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The nature of the laws of physics and their mysterious biofriendliness

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Abstract

For thousands of years, human beings have contemplated the world about them and asked the great questions of existence: Why are we here? How did the universe begin? How will it end? How is the world put together? Why is it the way it is? For all of recorded human history, people have sought answers to such ultimate questions in religion and philosophy, or declared them to be completely beyond human comprehension. Today, however, many of these big questions are part of science, and some scientists claim that they may be on the verge of providing answers.

1. The universe is weirdly fine-tuned for life

One of the most significant facts —arguably the most significant fact— about the universe is that we are part of it. For life to emerge, and then to evolve into conscious beings like ourselves, certain conditions have to be satisfied. Among the many prerequisites for life — at least, for life as we know it— is a good supply of the various chemical elements needed to make biomass. Carbon is the key life-giving element, but oxygen, hydrogen, nitrogen, sulphur and phosphorus are crucial too. Liquid water is another essential ingredient. Life also requires an energy source, and a stable environment, which in our case are provided by the sun. For life to evolve past the level of simple microbes, this life-encouraging setting has to remain benign for a very long time; it took billions of years for life on earth to reach the point of intelligence.

On a larger scale, the universe must be sufficiently old and cool to permit complex chemistry. It has to be orderly enough to allow the untrammelled formation of galaxies and stars. There have to be the right sorts of forces acting between particles of matter to make stable atoms, complex molecules, planets and stars. If almost any of the basic features of the universe, from the properties of atoms to the distribution of the galaxies, were different, life would very probably be impossible[1].

Now, it happens that to meet these various requirements, certain stringent conditions must be satisfied in the underlying laws of physics that regulate the universe, so stringent in fact that a bio-friendly universe looks like a fix — or a put-up job, to use the pithy description of the late British cosmologist Fred Hoyle. It appeared to Hoyle as if a super-intellect had been monkeying with the laws of physics [2]. He was right in his impression. On the face of it, the universe does look as if it has been designed by an intelligent creator expressly for the purpose of spawning sentient beings. Like the porridge in the tale of Goldilocks and the three bears, the universe seems to be just right for life, in many intriguing ways. No scientific explanation for the universe can be deemed complete unless it accounts for this appearance of judicious design.

Until recently, the Goldilocks factor was almost completely ignored by scientists. Now, that is changing fast. Science is at last coming to grips with the enigma of why the universe is so uncannily fit for life. The explanation entails understanding how the universe began and evolved into its present form, and knowing what matter is made of and how it is shaped and structured by the different forces of nature. Above all, it requires us to probe the very nature of physical laws.

2. The cosmic code

Science is familiar, and familiarity breeds contempt. People show little surprise that science actually works, that we are in possession of the key to the universe. Beneath the surface complexity of nature lies a hidden subtext, written in a subtle mathematical code. This cosmic code[2] contains the rules on which the universe runs. Newton, Galileo and other early scientists treated their investigations as a religious quest. They thought that by exposing the patterns woven into the processes of nature they truly were glimpsing the mind of God.[3] Modern scientists are mostly not religious, yet they still accept that an intelligible script underlies the workings of nature, for to believe otherwise would undermine the very motivation for doing research, which is to uncover something meaningful about the world that we do not already know.

Finding the key to the universe was by no means inevitable. For a start, there is no logical reason why nature should have a mathematical subtext in the first place. And even if it does, there is no obvious reason why humans should be capable of comprehending it. You

[1] I shall restrict my discussion to life as we know it. The possibility of exotic forms of life based on other chemical elements, or other physical processes entirely, is certainly fascinating but completely speculative. If life is common, we have no reason to suppose that our form of life is atypical. Readers interested in a less conservative approach will find an up-to-date discussion in [1].

[2] The term was popularized by the physicist Heinz Pagels [3].

[3] See, for example, [4].

would never guess by looking at the physical world that beneath the surface hubbub of natural phenomena lies an abstract order, an order that can not be seen or heard or felt, but deduced. Even the wisest mind could not tell merely from daily experience that the diverse physical systems making up the cosmos are linked, deep down, by a network of coded mathematical relationships. Yet science has uncovered the existence of this concealed mathematical domain. We human beings have been made privy to the deepest workings of the universe. Other animals observe the same natural phenomena as we do, but alone among the creatures on this planet, Homo sapiens can also explain them.

How has this come about? Somehow the universe has engineered, not just its own awareness, but its own comprehension. Mindless, blundering atoms have conspired to make, not just life, not just mind, but understanding. The evolving cosmos has spawned beings that are able not merely to watch the show, but to unravel the plot. What is it that enables something as small and delicate and adapted to terrestrial life as the human brain to engage with the totality of the cosmos and the silent mathematical tune to which it dances?

Could it just be a fluke? Might the fact that the deepest level of reality has connected to a quirky natural phenomenon we call the human mind represent nothing but a bizarre and temporary aberration in an absurd and pointless universe? Or is there an even deeper sub-plot at work?

3. The concept of laws

The founding assumption of science is that the physical universe is neither arbitrary nor absurd; it is not just a meaningless jumble of objects and phenomena haphazardly juxtaposed. Rather, there is a coherent scheme of things. This is often expressed by the simple aphorism that there is order in nature. But scientists have gone beyond this vague notion to formulate a system of well-defined laws. The existence of laws of nature is the starting point for science. But right at the outset we encounter an obvious and profound enigma: where do the laws of nature come from? Galileo, Newton and their contemporaries regarded the laws as thoughts in the mind of God, and their elegant mathematical form as a manifestation of Gods rational plan for the universe. Few scientists today would describe the laws of nature using such quaint language. Yet the questions remain of what these laws are and why they have the form that they do. If they are not the product of divine providence, how can they be explained?

By the thirteenth century, European theologians and scholars such as Roger Bacon had arrived at the conclusion that laws of nature possess a mathematical basis, a notion that dates back to the Pythagoreans. Given the cultural background, it is no surprise that when modern science emerged in Christian Europe in the sixteenth and seventeenth centuries, it was perfectly natural for the early scientists to believe that the laws they were discovering in the heavens and on earth were the mathematical manifestations of Gods ingenious handiwork.

