failing to solve a problem beyond his competence. The most he can hope for is the kindly contempt earned by utopian politicians."[6]

Despite Einstein's aphorism about the comprehensibility of the world that I quoted in the Prologue of this book, it would be astonishing if human brains were "matched" to all aspects of the external world. Some of nature's complexity may never be explained or understood.

Martin Rees

CHAPTER 11 Laws and Bylaws in the Multiverse

Many Universes?

I described in chapter 9 how the entire domain astronomers observe, extending at least 10 billion light-years, could have inflated from an infinitesimal speck; moreover, the inflationary growth could have led to a universe so large that its extent requires a million-digit number to express it. But even this vast expanse of space may not be everything there is: patches where inflation does not end may grow fast enough to provide the seeds for other Big Bangs. If so, our Big Bang wasn't the only one but may even be part of an eternally reproducing cosmos.

There are other conjectures that suggest a multiplicity of universes. For instance, whenever a black hole forms, processes deep inside it might trigger the creation of another universe into a space disjoint from our own. If that new universe were like ours, stars, galaxies, and black holes would form in it, and those black holes would in turn spawn another generation of universes, and so on, perhaps ad infinitum. Alternatively, if there were extra spatial dimensions that were not tightly rolled up, we may be living in one of many separate universes embedded in a higher-dimensional space.

All these theories are tentative and should be prefaced by something akin to a health warning. But they give us tantalizing glimpses of a dramatically enlarged cosmic perspective. The entire history of our universe could be just an episode, one facet, of the infinite multiverse. Were this indeed so, some features of our universe would be less surprising. Let me sketch why I think this is so.

A Special Recipe?

The distinctive details of our universe, and of everything in it (ourselves included), seem to be the outcome of what might be called an accident. The size and shape of our home Galaxy are the outcome of quantum fluctuations imprinted when the universe was the size of a golf ball; so is the layout of galaxies in the Local Group around us. The gases that ended up in our Sun had been, for billions of years, churned up by the shearing motions in our rotating Galaxy and buffeted by supernova explosions. Our Earth (along with the other inner planets, Mercury, Venus, and Mars) is an agglomeration of rocks and asteroids; the largest crash scooped out the material that made the Moon. Earth's surface has been molded by continental drift, by volcanism, and by further impacts. These and other terrestrial contingencies have controlled the topography and climate and determined the emergence and extinction of species. On a more parochial scale of space and time, each of us is the outcome of time and chance—the key events in the lives of all our ancestors. On a still smaller, microscopic, scale we owe our genetic inheritance to the near-random fate of individual spermatozoa.

Obviously, we can never explain all the contingencies that led from a Big Bang to our own birth here 13 billion years later. The outcome depended crucially on a recipe encoded in the Big Bang, and this recipe seems to have been rather special. I argued in chapter 5 that the emergence of such an intricate variety from a simple beginning does not conflict with any fundamental principle. But a degree of fine-tuning—in the expansion speed, the material content of the universe, and the strengths of the basic forces—seems to have been a prerequisite for the emergence of the hospitable cosmic habitat in which we live.

The following are some prerequisites for a universe containing organic life of the kind we find on Earth.

First of all, it must be very large in its spatial extent compared to individual particles, and very long-lived compared with basic atomic processes. Indeed, this is surely a requirement not only for our universe, but for any hypothetical universe that a science fiction writer could plausibly find interesting. If atoms are the basic building blocks, then clearly nothing as elaborate as an ecosystem could be constructed unless there were huge numbers of them. Nothing much could happen in a universe that was was too short lived: an expanse of time, as well as space, is needed for evolutionary processes.

We have seen that a force such as gravity is crucial. But an interesting universe requires it to be very weak. If gravity were not exceedingly weak on the scale of atoms, then stars (gravitationally bound fusion reactors) would be small and short lived; gravity would crush anything larger than an insect, and there would be no time for complex evolution. Any interesting recipe must involve at least one very large number. This in itself is not fine-tuning—it is merely a constraint. And there is another constraint: the cosmic repulsion in empty space must be very weak (equivalently, the number lambda must be very small); otherwise, this disruptive force would have prevented gravitationally bound structures from forming.

