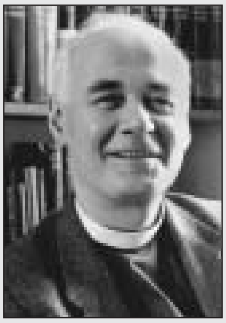
The Anthropic Principle and the Science and Religion Debate

John Polkinghorne

Summary

Carbon-based life could only develop in a universe that was remarkably specific in its given laws of nature. Possible explanations of this fine-tuning appeal either to the conjecture of a multiverse or to the concept of creation. This paper weighs up these competing explanations.



About the Author

The Revd Dr John Polkinghorne KBE FRS worked in theoretical elementary particle physics for 25 years and was previously Professor of Mathematical Physics at Cambridge University and then President of Queens' College, Cambridge. Dr Polkinghorne was the Founding President of the International Society for Science and Religion (2002-2004) and is the author of numerous books on science and religion, including *Science and Theology* (London: SPCK, 1998).

The universe we observe today originated, some 13.7 billion years ago, in the singular state of extreme density and temperature that colloquially we call the 'big bang'. The very early universe was structurally very simple, being an almost uniform expanding ball of matter/energy. One of the reasons why cosmologists can talk with a fair degree of confidence about that early epoch is that things then were uncomplicated and they are therefore easy to model. After almost fourteen billion years of evolving process, the universe has become very complex, with the human brain (with its 10^{11} neurons and their more than 10^{14} connections) the most complicated system that science has encountered in its exploration of the world.

Evolutionary processes involve an interplay between two aspects of the natural world that, in a slogan way, can be labelled as 'chance and necessity'. Only a very small proportion of what is theoretically possible has actually happened and 'chance' stands for the contingent detail of actual events. For example, in the very early universe there were slight fluctuations in the distribution of matter. These inhomogenities provided the random seeds from which the grainy structure of galaxies and stars would eventually grow. The actual details of this cosmic structure were matters of chance, but the process also involved lawful 'necessity' in the form of the action of gravity. Slightly more matter 'here' implied slightly stronger gravitational attraction towards 'here', initiating a snowballing process by which the galaxies condensed.

The central insight of the Anthropic Principle (AP) is that the specific character of lawful necessity had to have a very particular form – often expressed in the metaphor of a 'fine-tuning' of the laws of nature – if the coming-to-be of *anthropoi*[1] were to be possible at all within the span of cosmic history. In other words, simple evolutionary exploration of what might happen (chance) would not have been sufficient if the lawful regularity of the universe (necessity) had not taken the very specific form required for biological potentiality. The universe was billions of years old before life appeared in it, but it was pregnant with that possibility from the beginning.

Many scientific insights combine to lead to this unexpected conclusion. They relate to processes taking place at various stages of cosmic history, from times within a minute fraction of a second after the big bang, through the first generation of stars and galaxies, to processes at work in the cosmos today. It will be sufficient to indicate some examples that illustrate the kind of considerations involved. For more comprehensive and detailed treatments, reference can be made to a number of detailed studies[2].

Anthropic Specificity

If carbon-based life is to be a possibility, the laws operating in the universe are subject to a number of constraints.

1. Open Character

Science has increasingly come to recognise that the emergence of true novelty depends upon the existence of regimes that can be said to be 'at the edge of chaos'. By this is meant that in them regularity and openness, order and disorder, interlace in a subtle way. Regimes in which a rigid order dominates are too inflexible to allow for the appearance of the really new. Rearrangements of existing elements are possible, but there can be no true novelty. Yet, regimes that are too haphazard in character exhibit an instability that means that nothing new can ever persist. The familiar story of biological evolution illustrates the point being made. If there were no genetic mutations, life would never develop new forms; if there was too much genetic mutation, species would

1 Greek for human beings - here not necessarily literally meaning humanity in its five-fingered particularity, but in the general sense of the complexity of carbon-based life.

2 Barrow, J.D. and Tipler, F.J. *The Anthropic Cosmological Principle*, Oxford University Press (1986); Leslie, J. *Universes*, London: Routledge (1989); Holder, R.D. *God, the Multiverse, and Everything*, Aldershot: Ashgate (2004).

never become established on which natural selection could act.