Even atheistic scientists will wax lyrical about the scale, the majesty, the harmony, the elegance, the sheer ingenuity of the universe of which they form so small and fragile a part. As the great cosmic drama unfolds before us, it begins to look as though there is a scripta scheme of thingswhich its evolution is following. We are then bound to ask, who or what wrote the script? Or did the script somehow, miraculously, write itself? Is the great cosmic text laid down once and for all, or is the universe, or the invisible author, making it up as it goes along? Is this the only drama being staged, or is our universe just one of many shows in town?

The fact that the universe conforms to an orderly scheme, and is not an arbitrary muddle of events, prompts one to wonder –God or no God– whether there is some sort of meaning or purpose behind it all. Many scientists are quick to pour scorn even on this weaker suggestion, however. Richard Feynman, arguably the finest theoretical physicist of the mid-twentieth century, thought that [5] "the great accumulation of understanding as to how the physical world behaves only convinces one that this behaviour has a kind of meaninglessness about it". This sentiment is echoed by the theoretical physicist and cosmologist Steven Weinberg: The more the universe seems comprehensible the more it also seems pointless" [6].

To be sure, concepts like meaning and purpose are categories devised by humans, and we must take care when attempting to project them onto the physical universe. But all attempts to describe the universe scientifically draw on human concepts: science proceeds precisely by taking concepts that humans have thought up, often from everyday experience, and applying them to nature. Doing science means figuring out what is going on in the worldwhat the universe is up to, what it is about. If it isnt about anything, there would be no good reason to embark on the scientific quest in the first place, because we would have no rational basis for believing that we could thereby uncover additional coherent and meaningful facts about the world. So we might justifiably invert Weinbergs dictum and say that the more the universe seems pointless, the more it also seems incomprehensible. Of course, scientists might be deluded in their belief that they are finding systematic and coherent truth in the workings of nature. Ultimately there may be no reason at all for why things are the way they are. But that would make the universe a fiendishly clever bit of trickery. Can a truly absurd universe so convincingly mimic a meaningful one?

4. Are the laws real?

The fact that the physical world conforms to mathematical laws led Galileo to make a famous remark. The great book of nature", he wrote, can be read only by those who know the language in which it was written. And this language is mathematics" [7]. The same point was made more bluntly three centuries later by the English cosmologist James Jeans: The universe appears to have been designed by a pure mathematician" [8]. It is the mathematical aspect that makes possible what physicists mean by the much-misunderstood word theory.

Theoretical physics entails writing down equations that capture (or model, as scientists say) the real world of experience in a mathematical world of numbers and algebraic formulas. Then, by manipulating the mathematical symbols, one can work out what will happen in the real world, without actually carrying out the observation! That is, by applying the equations that express the laws relevant to the problem of interest, the theoretical physicist can predict the answer. And it works! But why is nature shadowed by a mathematical reality?

Given that the laws of physics underpin the entire scientific enterprise, it is curious that very few scientists bother to ask what these laws actually mean. Speak to physicists, and most of them will talk as if the laws are real thingsnot physical objects of course, but abstract relationships between physical entities. Importantly, though, they are relationships that really exist, out there in the world, and not just in our heads.

The idea of laws began as a way of formalizing patterns in nature that connect together physical events. Physicists became so familiar with the laws that somewhere along the way the laws themselves —as opposed to the events they describe— became promoted to reality. The laws took on a life of their own. One reason for this way of thinking about the laws concerns the role of mathematics. Numbers began as a way of labelling and tallying physical things such as beads or sheep. As the subject of mathematics developed, and extended from simple arithmetic into geometry, algebra, calculus, and so forth, so these mathematical objects and relationships came to assume an independent existence. Mathematicians believe that statements such as $3 \times 5 = 15$ and 11 is a prime number are inherently true —in some absolute and general sense— without being restricted to three sheep or eleven beads.

Plato considered the status of mathematical objects, and chose to locate numbers and idealized geometrical shapes in an abstract realm of perfect forms. In this Platonic heaven there would be found, for example, perfect circles — as opposed to the circles we encounter in the real world, which will always be flawed approximations to the ideal. Many modern mathematicians are Platonists (at least at weekends). They believe that mathematical objects have real existence, yet are not situated in the physical universe. Theoretical physicists, who are steeped in the Platonic tradition, also find it natural to locate the mathematical laws of physics in a Platonic realm.

5. Does a multiverse explain the Goldilocks enigma?

A popular explanation for the Goldilocks enigma is the multiverse theory, according to which what we have all along been calling the universe is, in this theory, just an infinitesimal part of a single bubble, or pocket universe, set amid an infinite assemblage of universes a multiverse. This follows naturally if we regard the big bang origin of our universe as a natural physical process, in which case it cannot be unique. There will be many big bangs scattered throughout space and time. An explicit model of multiple big bangs is the theory of eternal inflation, which describes an inexhaustible universe-generating mechanism, of which our universe —our bubble— is but one product [9]. Each pocket universe will be born in a burst of heat liberated in that bubble when inflation ceases, will go on to enjoy a life cycle of evolution, and will perhaps eventually suffer a death, but the assemblage as a whole is immortal.

Life will arise only in those universes, or cosmic regions, where conditions favour life. Universes which cannot support life will go unobserved. It is therefore no surprise that we find ourselves located in a universe which is suited to life, for observers like us could not have emerged in a sterile universe. If the universes vary at random, then we would be winners in a gigantic cosmic lottery which created the illusion of design. Like many winners of national lotteries, we may mistakenly attribute some deep significance to our having won (being smiled on by Lady Luck, or suchlike) whereas in reality our success boils down to chance. However, to explain the cosmic coincidences this way –that is, in terms of observer selection– the laws of physics themselves would have to vary from one cosmic region to another. Is this credible? If so, how could it happen?

Laws of physics have two features which might in principle vary from one universe to another. First, there is the mathematical form of the law, and second, there are various constants that come into the equations. Newtons inverse square law of gravitation is an example. The mathematical form relates the gravitational force between two bodies to the distance between them. But Newtons gravitational constant G also comes into the equation: it sets the actual strength of the force. When speculating about whether the laws of physics might be different in another cosmic region, we can imagine two possibilities. One is that the mathematical form of the law is unchanged, but one or more of the constants takes on a different value. The other, more drastic, possibility is that the form of the law is different.