But even if such structures form in a universe as large and long lived as ours, the outcome could be very boring: it could contain just black holes or inert dark matter, and no atoms at all. An interesting universe requires the kind of asymmetry in the laws that allows an excess of matter or antimatter, so that enough atoms can exist. Atoms need not be the *dominant* constituent in terms of mass: in our own universe the dark matter outweighs them by a factor of 5 to 10. But if there were, say, ten times fewer atoms than there actually are, they would remain in diffuse gas that would never condense into galaxies and stars.

The requirement of an interesting universe pins down other numbers in a specific narrow range. As discussed in chapter 5, the number Q, measuring the cosmic texture, cannot be too far from 1/100,000. If it were still smaller, the expansion could be so smooth—with no initial ripples or fluctuations—that no structures would develop. If Q were much larger, the universe would be so rough that it would collapse into huge black holes: an inclement environment for any form of life that we can readily imagine.

There is tuning in the microworld as well. The nuclear fusion that powers stars depends on the balance between two forces: the electrical repulsion between any two protons, and the strong countervailing nuclear force that attracts them to each other (and which also attracts the electrically neutral neutrons). The laws must not only allow protons and neutrons to exist, but they must allow the variety of atoms required for complex chemistry. If nuclear forces were slightly weaker, no chemical elements other than hydrogen would be stable: there would be no periodic table, chemistry would be a trivially simple subject, and there would be no nuclear energy to power the stars. But if the nuclear forces were slightly stronger than they actually are relative to electric forces, two protons could stick together so readily that ordinary hydrogen would not exist, and stars would evolve quite differently. Some of the details are still more sensitive. For instance, we noted in chapter 3 that carbon would not be so readily produced in stars were it not for some apparent fine-tuning in the properties of its nucleus, which depend even more sensitively on this same number.

What Does the Fine-Tuning Mean?

If our existence depends on a seemingly special cosmic recipe, how should we react to the apparent fine-tuning? We seem to have three choices: we can dismiss it as happenstance; we can acclaim it as the workings of providence; or (my preference) we can conjecture that our universe is a specially favored domain in a still vaster multiverse. Let's consider them in turn.

Happenstance (or Coincidence)

Perhaps a fundamental set of equations, which may some day be written on T-shirts, fixes all key properties of our universe uniquely. It would then be just an unassailable fact that these equations permitted the immensely complex evolution that led to our emergence.

But I think there would still be something to wonder about. It is not guaranteed that simple equations permit complex consequences. To take an analogy from mathematics, consider the beautiful pattern known as the Mandelbrot set. This pattern is encoded by a short algorithm but has an infinitely deep structure: tiny parts of it reveal novel intricacies no matter much they are magnified. In contrast, you can readily write down other algorithms, superficially similar, that yield very dull patterns. Why should the fundamental equations encode something with such potential complexity as our actual universe rather than the boring or sterile universe that many recipes would lead to?

One hard-headed response is that we could not exist if the laws had boring consequences. We manifestly are here, so there's nothing to be surprised about. But I am afraid this leaves me unsatisfied. I am impressed by a metaphor given by the Canadian philosopher John Leslie. Suppose you are facing a firing squad. Fifty marksmen take aim, but they all miss hitting you, the target. If they had not all missed, you would not have survived to ponder the matter. But you would not leave it at that: you would still be baffled, and you would seek some further reason for your luck. Likewise, we should surely probe deeper, and ask why a unique recipe for the physical world should permit consequences as interesting as those we see around us (and which, as a by-product, allowed us to exist).