The basic character of physical law is quantum mechanical, with consequences that include both reliability (e.g. the stability of atoms) and openness (the unpredictability of many outcomes). It is plausible that these features have been necessary for the emergence of life, which would have been impossible in a universe governed by Newtonian determinism.

2. Overall Setting

The stability of planetary orbits, an obvious necessity for the development of life on one of them, derives from the fact that gravity obeys an inverse square law. An inverse cube law, for instance, would have made the solar system incapable of holding together for any appreciable time. The inverse square character of gravity is linked to the dimensions of space. If space had been four-dimensional, rather than three, gravity would indeed have been an inverse cube.

3. Quantitative Specificity

Four fundamental forces of nature operate in our universe. Their intrinsic strengths are determined by the values of four corresponding constants of nature. The fine structure constant (α) specifies the strength of electromagnetism; Newton's gravitational constant (G) specifies the strength of gravity; and two constants specify the strengths of the nuclear forces, g_s for the strong forces that hold nuclei together, and g_w for the weak forces that cause some nuclear decays and also control the interactions of neutrinos. The magnitudes of all these constants are tightly constrained if the universe is to be capable of producing life.

If g_w were a little smaller, the early universe would have converted all its hydrogen into helium before it had cooled below the temperature at which cosmic nuclear processes ceased. Not only would this have meant no water, so essential to life, but there would also only have been helium-burning stars, which would not have lived long enough to support the development of life on one of their planets. If g_w had been somewhat bigger, supernova explosions would have been inhibited.

The latter fact would have had serious consequences for the elaborate and delicately balanced processes by which the chemical raw material of life are made. Because the very early universe is simple, it only produces the two simplest elements, hydrogen and helium. They have too boring a chemistry to provide the basis for anything as interesting as life. That requires more than twenty further elements, above all carbon, whose chemical properties enable the formation of the long chain molecules that afford the biochemical basis of life. The only place in the universe where carbon is made is in the interior nuclear furnaces of the stars. All living beings are made of stardust. Untangling the chain of nuclear interactions by which carbon and the heavier elements were made was one of the triumphs of twentieth-century astrophysics. Fred Hoyle, who was a pioneer in this work, saw that stellar carbon production was only possible because there was a resonance (a large enhancement effect) occurring at a particular energy in carbon, and also there was the absence of a similar resonance in oxygen, which prevented the carbon's being lost because it had all got turned into oxygen. These detailed nuclear properties depend upon the value of g_s, and if that value had been somewhat different, there could have been no carbon, and thus no carbon-based life. When he realised this, Hoyle, atheist though he was, is reported to have said that the universe was a 'put-up job'. He could not suppose that such significant fine-tuning was merely a happy accident.

Inside a star it is not possible to produce elements beyond iron, the most stable of the nuclear species. Two problems therefore remain: how to make the heavier elements, some of which are also necessary for life, and how to get the lighter elements out of the star that has made them. A supernova explosion solves both problems since the neutrino interactions that accompany it also make elements heavier than iron, provided that g_w takes an appropriate value.

Stars have a second role to play in enabling life, simply by providing long-term (billions of years) and relatively stable sources of energy to fuel the process. This requires the ratio of electromagnetism to gravity (α to G) to lie within close limits – otherwise stars would either burn so furiously that they could only live for a few million years, or so feebly that they were not much use anyway.

Many other anthropic constraints could be mentioned. One of the most precise relates to the cosmological constant (λ), a parameter associated with a kind of antigravity, driving matter apart. The possibility of a non-zero λ was recognised by Einstein, but people soon saw that if it exists at all it must be very tiny, since otherwise the universe would very quickly have been blown apart. We now know that λ's value must be no more than 10^{-120} of what would be its naturally expected strength. This represents a quite extraordinary degree of necessary fine-tuning.