The Standard Model of particle physics has twenty-odd undetermined parameters. These are key numbers such as particle masses and force strengths which cannot be predicted by the Standard Model itself, but must be measured by experiment and inserted into the theory by hand. Nobody knows whether the measured values of these parameters will one day be explained by a deeper unified theory that goes beyond the Standard Model, or whether they are genuinely free parameters which are not determined by any deeper-level laws. If the latter is correct, then the numbers are not God-given and fixed but could take on different values without conflicting with any physical laws. By tradition, physicists refer to these parameters as constants of nature because they seem to be the same throughout the observed universe. However, we have no idea why they are constant and (based on our present state of knowledge) no real justification for believing that, on a scale of size much larger than the observed universe, they are constant. If they can take on different values, then the question arises of what determines the values they possess in our cosmic region.

A possible answer comes from big bang cosmology. According to orthodox theory, the universe was born with the values of these constants laid down once and for all, from the outset. But some physicists now suggest that perhaps the observed values were generated by some sort of complicated physical processes in the fiery turmoil of the very early universe. If this idea is generally correct, then it follows that the physical processes responsible could have generated different values from the ones we observe, and might indeed have generated different values in other regions of space, or in other universes. If we could magically journey from our cosmic region to another region a trillion light years beyond our horizon we might find that, say, the mass or charge of the electron was different. Only in those cosmic regions where the electron mass and charge have roughly the same values as they do in our region could observers emerge to discover a universe so propitiously fit for life. In this way, the intriguingly life-friendly fine tuning of the Standard Model parameters would be neatly explained as an observer selection effect.

According to the best attempts at unifying the fundamental forces of nature, such as string theory, the laws of physics as they manifest themselves in laboratory experiments are generally not the true, primary, underlying laws, but effective, or secondary laws valid at the relatively low energies and temperatures that characterize the present state of the universe compared to the ultra-hot conditions that accompanied the birth of the universe. But these same theories suggest (at least to some theorists) that there might be many different ways that the primary underlying laws might freeze into the effective low-energy laws, leading not merely to different relative strengths of the forces, but to different forces entirely — forces with completely different properties than those with which we are familiar. For example, there could be a strong nuclear force with twelve gluons instead of eight, there could be two flavours of electric charge and two distinct sorts of photon, there could be additional forces above and beyond the familiar four. So the possibility arises of a domain structure in which the low-energy physics in each domain would be spectacularly different, not just in the constants such as masses and force strengths, but in the very mathematical form of the laws themselves. The universe on a mega-scale would resemble a cosmic United States of America, with different shaped states separated by sharp boundaries. What we have hitherto taken to be universal laws of physics, such as the laws of electromagnetism, would be more akin to local by-laws, or state laws, rather than national or federal laws. And of this potpourri of cosmic regions, very few indeed would be suitable for life.

6. Many scientists hate the multiverse idea

In spite of its widespread appeal, and its apparently neat solution of the Goldilocks enigma, the multiverse has some outspoken critics from both inside and outside the scientific community. There are philosophers who think that multiverse proponents have succumbed to fallacious reasoning in their use of probability theory.[4] There are many scientists who dismiss

[4] An excellent in-depth discussion and critique of these issues can be found in [10].

the multiverse as a speculation too far. But the most vociferous critics come from the ranks of theorists working on the most fashionable attempt to universe physics, which is known as string theory or, in its generalized version, M theory. Many string/M theorists deny the existence of a set of vastly many different worlds. They expect that future developments will expose this mind-boggling diversity as a mirage, and that when physics is finalized it will yield a unique description — a single world, our world.

The argument used by anti-multiverse proponents is that the path to a theory of everything involves a progressive unification of physics, a process in which seemingly different and independent laws are found to be linked at deeper conceptual levels. As more of physics falls within the compass of unification, there are fewer free parameters to fix, and less arbitrariness in the form of the laws. It isnt hard to imagine the logical extreme of this process: all of physics amalgamated into one streamlined set of equations. Maybe if we had such a theory, we would find that there were no free parameters left at all: I shall call this the no free parameters theory. If that were the case, it would make no sense to consider a world in which, say, the strong force was stronger and the electron lighter, because the values of these quantities wouldnt be independently adjustable — they would be fixed by the theory. So far, however, there is little or no evidence to support that viewpoint; it remains an act of faithpromissory triumphalism.

7. Who designed the multiverse?

Just as one can mischievously ask who made God, or who designed the designer, so one can equally well ask why the multiverse exists and who or what designed it. Although a strong motivation for introducing the multiverse concept is to get rid of the need for design, this bid is only partially successful. Like the proverbial bump in the carpet, the popular multiverse models merely shift the problem elsewhere – up a level from universe to multiverse. To appreciate this, one only has to list the many assumptions that underpin the multiverse theory.

First, there has to be a universe-generating mechanism, such as eternal inflation. This mechanism is supposed to involve a natural, law-like process — in the case of eternal inflation, a quantum nucleation of pocket universes, to be precise. But that raises the obvious question of the source of the quantum laws (not to mention the laws of gravitation, including the causal structure of spacetime on which those laws depend) that permit inflation. In the standard multiverse theory, the universe-generating laws are just accepted as given: they dont come out of the multiverse theory. Second, one has to assume that although different pocket universes have different laws, perhaps distributed randomly, nevertheless laws of some sort exist in every universe. Moreover, these laws are very specific in form: they are described by mathematical equations (as opposed to, say, ethical or aesthetic principles). Indeed, the entire subject is based on the assumption that the multiverse can be captured by (a rather restricted subset of) mathematics.

Furthermore, if we accept that the multiverse is predicted by something like string/M theory, then that theory, with its specific mathematical form, also has to be accepted as given — as existing without need for explanation. One could imagine a different unified theory —N theory, say— also with a dense landscape of possibilities. There is no limit to the number of possible unified theories one could concoct: O theory, P theory, Q theory… Yet one of these is assumed to be the right one — without explanation. Now it may be argued that a decent theory of everything would spring from some deeper level of reasoning, containing natural and elegant mathematical objects which already commend themselves to pure mathematicians for their exquisite properties. It would —dare one say it?— display a sense of ingenious design (certainly the theoretical physicists who construct such theories consider their work to be designed with ingenuity). In the past, mathematical beauty and depth have been a reliable guide to truth. Physicists have been drawn to elegant mathematical relationships which bind the subject together with economy and style, melding disparate qualities in subtle and harmonious ways. But this is to import a new factor into the argumentquestions of aesthetics and taste. We are then on shaky ground indeed. It may be that M theory looks beautiful to its creators, but ugly to N theorists, who think that their theory is the most elegant. But then the O theorists disagree with both groups...