Providence or Design

Design in the cosmos is the traditional theme of what used to be called "natural theology." Two centuries ago, William Paley introduced the famous metaphor of the watch and the watchmaker—adducing the eye, the opposable thumb and so on as evidence of a benign Creator. This line of thought fell from favor, even among most theologians, in post-Darwinian times. We now view any biological contrivance as the outcome of prolonged evolutionary selection and symbiosis with its surroundings.

As mentioned in chapter 10, Paley included the fact that gravity obeys an inverse square law among his design arguments. He actually could not muster much astronomical ammunition for his main theological thesis. He said, in his quaint way, that "astronomy is not the best medium through which to prove . . . an intelligent creator, but that, this being proved, it shows beyond all other sciences the magnificence of his operations."

Paley might have reacted differently, however, if he had known about the providential-seeming physics that led to galaxies, stars, planets, and the ninety-two elements of the periodic table (encapsulated in the fine-tuned strength of the nuclear force) and the number *Q* that imprints cosmic structure. And he would have been impressed by other seemingly biophilic features of basic physics and chemistry—for instance, those that give water its unusual properties of expanding when it cools and freezes.

These features can not be as readily dismissed as the old claims for design in living things. This is because the basic laws governing stars and atoms are a given, and nothing biological can react back on them to modify them. A modern counterpart of Paley is John Polkinghorne, a Cambridge physics professor who turned theologian in later life (and who was one of my own physics teachers). He interprets our fine-tuned habitat as "the creation of a Creator who wills that it should be so."[1]

A Special Universe Drawn from an Ensemble, or Multiverse

If one does not believe in providential design, but still thinks the fine-tuning needs some explanation, there is another perspective—a highly speculative one, so I should reiterate my health warning at this stage. It is the one I much prefer, however, even though in our present state of knowledge any such preference can be no more than a hunch.

There may be many "universes" of which ours is just one. In the others, some laws and physical constants would be different. But our universe would not be just a random one. It would belong to the unusual subset that offered a habitat conducive to the emergence of complexity and consciousness. The analogy of the watchmaker could be off the mark. Instead, the cosmos may have something in common with an off-the-rack clothes shop: if the shop has a large stock, we are not surprised to find one suit that fits. Likewise, if our universe is selected from a multiverse, its seemingly designed or fine-tuned features would not be surprising.

This hypothesis may not seem "economical": indeed, it might seem to flout, absolutely maximally, the dictum now known as Ockham's Razor—the injunction of the fourteenth-century sage William of Ockham "not to multiply hypotheses more than necessary." At first sight, nothing seems more conceptually extravagant than invoking multiple universes. But this concept follows from several different theories (albeit all speculative), and opens up a new vision of our universe as just one atom selected from an infinite multiverse.*

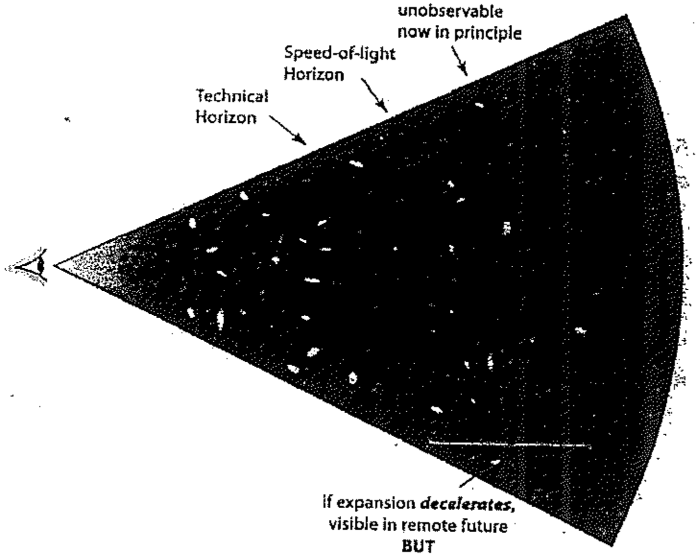
Are Questions about Other Universes Part of Science?

