Chapter 1
Introduction To The Cosmic Coincidences

§1.1 Introduction to Our Complex Universe

Almost everything in the physical universe we know is a result of the following ten numbers,

5.906 x 10^{-39}; 1.02682 x 10^{-5}; 0.00729735257; 14.4;

0.001378; 1836.15

1.9 x 10^{9}; 0.20; 0.76; 2 x 10^{-5}

What are these numbers? In what way does the universe depend upon them? How would the universe change if they were different? These are the questions which this exposition addresses. It has been claimed that relatively small changes in these numbers would give rise to a sterile universe, unfit for life (References). That these numbers happen to take just the right values to permit the emergence of a complex universe fit for life has been called a cosmic coincidence (References). The purpose of this initial chapter is to explain what we mean by the ‘cosmic coincidences’.

This exposition is primarily about how the stuff of the universe came to be arranged the way it is. More specifically, we wish to know how the universe came to be *interesting*. It could so easily have been a featureless cloud of gas, a cosmic desert. The most interesting thing about it is the emergence of life, and especially intelligent life. Unfortunately, the emergence of life is a problematical criterion to use to define *interesting*. The reason is that the conditions *sufficient* for the emergence of life are unknown. Nor is a great deal known about what conditions might be *necessary* for the emergence of life. However, there are some elementary conditions the necessity of which is likely to be uncontroversial.

These are firstly that the universe must depart from homogeneity. Otherwise how could life be distinguished from its environment? Secondly, there must be sufficient chemical diversity. Nothing much could be made of just hydrogen and helium. Which chemical elements are essential for life? Again the answer is unknown. At the risk of being parochial, a working assumption is that hydrogen, carbon, oxygen, nitrogen and phosphorus, and perhaps a few other elements, are essential. Of course, life forms as they have evolved on earth also require many other elements, but that is not the point. The question is, what is the minimum set of elements for which any form of life might emerge? No one knows. But a certain minimum of chemical complexity must be required. The suggested list of hydrogen, carbon, oxygen, nitrogen and phosphorus is a signature of potential complexity.

Life will also require a source of energy. This energy source must persist for long enough for life to evolve. So a universe has the potential to be *interesting* (and potentially life supporting or *biophilic*) if it has density contrasts, long lived energy sources and contains hydrogen, carbon, oxygen, nitrogen and phosphorus.

Probably a great many other things are necessary for the emergence of life. More controversially, it may be necessary that rigid (solid) matter exists. Or could life emerge in the gas or liquid phase? Are planets necessary for the evolution of higher forms of life? Is an aqueous environment essential? In respect of the elements required, are radioactive isotopes essential? We suffer from the disadvantage of having only one example for the emergence of life: planet earth. It is credible that terrestrial vulcanism played an essential role in the evolution of life on earth [Davies (1999)]. But vulcanism, and tectonic activity generally, have their root cause in the radioactive decay of heavy nuclei. It is possible that even heavy elements like uranium may be essential to the origin of life, despite not being necessary to the functioning of our bodies.

These questions are impossibly difficult, but thankfully it is not essential to answer them. The purpose in examining the changes that would occur in the universe if one of the above numbers were varied is not to prove that life would evolve. That would be a hopeless task, for it could not even be done for this universe. The purpose is a lesser one: it is to determine if the minimum requirements for an interesting/biophilic universe are still met. To reiterate, these requirements are that the universe has density contrasts, long lived energy sources and contains hydrogen, carbon, oxygen, nitrogen and phosphorus. If it also contains rigid, solid matter, including planets and comets, and contains other elements, perhaps including radioactive elements, then that is a bonus. Often the outcome is unambiguous. It is often clear that the tweaked universe fails to achieve even the minimum requirements, for example because it would contain nothing but hydrogen, or survives for only a fraction of a second.

