. Luskin 2006. The suspicion of double standards is also discussed by Robert Ehrlich, a physics professor with no sympathy for intelligent design and no sympathy for the multiverse either (Ehrlich 2006).