Science is an experimental or observational enterprise, and it is natural to be troubled by assertions that cannot be checked empirically. Some might regard the other universes as being in the province of metaphysics rather than physics. But I

*There is a risk of semantic confusion here. The usual definition of "universe" is of course "everything there is." It would be neater to redefine the whole enlarged ensemble as "the universe" and then introduce some new term—for instance, "the metagalaxy"—for the domain that cosmologists and astronomers can directly observe. But so long as these concepts all remain so conjectural, it is best to leave the term "universe" undisturbed, with its traditional connotations, even though this then demands a new word, the "multiverse," for a (still hypothetical) ensemble of "universes."

think they already lie within the proper purview of science. It is not absurd or meaningless to ask, "Do unobservable universes exist?" even though no quick answer is likely to be forthcoming. The question plainly cannot be settled by *direct* observation, but relevant empirical evidence *can* be sought, which could lead to an answer.

There is actually a blurred transition between the readily observable and the absolutely unobservable, with a very broad gray area in between. To illustrate this, one can envisage a succession of four horizons (see fig. 11.1), each taking us farther than the last from our direct experience:



11.1
Successive "credibility horizons" (see text for an explanation).

1. Limit of present-day telescopes

There is a limit to how far out into space our present-day instruments can probe. Obviously there is nothing fundamental about this limit: it is constrained by current technology. Many more galaxies will undoubtedly be revealed in the coming decades by bigger telescopes now being planned. We would obviously not demote such galaxies from the realm of proper scientific discourse simply because they have not been seen yet. When ancient navigators speculated about what existed beyond the boundaries of the then-known world, or when we speculate now about what lies below the oceans of Jupiter's moons, Europa and Ganymede, we are speculating about something "real"—we are asking a scientific question. Likewise, conjectures about remote parts of our universe are genuinely scientific, even though we must await better instruments to check them.

2. Limit in principle at present era

Even if there were absolutely no technical limits to the power of telescopes, our observations are still bounded by a horizon, set by the distance that any signal, moving at the speed of light, could have traveled since the Big Bang. This horizon demarcates the spherical shell around us at which the redshift would be infinite. There is nothing special about the galaxies on this shell, any more than there is anything special about the circle that defines your horizon when you are in the middle of an ocean. On the ocean, you can see farther by climbing up your ship's mast. But our cosmic horizon cannot be extended unless the universe changes, so as to allow light to reach us from galaxies that are now beyond it.

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When our universe is, say, twice as old as it is now, this horizon will be twice as far away. But if that expansion is decelerating, then each galaxy, having slowed down, will be *less than* twice as far away, so the horizon of our remote descendants will also encompass extra galaxies that are beyond our horizon today. It is, to be sure, a practical impediment if we have to await a cosmic change taking billions of years, rather than just a few decades—maybe—of technical advance, before a prediction about a particular distant galaxy can be put to the test. But does that introduce a difference of principle? Surely the longer waiting time is a merely quantitative difference, not one that changes the epistemological status of these faraway galaxies.

3. Never-observable galaxies from "our" Big Bang

But what about galaxies that we can *never* see, however long we wait? In chapter 5 I discussed evidence that we inhabit an accelerating universe. As in a decelerating universe, there would be galaxies so far away that no signals from them could yet have reached us; but if the cosmic expansion is accelerating, we are now receding from these remote galaxies at an ever increasing rate, so if their light has not reached us yet, it never will. Such galaxies are not merely *unobservable in principle now*—they will be beyond our horizon *forever*. But if a galaxy is *now* unobservable, it hardly seems to matter whether it remains unobservable forever, or whether, as in a decelerating universe, it would come into view if we waited a trillion years. (And I have argued, under (2) above, that the latter category should certainly count as "real.")

4. Galaxies in disjoint universes

The never-observable galaxies in (3) would have emerged from the same Big Bang as we did. But suppose that, instead of causally disjoint regions emerging from a single Big Bang (via an episode of inflation), we imagine separate Big Bangs. Are space-times that are completely disjoint from ours any less real than regions that never come within our horizon in what we would traditionally call our own universe? Surely not. So these other universes should count as real parts of our cosmos, too.