The fact that the origin of the elements is understood in some quantitative detail is a major intellectual triumph of twentieth century physics - all the more so because the starting point is, perhaps literally, nothing. Nor is the story brief and simple. Enormous spans of time and space are involved. The production of the elements beyond lithium requires the spontaneous evolution of auto-stabilised fusion reactors, commonly known as stars. Why should this happen? And assuming it does, why should the elements forged in the stars escape into the rest of the universe where the conditions are less extreme and hence more conducive for the emergence of life? Stars are surprisingly complex in their structure and behaviour. They very conveniently provide the two key necessities for life: the production of matter with the right chemistry, and a long-lived source of radiant energy of the right temperature.

The complexity of stars is, however, nothing compared with that of galaxies. Galaxies are not merely functionless collections of stars. These conglomerations of typically 100 billion stars are an ecosystem in their own right, even an organism. They have highly complex internal structures, consisting of giant gas clouds of various kinds and with masses which dwarf individual stars. They act as nurseries within which new stars are born from the death throes of the old. The gestation of embryonic stars relies crucially on the ability of the giant gas clouds to provide a cooling mechanism. With poetic resonance, this cooling mechanism involves the life-element itself, carbon. In short, galaxies are complex enough to be *interesting* in their own right. Even if we had not life to explain, it is impressive enough that the universe has spontaneously evolved entities as complex as galaxies from a featureless beginning.

The universe today is clearly a long way from thermodynamic equilibrium. The stars are extremely hot. We are not. Comets are snowballs. Intergalactic space is generally at just a few degrees absolute (if any temperature can be assigned to it at all). And the gas clouds within galaxies take on a rich diversity of different temperatures, from tens of degrees absolute up to half a million degrees. The Big Bang theory holds that the universe started a finite time in the past in a very hot, dense state. Who would have thought that a universe initially in a state of uniformity and thermodynamic equilibrium – a homogeneous fireball - could possibly evolve into the present, complex, universe? People familiar with the second law of thermodynamics will be justifiably concerned at this thought (though the law is respected).

Could it be that the Big Bang theory is just wrong? Well, the Big Bang is extremely compelling. The point is that the broad picture of the evolution of the universe *can* be understood as a natural consequence of the Big Bang. Moreover, after the first fraction of a second, this mostly requires only tried and trusted physics. Providing we do not start the clock running too early, leaving out the first millisecond or so, the derivations require no esoteric physics. Indeed much of the very early fireball phase can be developed, at least approximately, using the simplest of physics.

Many people might have difficulty taking seriously a subject which appears to extrapolate physical theory to conditions far from their known range of applicability. There are at least two compelling counter-arguments. The first is that the temperature and density in the seconds and minutes after the Big Bang can be deduced from reasoning so simple as to be virtually inescapable. The second is the realisation that, although the temperatures at this time are extremely high by human standards, the corresponding particle energies are actually quite modest compared with the energies routinely reached by particle accelerators.

Key pieces of evidence in support of the Big Bang include: the observed expansion of the universe; the existence and temperature of the cosmic microwave background radiation; the abundances of hydrogen, deuterium, helium-3 and helium-4 in the universe; and, the angular variation of the anisotropy of the cosmic microwave background radiation. The signature of a successful theory is its explanation of previously contingent facts as being necessary consequences of the theory. These are excellent examples.

The most elementary observational evidence in favour of the Big Bang, is that the universe is expanding. This immediately suggests that earlier conditions were denser and hence hotter. By extrapolation, the age of the universe is estimated as the reciprocal of the constant relating the recessional velocity to the distance, $t_{univ} \approx 1/H$, where v = Hr. The oldest stars and galaxies are of an age just a little less, but of the same order, as 1/H. From the perspective of the Big Bang theory, in which 1/H is essentially the age of the universe, this is exactly what would be expected. In contrast, if we adopt a steady state perspective, without a universal creation event at a finite past time, the fact that 1/H is roughly the same as the age of the oldest stars and galaxies appears as an odd coincidence crying out for explanation.