8. If there were a unique final theory, God would be redundant

Let me now turn to the main scientific alternative to the multiverse: the possible existence of a unique final theory of everything, a theory that permits only one universe.[5] Einstein once remarked that what interested him most was whether God had any choice in the creation of the world.” If some string theorists are right, the answer is no: the universe has to be as it is. There is only one mathematically self-consistent universe possible. And if there were no choice, then there need be no Chooser. God would have nothing to do because the universe would necessarily be as it is.

Intriguing though the idea of a no-free-parameters theory may seem, there is a snag. If it were correct it would leave the peculiar bio-friendliness of the universe hanging as a complete coincidence. Here is a hypothetical unique theory which just happens, obligingly, to permit life and mind. How very convenient! But there is another, more direct argument against the idea of a unique final theory. The job of the theoretical physicist is to construct possible mathematical models of the world. These are often what are playfully called toy models: clearly too far removed from reality to qualify as serious descriptions of nature. Physicists construct them sometimes as a thought experiment, to test the consistency of certain math-

[5]The unique, no-free-parameters theory is indifferent about whether there is only one representation of the universe or many. If there are many, they will be in identical quantum states. Because of the inherent uncertainty of quantum mechanics, this does not require the universes to be precise clones. So even the supposedly unique universe theory is consistent with a limited form of multiverse.

ematical techniques, but usually because the toy model accurately captures some limited aspect of the real world in spite of being hopelessly inadequate about the rest. The attraction is that such slimmed-down world models may be easy to explore mathematically, and the solutions can be a useful guide to the real world, even if the model is obviously unrealistic overall. Such toy models are a description, not of the real world but of impoverished alternatives. Nevertheless, they describe possible worlds. Anyone who wanted to argue that there can be only one truly self-consistent theory of the universe would have to give a reason why these countless mathematical models that populate the pages of theoretical physics and mathematics journals were somehow unacceptable descriptions of a logically possible world.[6]

Its not necessary to consider radically different universes to make the foregoing point. Lets start with the universe as we know it, and change something by fiat: for example, make the electron heavier and leave everything else alone. Would this arrangement not describe a possible universe, yet one that is different from our universe? "Hold on", cries the no-free-parameters proponent, "you cant just fix the constants of nature willy-nilly and declare that you have a theory of everything! There is much more to a theory than a dry list of numbers. There has to be a unifying mathematical framework from which these numbers emerge as only a small part of the story". That is true. But I can always fit a finite set of parameters to a limitless number of mathematical structures, by trial and error if necessary. Of course, these mathematical structures may well be ugly and complicated, but that is an aesthetic judgement, not a logical one. So there is clearly no unique theory of everything if one is prepared to entertain other possible universes and ugly mathematics.

So we are still be left with the puzzle of why a theory that permits a life-giving universe is the chosen one. Stephen Hawking has expressed this more eloquently [12]: What is it that breathes fire into the equations and makes a universe for them to describe?" Who, or what, does the choosing? Who, or what, promotes the merely possible to the actually existing? This question is the analogue of the problem of who made God or who designed the Designer. We still have to accept as given, without explanation, one particular theory, one specific mathematical description, drawn from a limitless number of possibilities. And the universes described by almost all the other theories would be barren.

Perhaps there is no reason at all why the chosen one is chosen. Perhaps it is arbitrary. If so, we are left still with the Goldilocks puzzle. What are the chances that a randomly chosen theory of everything would describe a life-permitting universe? Negligible. If any one of these infinitely many other possibilities had been the one to have fire breathed into it (by a Designer with poor taste perhaps?), we wouldnt know about it because it would have gone

[6]There is also a technical explanation, in terms of the foundations of mathematics and logic, of why a unique final theory is impossible. This has to do with what is known as Godels incompleteness theorem. For a recent discussion of this theorem, see for example [11]. It was partly in consideration of Godels theorem that Stephen Hawking, in a much publicized U-turn, recently repudiated the existence of a unique theory of everything.

unobserved and uncelebrated. So it remains a complete mystery as to why this universe, with life and mind, is the one.[7]

My conclusion is that both the multiverse theory and the putative no-free-parameters theory might go a long way to explaining the nature of the physical universe, but nevertheless they would not, and cannot, provide a complete and final explanation of why the universe is fit for life, or why it exists at all.

9. What exists and what doesnt: who or what gets to decide?

We have now reached the core of this entire discussion, the problem that has tantalized philosophers, theologians and scientists for millennia: what is it that determines what exists? The physical world contains certain objects – stars, planets, atoms, living organisms, for example. Why do those things exist rather than others? Why isnt the universe filled with, say, pulsating green jelly, or interwoven chains, or disembodied thoughts... The possibilities are limited only by our imagination. The same sort of conundrum arises when we contemplate the laws of physics. Why does gravity obey an inverse square law rather than, for example, an inverse cubed law? Why are there two varieties of electric charge (+ and) instead of four? And so on. Invoking a multiverse merely pushes the problem back to why that multiverse. Resorting to a no-free-parameters single universe described by a unified theory invites the retort why that theory?

There are only two of what one might term natural states of affairs, by which I mean states of affairs that require no additional justification, no Chooser and no Designer, and are not arbitrary and reasonless. The first is that nothing exists. This state of affairs is certainly simple, and I suppose it could be described as elegant in an austere sort of way, but it is clearly wrong. We can confidently rule it out by observation. The second natural state of affairs is that everything exists. By this I mean that everything that can exist does exist. Now that contention is much harder to knock down. We can not observe everything in the universe, and absence of evidence is not the same as evidence of absence. We cannot be sure that any particular thing we might care to imagine[8] does not exist somewhere, perhaps beyond the reach of our most powerful instruments, or in some parallel universe.