This step-by-step argument (those who don't like it might dub it a slippery slope argument) suggests that whether other universes exist or not is a scientific question. So how do we answer it?

Scenarios for a Multiverse

Many scenarios could lead to multiple universes. Andrei Linde, Alex Vilenkin, and others have performed computer simulations depicting an "eternal" inflationary phase where many universes sprout from separate Big Bangs into disjoint regions of space-time. Alan Guth and Lee Smolin have, from different viewpoints, suggested that a new universe could sprout inside a black hole, expanding into a new domain of space and time inaccessible to us. And Lisa Randall and Raman Sundrum suggest that other universes could exist, separated from us in an extra spatial dimension. These disjoint universes may interact gravitationally, or they may have no effect whatsoever on one another. In the hackneyed analogy where the surface of a balloon represents a two-dimensional universe embedded in our three-dimensional space, these other universes would be represented by the surfaces of other balloons: any bugs confined to one, and with no conception of a third dimension, would be unaware of their counterparts crawling around on another balloon. Other universes would be separate domains of space and time. We could not even meaningfully say whether they existed before, after, or alongside our own because such concepts make sense only insofar as we can impose a single measure of time, ticking away in all the universes.

Guth and Edward Harrison have even conjectured that universes could be made in the laboratory by imploding a lump of material to make a small black hole. Is our entire universe perhaps the outcome of some experiment in another universe? Smolin speculates that the daughter universe may be governed by laws that bear the imprint of those prevailing in its parent universe. If so, the theological arguments from design could be resuscitated in a novel guise, further blurring the boundary between natural and supernatural phenomena.

Parallel universes are also invoked as a solution to some of the paradoxes of quantum mechanics, in the "many worlds" theory first advocated by Hugh Everitt and John Wheeler in the 1950s. This concept was prefigured by Olaf Stapledon, as one of the more sophisticated creations of his *Star Maker:* "Whenever a creature was faced with several possible courses of action, it took them all, thereby creating many . . . distinct histories of the cosmos. Since in every evolutionary sequence of the cosmos there were many creatures and each was constantly faced with many possible courses, and the combinations of all their courses were innumerable, an infinity of distinct universes exfoliated from every moment of every temporal sequence."

None of these scenarios has been simply dreamed up out of the air: each has a serious, albeit speculative, theoretical motivation. However, one of them, at most, can be correct. Quite possibly none is: there are alternative theories that would lead just to one universe.

Firming up any of these ideas will require a theory that consistently describes the extreme physics of ultra-high densities, how structures on extra dimensions are configured, and so forth. But consistency is not enough: there must be grounds for confidence that such a theory is not a mere mathematical construct but applies to external reality. We would develop such confidence if the theory accounted for things we *can* observe that are otherwise unexplained. At the moment, we have an excellent framework called the "standard model" that accounts for almost all subatomic phenomena that have been observed. But the formulas of the standard model involve numbers, about eighteen altogether, which cannot be derived from the theory but have to be inserted from experiment. Any theory that gave some insight into why there are particular families of particles, and into the nature of the nuclear and electric forces, would acquire credibility; we would then be disposed to pay serious regard to other predictions it made, even if we could not directly test them.

Einstein's theory of gravity, or general relativity—dates from 1916. It took more more than fifty years before any tests could measure the distinctive effects of the theory with better than 10 percent accuracy. But now the scope and precision of empirical tests have improved so much, and yielded such comprehensive and precise support for Einstein, that it would require very compelling evidence indeed to shake our belief that general relativity is the correct classical theory of gravity. In consequence, we now have confidence in what the theory tells us even about regions we cannot probe, such as the interiors of black holes. Likewise, we take seriously our ideas about nuclear reactions inside stars and in the hot early universe because they are based on theories of atoms and their nuclei that have been well confirmed experimentally.