4. Initial and Other Conditions

Cosmic history is a tug-of-war between the opposing tendencies of the contractive pull of gravity (drawing matter together) and the sum of expansive effects (such as the initial velocities after the big bang, together with other effects, such as that due to a non-zero λ). These two tendencies must be closely balanced if the universe is not to collapse quickly into a 'big crunch', or rapidly become so dilute that fruitful process is an impossibility. In fact, if cosmologists extrapolate back to the Planck era, when the cosmos was 10^{-43} seconds old, they conclude that the difference then could only have been one part in 10^{60}. We shall return to this particular point again later.

Roger Penrose has emphasised the fact that the universe appears to have started in a state of extremely high order (or low entropy). This is thought to be intimately related to the universe's thermodynamic properties, and even possibly to the nature of time. Penrose[3] estimates the odds of this happening by chance at one in ten raised to the power 10^{123}.

Another anthropic necessity is the size of the observable universe, with its 10^{11} galaxies, each with an average of 10^{11} stars. While such immensity can sometimes seem daunting to the inhabitants of what is effectively a speck of cosmic dust, we should not be upset, because only a universe at least as big as ours could have lasted the fourteen billion years required to enable human beings to appear on its scene. Anything significantly smaller would have had too brief a history.

5. Biological Considerations

The complexity of biology compared to physics makes it much more difficult to derive anthropic constraints directly from the details of biological processes. It is clear, however, that life depends in many ways on the details of the properties of matter in our world[4]. A simple example is the anomalous property of water that it expands on freezing, thereby preventing lakes from becoming solid

3 Penrose, R. *The Emperor's New Mind*, Oxford University Press (1989), pp.339-345.
4 See Denton, M.J. *Nature's Destiny*, New York: The Free Press (1998).

ice from the bottom up and thus killing any life that might be in them. Changes in the value of α would alter these properties.

This section has sketched some of the considerations that make it clear that an anthropic universe is a very particular universe indeed. It is also worthy of note that, while multiple conditions constrain the constants of nature, yet there is a set of values consistently satisfying them all, a remarkable fact in itself about the constitution of the world.

Interpretation.

All scientists agree that the physical fabric of the universe had to take a very particular form if carbon-based life were to be able to evolve within its history. Where disagreements begin is in discussing what might be the significance of this remarkable fact.

For many scientists, cosmic fine-tuning came as an unwelcome shock. Professionally, scientists aspire to generality, and this makes many of them unduly wary of the particular. Their natural inclination is to believe that our universe is just a fairly typical specimen of what a cosmos might be like. The Anthropic Principle showed that this is not so, but rather that our universe is special, one in a trillion, so to speak. Recognising this seemed like an anti-Copernican revolution. Of course, human beings do not live at the centre of the cosmos, but the intrinsic physical structure of that world has to be constrained within narrow limits if the evolution of carbon-based life is to be feasible. Some also feared that they detected here an unwelcome threat of theism. If the universe is endowed with fine-tuned potentiality, this might indicate that there is a divine Fine-Tuner.

Hume had urged acceptance of the properties of matter as a brute fact, but nature's fine-tuned character makes it intellectually unsatisfying to stop the quest for understanding at this point.

A quite new form of the argument from design had been brought onto the agenda. Darwinian insight had taken away the force of the old style design argument for the existence of God, pursued in the past by people such as John Ray and William Paley. They had appealed to the functional aptness of living beings, but evolutionary thinking had shown how the patient accumulation and sifting of small differences could give rise to the appearance of design without calling for the direct intervention of a divine Designer. Theologians came to recognise that the former kind of natural theology had made the mistake of setting itself up as a rival to science in the latter's legitimate domain, seeking to deal with questions such as the origin of the optical system of the mammalian eye, whose answering properly lay within biological competence. This criticism could not be made about the new argument, appealing to anthropic potentiality. The new natural theology sought to be complementary to science, rather than in competition with it. Its concern was the laws of nature themselves, something that an honest science cannot explain since it has to assume them as the unexplained basis of its detailed account of occurrences. David Hume had urged acceptance of the properties of matter as a brute fact, but nature's fine-tuned character makes it intellectually unsatisfying to stop the quest for understanding at this point. Hume had criticised the old-style argument from design as being too anthropomorphic, as if the work of the Creator could fittingly be compared to that of carpenters building a ship. This criticism does not apply to anthropic arguments, since endowing matter with intrinsic potentialities has no human analogue. In terms of Hebrew words used in the Old Testament, fine-tuning corresponds to *bara* (a word reserved for divine activity), rather than *'asah* ('making', used of God and humans alike).