An enthusiastic proponent of this extravagant hypothesis is Max Tegmark.[9] He was contemplating the fire-breathing conundrum I discussed above (allegedly over a few beers in a pub). If the universe is inherently mathematical, then why was only one of the many mathemati-

[7]Leibniz, who was a theist, considered this problem, and famously concluded that ours is the best of all possible worlds (for why would an all-good, perfect God create something less than best?). Leibnizs definition of best refers not to maximum happiness for humans, but more abstractly to mathematical optimization: simplicity consistent with richness and diversity.

[8]Anything that is logically self-consistent, I mean. A round square, for example, could not exist anywhere.

[9]Tegmark was certainly not the first to suggest that all possible universes really exist. The idea was embraced, for example, by the Princeton philosopher David Lewis.

cal structures singled out to describe a universe?" he wondered. A fundamental asymmetry appears to be built into the heart of reality." To restore the symmetry completely, and eliminate the need for a Cosmic Selector, Tegmark proposed that every mathematical structure corresponds to a parallel universe." So this is a multiverse with a vengeance. On top of the standard multiverse I have already described, consisting of other bubbles in space with other laws of physics, there would be much more: The elements of this [extended] multiverse do not reside in the same space but exist outside of space and time. Most of them are probably devoid of observers" [13].

10. The origin of the rule that separates what exists from what doesnt

Few scientists are prepared to go as far as Tegmark. When it comes to the existence business, most people think that some things got left out. But what? And why those things? If one stops short of declaring that every universe that can exist does exist, we face a puzzle. If less than everything exists, there must be a prescription that specifies how to separate the actual from the possible-but-in-fact-non-existent. The inevitable questions then arise: what is the prescription that divides them? What, exactly, determines that-which-exists and separates it from that-which-might-have-existed-but-doesnt? From the bottomless pit of possible entities, something plucks out a subset and bestows upon its members the privilege of existing. Something breathes fire into the equations and makes a universe or a multiverse for them to describe. And the puzzle doesnt stop there. Not only do we need to identify a fire-breathing actualizer to promote the merely possible to the actually existing, we need to think about the origin of the rule itself — the rule that decides what gets fire breathed into it and what does not. Where did that rule come from? And why does that rule apply rather than some other rule? In short, how did the right stuff get selected? Are we not back with some version of a Designer/Creator/Selector entity, a necessary being who chooses the Prescription and breathes fire into it?

We here encounter an unavoidable problem that confronts all attempts to give a complete account of reality, and that is how to terminate the chain of explanation. In order to explain something, in the everyday sense, you have to start somewhere. To avoid an infinite regress — a bottomless tower of turtles according to the famous metaphor— you have at some point to accept something as given, something which other people can acknowledge as true without further justification. In proving a geometrical theorem, for example, one begins with the axioms of geometry,[10] which are accepted as self-evidently true and are then used to deduce the theorem in a step-by-step logical argument. Sticking to the herpetological metaphor, the axioms of geometry represent a levitating super-turtle, a turtle that holds itself up without the need for additional support. The same general argument applies to the search for an ultimate explanation of physical existence.

[10] For example, one axiom states that any two points in space can be connected by a straight line.

The trouble is, one mans super-turtle is another mans laughing stock. Scientists who crave a theory of everything with no free parameters are happy to accept the equations of that theory (e.g. M theory) as their levitating super-turtle. That is their starting point. The equations must be accepted as given, and used as the unexplained foundation upon which an account of all physical existence is erected. Multiverse devotees (apart perhaps from Tegmark) accept a package of marvels, including a universe-generating mechanism, quantum mechanics, relativity and a host of other technical prerequisites as their super-turtle. Monotheistic theologians cast a necessary God in the role of super-turtle. All three camps denounce the others super-turtles in equally derisory measure. But there can be no reasoned resolution of this debate, because at the end of the day one super-turtle or another has to be taken on faith (or at least provisionally accepted as a working hypothesis), and a decision about which one to pick will inevitably reflect the cultural prejudices of the devotee.[11] You cannot use science to disprove the existence of a supernatural God, and you cant use religion to disprove the existence of self-supporting physical laws.

The root of the turtle trouble can be traced to the orthodox nature of reasoned argument. The entire scientific enterprise is predicated on the assumption that there are reasons for why things are as they are. A scientific explanation of a phenomenon is a rational argument that links the phenomenon to something deeper and simpler. That in turn may be linked to something yet deeper, and so on. Following the chain of explanation back (or the turtles down), we may reach the putative final theorythe super-turtlewhat then? One can ask: Why that unified theory rather than some other? One answer you may be given is that there is no reason: the unified theory must simply be treated as the right one,[12] and its consistency with the existence of a moon, or of living observers, is dismissed as an inconsequential fluke. If that is so, then the unified theory —the very basis for all physical reality— itself exists for no reason at all. Anything which exists reasonlessly is by definition absurd. So we are asked to accept that the mighty edifice of scientific rationality —indeed, the very mathematical order of the universe— is ultimately rooted in absurdity! There is no reason at all for the scientific super-turtles amazing levitating power.

A different response to such questions comes from the multiverse theory. Its starting point is not a single, arbitrary set of monolithic laws, with fluky, unexplained bio-friendliness, but a vast array of laws, with the life factor accounted for by observer selection. But unless one opts for the Tegmark anything goes extreme, then there is still an unexplained super-turtle in the guise of a particular form of multiverse based on a particular universe-generating mechanism and all the other paraphernalia. So the multiverse likewise retains an element of arbitrariness and absurdity. Its super-turtle also levitates for no reason, so that theory too is ultimately absurd.

[11] This is perhaps a simplification. One may have evidential reasons for believing in a particular starting point. For example, support for a multiverse might come from evidence of variations of the constants of nature. Support for God might come from religious experience or moral arguments.

[12] Sometimes as the only one, but I have already pointed out the dubiousness of that claim.

Monotheistic theologians, for whom God plays the role of super-turtle, have had longer to think about this problem. They believe, or at least some do, that the threat of ultimate absurdity is countered by positing that God is a so-called necessary being. This is an attempt (and one that is not obviously successful) at describing a self-levitation mechanism —God explains Gods own existence— without which we would be right back to arbitrariness, reasonlessness and absurdity: if God exists reasonlessly, then the theistic explanation is also absurd.