Perhaps, in the twenty-first century, physicists will formulate a theory that copes with an extrapolation right back to the Planck time and earns our confidence by accounting for hitherto unexplained phenomena accessible to experiment. If such a theory were to predict many Big Bangs, then we would have as much reason to believe in separate universes as we now have for believing statements about black holes, or about helium formation in the first few minutes after the Big Bang. Some day we may therefore have grounds either for belief or for disbelief in other universes.

Universal Laws, or Mere Bylaws?

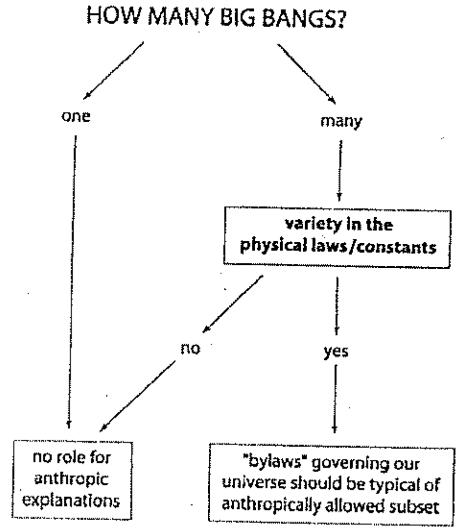
If other universes exist, theory may also offer clues to a further key question about them: How much variety do they display? Some theorists, Frank Wilczek for instance, regard the question "Are the laws of physics unique?"—a less poetic paraphrase of Einstein's question quoted in the Prologue—as a key scientific challenge for the new century. If there were something uniquely self-consistent about the actual recipe, then any Big Bang would trigger a universe that was just a rerun of ours.

But a far more interesting possibility (which is certainly tenable in our present state of ignorance of the underlying laws) is that *the underlying laws governing the entire multiverse may allow variety among the universes.* What we call the laws of nature govern the entire domain we observe, but they may in this grander perspective be *local bylaws*, consistent with some overarching theory governing the ensemble but not uniquely fixed by that theory. Many things in our cosmic environment—for instance, the exact layout of the planets and asteroids in our solar system—are accidents of history. Likewise, the recipe for an entire universe may be arbitrary.

The same balance between chance and necessity arises in biology. Our basic development—from embryo to adult—is encoded in our genes, but many aspects of our development are molded by our environment and experiences. There are far simpler examples of the same dichotomy—snowflakes, for instance. Their ubiquitous sixfold symmetry is a direct consequence of the properties and shape of water molecules. But their immense variety depends on their environment—on the fortuitous temperature and humidity changes during each flake's growth. If we had a fundamental theory, we would know which aspects of nature were direct consequences of the bedrock theory (just as the symmetrical template of snowflakes is due to the basic structure of a water molecule) and which are the outcome of accidents (like the distinctive pattern of a particular snowflake). The accidental features could be imprinted during the cooling that follows the Big Bang, rather as a piece of red-hot iron becomes magnetized when it cools down, but with an alignment that may depend on chance factors. They could have other contingent causes, such as the influence of another nearby universe separated from ours in a fifth dimension.

The cosmological numbers in our universe, omega, Q, and lambda, and perhaps some of the so-called constants of laboratory physics as well, could be arbitrary rather than uniquely fixed by some final theory. If so, then the off-the-rack clothes shop analogy—where there is a large stock of universes, as it were—would remove any reason for being surprised by the apparent fine-tuning of these numbers in our particular home universe.

Some features of our universe could then only be explained by "anthropic" argument (see fig. 11.2). Although this style of explanation raises hackles among some physicists, it is analogous to what observers or experimenters do when they allow for selection effects in their measurements: if there are many universes, most of which are not habitable, we should not be surprised to find ourselves in one of the habitable ones.