The first step in argument about interpretation was to distinguish between various formulations of the Anthropic Principle. The most modest was the Weak Anthropic Principle (WAP), simply stating the tautologous insight that the character of the universe that we observe must be consistent with our presence as observers within it. At first sight, that might not seem a very exciting point to make. It is clear, for example, that it is no surprise that we see a universe about fourteen billions years old, since beings of our complexity could not have emerged on its scene at an earlier epoch. However, we saw in the previous section that scientific investigations have shown that full anthropic conditions are far from trivial, for they include such constraints as setting narrow limits on the values of the constants of nature that define the physical fabric of the world.

Some people were then led to define a Strong Anthropic Principle (SAP), alleging that the universe necessarily *had* to have such properties as would allow life at some time to develop within it. The problem with that is to see what could be the source of the asserted necessity. SAP is a strongly teleological statement. The religious believer will be happy to ground necessity in the will of the Creator, but the status of SAP as a purely secular claim is mysterious. It certainly does not seem to be grounded in science itself.

Two other forms of Anthropic Principle are sometimes discussed. The Participatory Anthropic Principle (PAP) asserts that observers are necessary to bring the universe into being. Some sort of appeal is being made here to a contentious interpretation of quantum theory which speaks in terms of 'an observer-created reality'[5], but it is difficult to believe that the universe did not 'exist' until observers appeared. There is also the Final Anthropic Principle (FAP), claiming that once intelligent information-processing has started in the universe, it must continue for ever. Once again, a secular source of the alleged necessity is hard to find. PAP and FAP seem even less satisfactory than SAP.

Another line of attack on anthropic reasoning attempted to defuse the claim of cosmic particularity by pointing out that actually we only have one universe to study, and how could one conclude much from a sample of one? Yet, with our scientific imaginations we can visit other possible universes that are reasonably similar to ours. The consideration in the previous section of worlds whose constants of nature take different values from those in this universe, would be an example. In this notional collection of neighbourly worlds, we found that only a very narrow set could share anthropic potentiality with our actual world. Surely that is enough to establish a degree of specificity that calls for some sort of metascientific understanding of anthropic particularity.

Another approach suggested that in fact there might only be one possible world, a universe in which, of necessity, the force strengths took the values that we actually observe. Proponents of this view appealed to the difficulty found by physicists in successfully combining general relativity and quantum theory, and they suggested that maybe there was a unique Grand Unified Theory (GUT) that achieved this and which determined the values of all the constants of nature. Even if this were so – and it seems to many that it would be unlikely that a GUT would be wholly free from scale parameters – one would still have to explain why relativity and quantum theory are to be treated as givens. They certainly seem to

5 For a critique, see Polkinghorne, J.C. *Quantum Theory: A very short introduction*, Oxford University Press (2002), pp. 90-92.

be anthropic necessities, but they are by no means logically inevitable. Moreover, if there really were a unique GUT, the greatest anthropic coincidence of all would surely be that this theory, determined on grounds of logical consistency, also proved to be the basis for a world capable of evolving beings able to comprehend that consistency.

A more modest and realistic proposal suggests that some anthropic coincidences may be consequences of a deeper theory, so that they do not require fine-tuning. An actual example of this happening is probably provided in the case of the delicate balance between expansive and contractive effects in the very early universe that we discussed earlier. It is now believed that when the universe was about 10^{-35} seconds old, a cosmic phase transition took place (a kind of boiling of space), which for a short while blew up the cosmos with astounding rapidity. This process, called inflation, would have smoothed out the universe and created the close balance between expansive and contractive tendencies that we now observe. Yet, inflation itself, if it is to act satisfactorily, requires that the GUT operating in the universe is restricted in form, so that anthropic particularity has not been lost, but pushed deeper into the fabric of the world.