My proposed solution to the tower of turtles problem is to seek a self-consistent explanation for physical existence, an explanation in which the presence of life and mind in the universe is linked to the very bio-friendly laws that give rise to life and mind by a subtle form of feedback loop. If this scheme can be made to work, it offers the chance to explain the origin of the laws of physics, together with their peculiar bio-friendliness, scientifically, from entirely within the universe. There is no need to appeal to anything outside the universe, anything transcendent. But to make this feedback loop work, one has to take life and mind seriously as fundamental, and not merely incidental, features of the physical universe.

11. Why mind matters

Let me first mention a philosophical argument for why I believe that mind does indeed occupy a deep and significant place in the universe. Later I shall give a scientific reason too. The philosophical argument concerns the fact that minds (human minds, at least) are much more than mere observers. We do more than just watch the show that nature stages. Human beings have come to understand the world, at least in part, through the processes of reasoning and science. In particular, we have developed mathematics, and by so doing have unravelled some —maybe soon, all— of the hidden cosmic code, the subtle tune to which nature dances. Nothing in the entire multiverse/anthropic argument (and certainly nothing in the unique, no-free-parameters theory) requires that level of involvement, that degree of connection. In order to explain a bio-friendly universe, the selection process that features in the weak anthropic principle merely requires observers to observe. It is not necessary for observers to understand. Yet humans do. Why?

I am convinced that human understanding of nature through science, rational reasoning and mathematics points to a much deeper connection between life, mind and cosmos than emerges from the crude lottery of multiverse cosmology. In some manner that I shall endeavour to explicate shortly, life, mind and physical law are part of a common scheme, mutually supporting. Somehow, the universe has engineered its own self-awareness. I shall argue that the bio-friendliness of the universe is an observer selection effect, but that it operates at a much deeper level than the passive winners in a random lottery explanation.

There is no possibility of placing life and mind at the centre of an explanation for the universe as long as the origin and evolution of the universe are already determined by the laws of physics as we at present conceive them (e.g. by string/M theory). But this seemingly unassailable conclusion conceals a weakness, albeit a subtle one. The objection that there is no room at the bottom for an additional principle rests on a specific assumption about the nature of physical laws: the assumption of Platonism. Most theoretical physicists are Platonists in the way they conceptualize the laws of physics, as precise mathematical relationships possessing a real, independent existence which nevertheless transcends the physical universe. For example, in simple, pre-multiverse cosmological models, where a single universe emerges from nothing, the laws of physics are envisaged as inhabiting the nothingness that preceded space and time. Heinz Pagels expressed this idea vividly: It would seem that even the void [the state of no space and no time before the big bang] is subject to law, a logic that exists prior to time and space" [3, 14]. Likewise, string/M theory is regarded as really existing, out there in some transcendent Platonic realm. The universe-generating mechanism of eternal inflation exists out there. Quantum mechanics exists out there. Platonists take such things to be independently real — independent of us, independent of the universe, independent of the multiverse. But what happens if we relinquish this idealized Platonic view of the laws of physics?

Many physicists who do not concern themselves with philosophical issues prefer to think of the laws of physics more pragmatically as regularities found in nature, and not as transcendent immutable truths with the power to dictate the flow of events. Perhaps the most committed anti-Platonist was Wheeler. Mutability was his byword. He liked to quip that: There is no law except the law that there is no law" [15]. Adopting the catchy aphorism Law without law to describe this contrarian position, Wheeler maintained that the laws of physics did not exist a priori, but emerged from the chaos of the quantum big bang —coming out of higgledy-piggledy was the way he quaintly expressed it— congealing along with the universe that they govern in the aftermath of its shadowy birth.[13] So far as we can see today", he maintained, the laws of physics cannot have existed from everlasting to everlasting. They must have come into being at the big bang" [16]. Crucially, Wheeler did not suppose that the laws just popped up, ready-made, in their final form, but emerged in approximate form and sharpened up over time: The laws must have come into being. Therefore they could not have been always a hundred percent accurate" [17].

The idea that the laws of physics are not infinitely precise mathematical relationships, but come with a sort of inbuilt looseness that reduces over time, was motivated by a belief that physical existence is what Wheeler called an information-theoretic entity. He pointed out that everything we discover about the world ultimately boils down to bits of information.[14] For him, the physical universe was fundamentally informational, and matter was a derived

[13]This is not just the emergence of low-energy effective laws via symmetry-breaking. Wheeler proposes that all laws emerge from chaos after the origin of the universe.

[14]This is a general statement, but in practice the bits are determined by quantum mechanics, in the form of discrete yes/no answers, such as whether an electrons spin is up or down.

phenomenon (the reverse of the orthodox arrangement), via a transformation he called it from bit, where the it is a physical object such as an electron, and the bit is a unit of information [18].[15]

Why should it from bit imply law without law? Rolf Landauer, a physicist at IBM who helped to lay the foundations for the modern theory of computation, was able to clarify the connection. Landauer also rejected Platonism as an unjustified idealization. What bothered him was that, in the real world, all computation is subject to physical limitations.[16] Bits of information dont float freely in the universe: they always attach to physical objects. For example, genetic information resides on the four nucleotide bases that make up your DNA. In a computer, bits of information are stored in a variety of ways, such as in magnetized domains. Clearly, one can not have software without hardware to support it. Landauer set out to investigate the ultimate limits to the performance of a computer, the hardware of which is subject to the laws of physics and the finite resources of the universe. He concluded that idealized, perfect mathematical laws are a complete fiction as far as the real world of computation goes.

The question Landauer asked is whether the mathematical idealizations embodied in Newtons laws and the other laws of physics should really be taken seriously. As long as the laws are confined to some abstract realm of ideal mathematical forms, there is no problem. But if the laws are considered to inhabit, not a transcendent Platonic realm but the real universe, then it is a very different story. The real universe will be subject to real restrictions. In particular, it may have finite resources: it may, for example, be able to hold only a finite number of bits at one time. If so, there will be a natural cosmic limit to the computational prowess of the universe, even in principle. Landauers point of view was that there is no justification for invoking mathematical operations to describe physical laws if those operations cannot actually be carried out, even in principle, in the real universe, subject as it is to various physical limitations. In other words, laws of physics that appeal to physically impossible operations must be rejected as inapplicable. Platonic laws can perhaps be treated as useful approximations, but they are not reality. Their infinite precision is an idealization that is normally harmless enough, but not always. Sometimes it will lead us astray, and never more so than in discussion of the very early universe.