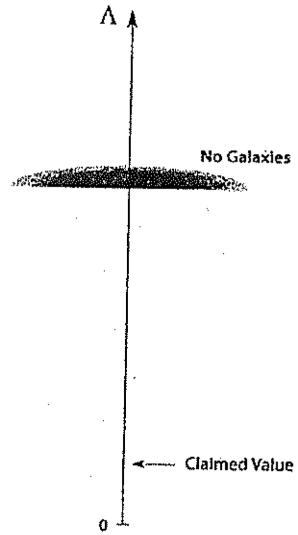


11.2
Flow chart illustrating how the status of anthropic explanations depends on the character of fundamental physical laws.

Testing Multiverse Theories Here and Now

We may one day have a convincing theory that tells us whether a multiverse exists and whether some of the so-called laws of nature are just parochial bylaws in our cosmic patch. But while we are waiting for that theory—and it could be a long wait—the "off-the-rack clothes shop" analogy can already be checked. It could even be refuted: this would happen if our universe turned out to be *even more specially* tuned than our presence requires.

To illustrate this line of reasoning, let's consider one seemingly tuned cosmic number: the energy latent in empty space which causes a cosmic repulsion and is measured by the number lambda. Physicists would expect lambda to be large because it is a consequence of a very complicated microstructure of space. A small lambda is, however, a prerequisite for our existence: an unduly fierce cosmic repulsion would disrupt galaxies. Perhaps there is only a rare subset of universes where lambda is below the threshold that allows galaxies and stars to form (as below the blurred line on fig. 11.3). Lambda in *our* universe obviously had to be below that threshold. But if our universe were drawn from an ensemble in which lambda was equally likely to take any value, we would not expect it to be *too far below it.*



11.3
Constraints on lambda: if cosmical repulsion were too strong, no galaxies would form. Is our universe typical of anthropically allowed universes, or is lambda far lower than our existence requires?

If we are indeed in an accelerating universe, as the current evidence suggests, the actual value is five to ten times below that threshold. That would put our universe between the tenth or twentieth percentile of universes in which galaxies could form. In other words, our universe is not significantly more special, with respect to lambda, than our emergence demanded. But suppose that, contrary to current indications, future observations showed that lambda made no discernible contribution to the expansion rate and was *thousands of times* below the threshold, not just five to ten times.

This "overkill precision" would raise doubts about the hypothesis that lambda was equally likely to have any value and suggest that it was zero for some fundamental reason (or that it had a discrete set of possible values, and all the others were well above the threshold).[2]

I have taken lambda just as an example. We could analyze other important numbers of physics in the same way to test whether our universe is typical of the habitable subset that could harbor complex life. The methodology requires us to decide what values are compatible with our emergence. It also requires a specific theory that gives the probability of any particular value. For instance, in the case of lambda, are all values equally probable, or is there some more complicated formula? With this information, one can then ask if our actual universe is "typical" of the subset in which we could have emerged. If it is an atypical member even of this subset (not merely of the entire multiverse), then our hypothesis would be disproved.

As another example of how "multiverse" theories can be tested, consider Smolin's conjecture that new universes are spawned within black holes, and that the physical laws in the daughter universe retain a memory of the laws in the parent universe: in other words, there is a kind of heredity. Smolin's concept is not yet bolstered by any detailed theory of how any physical information (or even an arrow of time) could be transmitted from one universe to another. It has, however, the virtue of making a prediction about our universe that can be checked.

If Smolin were right, universes that produce many black holes would have a reproductive advantage, which would be

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passed on to the next generation. Our universe, if it is an outcome of this process, should therefore be near-optimum in its propensity to make black holes, in the sense that any slight tweaking of the laws and constants would render black hole formation less likely.[3] In our universe, black holes form as the endpoint of massive stars, and also in the centres of galaxies. It would then require only astronomical observations and an astrophysical understanding of these formation processes to test whether any change in the physics of atoms, nuclei, or galaxies would enhance the propensity to form black holes. I personally think Smolin's prediction is unlikely be borne out, but he deserves our thanks for presenting an example that illustrates how a specific multiverse theory can be vulnerable to disproof.