You are about to be executed and the rifles of expert marksmen are levelled at your chest. An officer gives the order to fire ...

One might look instead at a kind of Moderate Anthropic Principle[6], which notes the special character of the universe and acknowledges that this should not be treated as a happy accident, for it calls for some explanation.

Two contrasting metascientific approaches have been pursued. John Leslie, who likes to do philosophy in a parabolic fashion, told a story that graphically illustrates the issues[7]. You are about to be executed and the rifles of expert marksmen are levelled at your chest. An officer gives the order to fire ... and you find you have survived! Do you just walk away, saying, ‘That was a close one!’? Certainly not, for so remarkable an event surely calls for an explanation. Leslie suggests that this must take one of two forms. Either, a vast number of executions are taking place today and, since marksmen occasionally miss, you by chance have been lucky enough to be in the execution where they all miss. Or, more was going on in the single event of your execution than you had been aware of – the marksmen were on your side and they missed by design. This charming tale translates into the following two approaches to taking anthropic issues with appropriate seriousness.

6 Polkinghorne, J.C. *Reason and Reality*, SPCK (1991), pp.77-80.
7 Leslie, J. *op. cit.*[2], pp. 13-14.

1. Multiverse

It is suggested that maybe there are very many different universes, each with very different kinds of laws of nature. In this vast portfolio of worlds, just by chance there is one capable of developing carbon-based life and that, of course, is our universe, since we are carbon-based life. An anthropic cosmos is simply a rare winning ticket in a multiversal lottery.

The most economical version of this idea supposes that these different worlds are actually large domains within a single physical universe. The way in which the symmetry of the primordial GUT was broken as expansion cooled the universe, thereby producing the forces that actually operate today, need not have been literally universal. Instead the cosmos could be a mosaic of different domains, in each of which symmetry-breaking took different detailed forms. We are unaware of this, because inflation has driven all the other domains out of our sight and, of course, our domain must be the one in which the results of symmetry-breaking fitted in with anthropic necessity. The idea is plausible, but it only modifies to some degree the requirement of specificity, since it is still necessary that the aboriginal GUT took a form that, when its symmetry was broken, could yield appropriate force strengths.

Any suggestion more radical than this, takes one into a realm of speculation beyond the scope of sober physical thinking. Shaky appeals need to be made to currently ill-defined notions of quantum cosmology, together with resort to ad hoc assumptions of radical differences between the lawful characters of the worlds supposed to have been generated in this way. The multiverse in this form is no more than a metaphysical guess of excessive ontological prodigality – appealed to, it might seem, partly in order to avoid the theism associated with the second approach.

2. Creation

The theist can believe that there is only one universe, whose anthropic character simply reflects the endowment of potentiality given it by its Creator in order that it should have a fruitful history. This too is a metaphysical guess but, in contrast to the multiverse, it is one that does a number of other explanatory pieces of work in addition to addressing anthropic issues. For example, the intelligible and wonderful order of the world, so striking to the scientist, can be understood as being a reflection of the mind of its Creator. Widespread human testimony to experience of encounter with the reality of the sacred, can be understood as arising from actual perception of the veiled presence of God. Understood in this way, the anthropic specificity of our world is not claimed to provide a logically coercive argument for belief in God that no one but a fool could deny, but it makes an insightful contribution to a cumulative case for theism, regarded as the best explanation of the nature of the world that we inhabit.

The Faraday Papers

The Faraday Papers are published by the Faraday Institute for Science and Religion, St Edmund’s College, Cambridge, CB3 0BN, UK, a charitable organisation for education and research (www.faraday-institute.org). The opinions expressed are those of authors and do not necessarily represent the views of the Institute. The Faraday Papers address a broad range of topics related to the interactions between science and religion. A full list of current Faraday Papers can be viewed at www.faraday-institute.org from where free copies can be down-loaded in pdf format. Print copies like this one can also be obtained in bulk quantities of ten or more at £1.50 per 10 copies + postage. Secure on-line ordering details are at www.faraday-institute.org.