12. The universe as a finite computer exposes the fiction of idealized laws

To see where the problem lies, let us estimate how the real universe, with its finite resources and processing power, measures up to the Platonic ideal. The observable universe is finite

[15] An attempt to build all of physics out of information has been made by Frieden in [19]. For up-to-date comment on it from bit, see also [20], part IV. See also [16].

[16] Two relevant papers by Rolf Landauer are Refs. [21, 22]

because the finite speed of light implies the existence of a horizon in space. Because no physical object or influence can go faster than light, objects separated by more than the distance to the horizon cannot communicate with each other. So Landauers criterion says that the great cosmic computer we call the observable universe must be limited to objects encompassed by a volume of space that is less than the distance to the horizonthe region I have been calling the observable universe. At the present epoch, the volume of space within the horizon contains about 10^{80} atoms, and about 10^{90} neutrinos and photons. Each particle can carry a few bits of information only. Additional information can be encoded in gravitons, which cosmologists believe permeate the universe, although nobody seriously expects to detect any in the foreseeable future. A careful calculation has been carried out by Seth Lloyd, a theoretical physicist at the Massachusetts Institute of Technology, and he comes up with a figure of about 10^{120} bits in total.[17] The actual number is less important than the fact that the total amount of information contained in the universe, though admittedly huge, is nevertheless finite.

According to Landauers philosophy, it is pointless applying any law of physics at a level of detail which requires the processing of more bits of information than the cosmic upper limit of 10^{120}, because there is an intrinsic inaccuracy (or higgledy-piggledy in Wheelerspeak) which is quantified by this huge number. To take a specific example, the law of conservation of electric charge states that the charge on an electron should be exactly constant with time. According to Landauers view, this statement is meaningless because it implies infinite precision. Instead, one should imagine that the law applies only with a finite accuracy of one part in about 10^{120}. Since we can currently measure the electrons charge to an accuracy of only about one part in 10^{12}, this is hardly a serious restriction. For almost all day-to-day purposes it doesnt matter whether the universe is considered to be a finite computer with limited accuracy, or a system conforming to infinitely precise mathematical laws.[18]

Although the sloppiness of the laws of physics implied by the cosmic upper limit derived by Lloyd is largely unimportant today, it may have been very important in the past. That is because the radius of the horizon is not fixed, but increases with time at the speed of light. The number of particles contained within a volume of space bounded by the horizon is therefore going up year by year as the horizon expands to encompass more and more matter so in the past, this number was smaller. At one second after the big bang, for instance, the horizon encompassed only about 10^{86} particles still too large for the implied inaccuracy to make much difference. At the time of inflation, however, the horizon was a mere trillion-trillionth of a centimetre in radius, and the total information content of a horizon volume was then only about a billion bits. Such a small number of bits represents a very large degree of looseness, or ambiguity, in the operation of any physical laws, including the laws that govern the inflationary process. I mentioned Wheelers suggestion that the laws of physics

[17] Seth Lloyds calculation is described in his paper [23]. See also his book [24].
[18] There may, however, be situations involving complex systems in which the limit of 10^{120} does matter [25].

emerged from higgledy-piggledy at the big bang in a less than precise form, and gradually congealed over time. In this section I have shown how, by accepting that the universe is a finite computational resource, and making use of the work by Landauer and Lloyd, Wheelers suggestion can be made explicit.

The main argument against the existence of any sort of universal principle favouring the emergence of life and mind is that the basic laws of physics plus initial conditions already fix what physical systems do, and there is simply no more room in which an additional teleological law can operate. But if the basic laws of physics are not in fact rigid in the Platonic sense, if there is a looseness or inherent limitation on the accuracy of those laws —especially in the early moments of the universe, when its bio-friendly nature was being laid down— then a loophole exists for a lawlike trend towards life and mind to peacefully coexist alongside the traditional laws of physics. There would no longer be any conflict.

Permitting a trend towards life is one thing; realizing it is another. Teleology has been out of favour not only because of its perceived conflict with the laws of physics. It also suffers from a seemingly insurmountable problem to do with cause and effect. Teleology is by definition a means to anticipate some future state (in this case life) and bring that state about in the fullness of time. This blatant element of predestination is in sharp contrast with the normal concept of causation in science, in which present events can influence the future but not the past. Teleology turns that around, and lets future states influence the present. How can that be? How could the very early universe —the epoch when the laws of physics were still in the melting pot— possibly know about life and mind emerging billions of years later?

13. Quantum mechanics could permit the feedback loop between mind and the laws of physics

Crazy though the idea may seem at first, there is in fact no fundamental impediment to a mechanism that allows later events to influence earlier events. In fact, there are some famous theories of physics that explicitly involve backward causation — future events having causative power over past events. Wheeler proposed one such theory with his then student Richard Feynman in the mid-1940s.[19] In the WheelerFeynman theory of electrodynamics, electromagnetic interactions can travel both forwards and backwards in time. There is no experimental evidence in favour of the theory, I hasten to add. Something similar was proposed for gravitation by Hoyle and Narlikar [27], and for quantum cosmology by Gell-Mann and Hartle [28], and by Hawking [29].[20] Again, observation and experiment are silent on these ideas, but the theories are certainly not anti-scientific, and variants of them are still being investigated today. It is only when the end states involve life and mind that most scientists take fright and bale out. That is because life and mind are not normally regarded

[19] I have given a popular account in my book [26].
[20] Hawking susequently retracted the idea.

by physicists as fundamental. Furthermore, they are tainted with mystical associations from a bygone era of vital forces. But I am endeavouring to make a case that life and mind are fundamental physical phenomena, and so must be incorporated into the overall cosmic scheme.