These examples show that some claims about other universes may be refutable, as any good hypothesis in science should be. We cannot confidently assert that there were many Big Bangs—we just don't know enough about the ultra-early phases of our own universe. But the physics of ultradense materials may, when applied to the Big Bang, predict multiple universes. Moreover, this same theory may tell us that each universe cools down differently, ending up with different expansion rates, contents, dimensionality, and microphysics.

Elucidating whether the underlying laws *are* as permissive as this is a challenge to twenty-first-century physicists. If things work out that way, then so-called anthropic explanations would become legitimate—indeed, they'd be *the only type of explanation we'll ever have* for some important features of our universe.[4] Efforts to seek fundamental formulas for some of the key numbers of physics would then be as misguided as Kepler's attempts to relate the sizes of planetary orbits to the Platonic solids (cubes, tetrahedra, and so forth).

A Seventeenth-Century Flashback

Kepler knew only about our solar system. Moreover, he thought that the orbits of the planets should be circles in exact mathematical ratios. Today we don't expect that. Our Earth traces just one ellipse out of an infinity of possibilities allowed by Newton's laws—the exact shape is a result of its complicated history and origins. Its orbit is special only insofar as it allows an environment conducive for evolution (not getting so close to the Sun that water boils, nor being so far away that it's perpetually frozen).

Perhaps our traditional perspective on the universe and the physical laws that govern it will go the way of Kepler's concept of Earth's orbit. What we have traditionally called "the universe" may be the outcome of one Big Bang among many, just as our solar system is merely one of many planetary systems in the Galaxy. Just as the pattern of ice crystals on a freezing pond is an accident of history rather than a fundamental property of water, so some of the seeming constants of nature may be arbitrary details rather than being uniquely defined by the underlying theory.

Our own universe—our cosmic habitat—has a simple recipe, but it isn't quite as simple as it might have been. It contains dark matter as well as atoms. As an extra complication, dark energy in empty space exerts a repulsion that overwhelms gravity on the cosmic scale. Some theorists are upset by these developments because they frustrate their craving for

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maximal simplicity. I think we can learn a lesson from the cosmological debates in the seventeenth century. Galileo and Kepler were upset that planets moved in elliptical orbits, not in perfect circles. But later Newton showed that all elliptical orbits could be understood by a single unified theory of gravity. Likewise, our universe may be just one of an ensemble of all possible universes, constrained only by the requirement that it allows our emergence. But to regard this outcome as ugly may be as myopic as Kepler's infatuation with circles. Newton was perhaps the greatest scientific intellect of the second millennium. Perhaps his third-millennium counterpart will uncover a mathematical system that governs the entire multiverse.

Finally, let us recall Hubble's words in his classic 1936 book, *The Realm of the Nebulae*: "Only when empirical resources are exhausted do we reach the dreamy realm of speculation." We still dream and speculate. But there has been astonishing empirical progress since Hubble's time owing to large telescopes on the ground, to the great instrument in space that bears his name, and to other technical advances.

There are three great frontiers in science: the very *big*, the very *small*, and the very *complex*. Cosmology involves them all. First, cosmologists must pin down the basic numbers such as Ω, and find what the dark matter is. I think there is a good chance of achieving this goal within ten years. Second, theorists must elucidate the exotic physics of the very earliest stages, which entails a new synthesis between cosmos and microworld. It would be presumptuous for me to place bets here. But cosmology is also the grandest environmental science, and its third aim is to understand how a Big Bang described by a simple recipe evolved, over 13 billion years, into our complex cosmic habitat: the filamentary layout of galaxies through space, the galaxies themselves, the stars, planets, and the prerequisites for life's emergence. No mystery in cosmology presents a more daunting challenge than the task of fully elucidating how atoms assembled—here on Earth and perhaps on other worlds—into living beings intricate enough to ponder their origins.