I already mentioned a philosophical argument in favour of taking mind seriously as a fundamental and deeply significant feature of the physical universe. Now let me turn to a scientific argument. One much discussed line of evidence comes from the way in which the act of observation enters into quantum mechanics. The world described by quantum mechanics does not contain a single reality, but an amalgam, or superposition, of contending realities. When an observation is made, however, a single world is discerned. There is no agreement among physicists on the mechanism that effects the transition from a superposition of ghostly alternative worlds to a concrete reality, but for my purposes it doesnt matter. Suffice it to say that the act of observation plays a fundamental role in the operation of the quantum realm. The key point I want to stress is that, when an observation is performed —such as a measurement of where an atom is located— and a definite result obtained, the entire system, in principle the entire universe, is affected. Einstein referred to this nonlocality as ghostly action-at-a-distance. It means, in effect, that an observation, or measurement, of a quantum system performed at a certain location in space, instantly affects the quantum situation at distant places. Einstein didnt like this. However, it is important to stress that quantum nonlocality cannot be used to send information instantaneously between widely-separated points, nor can an observation at one place be used to manipulate a distant part of the quantum system in a preconceived manner. So separate parts of a quantum system are linked, but in a subtle manner that does not permit a causal link.

Quantum nonlocality, or ghostly action-at-a-distance, is a real feature of quantum mechanics, Einsteins reservations notwithstanding, and has been tested experimentally many times. A simple change of reference frame transforms ghostly action-at-a-distance into ghostly action-back-in-time. What I mean by this is that an observation or measurement of a quantum system made at one moment has implications for the quantum system at earlier moments. Again, there is no question of something done now being able to send information to the past, or to change the past, but it can affect the past, in the following subtle manner. As I have explained, quantum mechanics describes not a single concrete reality, but a superposition, or amalgam, of contending worlds, or realities. This fuzziness in the nature of reality is often expressed using Heisenbergs uncertainty principle, which says that when an observation of a quantum system, e.g. an atoms position or energy or motion, is made at one moment, then the future behaviour of that system is inherently uncertain to within certain well-prescribed limits. But quantum uncertainty is time symmetric; it stretches back into the past as well as the future. There is not a single past history leading up to the moment of observation, just as there is not a single future determined by that observation. Rather, there is a fuzzy amalgam of many pasts and futures. Thus, when a quantum measurement is made at one moment, it affects what we can say about both the future and the past. For example, certain aspects of reality about the past might be eliminated by the observation.

A specific example of this was given by John Wheeler in his so-called delayed choice experiment. In this experiment, a decision is made at the last minute, immediately prior to an observation of a photon, whether the particle-like or wave-like aspect of that photon shall be observed. The experimenter has the choice, by simply determining which of two complementary experiments shall be done, one that reveals the photon as a particle, the other as a wave (this so-called wave-particle duality is a fundamental feature of quantum mechanics, related to Heisenbergs uncertainty principle). But the manner in which Wheelers experiment is constructed implies that, when the observation is performed, the wave or particle nature of the photons, whichever it is, applies to the past history of the photons as well as to the present. In other words, by deciding particle at some instant of time, the experimenter (or some computer-controlled surrogate) determines that the photon was a particle even before the decision was made. In principle, this entanglement between present and past can stretch right back to the origin of the universe. The best way of understanding this phenomenon is by remembering that there is not a unique past; the past history of a quantum system is inherently ambiguous, so that when an observation is made, some of the ambiguity about the past is resolved. In the case cited, the ambiguity represented by wave-particle is resolved in favour of particle.

Applied to an individual photon, this subtle linkage of future and past is a trifle underwhelming, but if the entire universe is described by quantum mechanics, as is usually supposed, then it takes on literally cosmic significance. Stephen Hawking and Thomas Hertog have expressed it as follows [30]:

> *The [. . .] approach we have described leads to a profoundly different view of cosmology, and the relation between cause and effect. [It] is a framework in which one essentially traces the histories backwards, from a space-like surface at the present time. The histories of the universe thus depend on what is being observed, contrary to the usual idea that the universe has a unique, observer independent history.*

They also consider, in the context of quantum cosmology, the backwards-in-time aspect of quantum observations: that what we choose to observe today helps to shape the nature of the universe in the remote past. Hawking and Hertog point out that, naturally, observations will select only histories consistent with life and observers, even if such histories are rare among the set of all possibilities.

Discussions about the backward reach of quantum observations are normally restricted to states of the universe, and not applied to the underlying laws of physics. However, as I have explained, the distinction between states and laws is becoming increasingly blurred. It may be that certain pervasive laws of physics are really frozen accidents — consequences of certain quantum states being selected just after the big bang, when the universe cooled from its ultra-hot state, and certain symmetries were broken, the outcomes of which lay at the mercy of quantum fluctuations. Furthermore, if I am right about the inherent fuzziness not just of states of matter, but laws too (on account of the finite information of the universe), then quantum observations now and in the future gain even more purchase on the way the laws were laid down in the past. This opens the way to a self-consistent explanatory loop in which the universe engineers its own awareness through life and mind, and mind in turn engineers (via the culling of quantum histories) the very laws and states that permit the emergence of life and mind. And all this without the need for an externally imposed preordained set of bio-friendly laws.

So, how come existence? At the end of the day, all the approaches I have discussed are likely to prove unsatisfactory. In fact, in reviewing them they all seem to me to be either ridiculous or hopelessly inadequate: a unique universe which just happens to permit life by a fluke; a stupendous number of alternative parallel universes which exist for no reason; a pre-existing God who is somehow self-explanatory; or a self-creating, self-explaining, self-understanding universe-with-observers, entailing backward causation and teleology. Perhaps we have reached a fundamental impasse dictated by the limitations of the human intellect. Both religion and science draw their methodology from ancient modes of thought honed by many millennia of evolutionary and cultural pressures. Our minds are the products of genes and memes.[21] Now we are free of Darwinian evolution and able to create our own real and virtual worlds, and our information processing technology can take us to intellectual arenas that no human mind has ever before visited, those age-old questions of existence may evaporate away, exposed as nothing more than the befuddled musings of biological beings trapped in a mental straightjacket inherited from evolutionary happenstance. The whole paraphernalia of gods and laws, of space, time and matter, of purpose and design, rationality and absurdity, meaning and mystery, may yet be swept away and replaced by revelations as yet undreamt of.

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