Of course, many aspects of the structure and evolution of the universe are still not understood quantitatively. Perhaps the most embarrassing for astrophysicists (or particle physicists) is that, in order to understand the motions of galaxies, and the overall dynamics of the universe, it is necessary to postulate the existence of large quantities of unseen substances. The standard cosmological model holds that 96% of the universe consists of dark matter or dark energy, thus outweighing ordinary matter by about 24:1. Of course, it is in no way surprising that much of the universe is dark. Our own planet would be 'dark matter' if it were situated sufficiently far from a source of light. However, the surprising thing is that both the dark matter and the dark energy appear to be of a radically different kind from the ordinary (so-called 'baryonic') matter of which we, our planet, our solar system and everything that we can see is composed.

The formation of stars is poorly understood in comparison with the quite detailed understanding of their structure once formed. The formation of the galaxies and the first stars is particularly challenging. Indeed, the understanding of the internal structure of galaxies is still at a rudimentary stage. However, relatively simple arguments reveal why galaxies are the size and mass that they are. In fact, many broad features are understood in some quantitative detail, as we shall see. Were this not so, the 'fine tuning' hypothesis would not be worth discussing. It is a testament to the maturity of astrophysics that sufficient understanding exists to permit the fine tuning to be discernible.

Most of this exposition will be theoretical in nature. However, it is appropriate to emphasise that cosmology is predominantly an observational science. In this respect the last decade has seen phenomenal progress, due partly to technological advances. Chief amongst these are the data obtained from the COBE and WMAP satellites, and the studies of Type Ia supernovae. The Wilkinson Microwave Anisotropy Probe (WMAP) in particular has become the revered oracle of cosmological parameters. Long gone are the days when astronomers were content to just observe the microwave background and measure its temperature. The precision of the WMAP data is now so great that it is the main source of information on most of the key cosmological parameters. The microwave background radiation provides information from about 360,000 years after the Big Bang. This is roughly 1000 times earlier than information obtained by observing the most distant galaxies or quasars. As for the Type Ia supernovae observations, these have profoundly changed cosmologist's views of the large scale dynamics of the universe. Specifically, it appears that the expansion of the universe is accelerating. This is as unexpected as if a stone thrown in the air, instead of falling back down to earth, were to shoot into space like a rocket. This provides a salutary reminder that theoretical speculation unconstrained by observation or experiment can degenerate into mere make believe.

However, theory is not optional. It is only through theory that any understanding is achieved. A stack of CDs full of experimental or observational data avails us nothing. This is a most pertinent point since the subject of this exposition, the cosmic coincidences, exists only within the theoretical realm. There is no observation that screams “coincidence”. But we are getting ahead of ourselves. First we must explain what we mean by a cosmic coincidence, or ‘fine tuning’. To do that we must say a little about how physics works.

§1.2 Physical Laws and Universal Constants

Physics, of course, has its ‘laws’. Whether these are, like the law of the land, of human invention, or whether they have their own independent existence, is a philosophical debate which will not be addressed here. Probably the majority of physicists regard the ‘laws’ as approximations to some objectively real ultimate expression of the Truth, essentially a Platonist view. More radically, it has been suggested that the physical laws are actually just local by-laws, applicable in our universe but varying across the multiverse [Rees (2002), Tegmark, Aguirre, Rees & Wilczek (2006)]. Perhaps every self-consistent law arises somewhere [Tegmark (1998)]. However, the investigation of the cosmic coincidences can be carried out independently of any particular philosophical stance on the nature of physical law. The practical function of the laws is to provide mathematical equations of broad applicability which express how measurable quantities depend upon each other.

As an example, Newton’s law of gravitation expresses how the acceleration of an object depends upon the mass of the gravitating body and their distance apart. From such an equation, it is a matter of pure mathematics to derive the path of the body through space and its velocity at every point. Scientific laws can be subject to experimental or observational test, and potentially refuted. It is this property, and this property alone, which distinguishes science from non-science. A scientific theory is required to constantly ‘stick its neck out’ and be exposed to experimental or observational tests which have the potential to prove it wrong.

The laws of physics also contain some special numerical ingredients. In the case of Newton’s law of gravitation applied to a comet, for example, the acceleration of the comet is expressed in terms of the mass of the sun (the gravitating body) and their distance apart. Specifically, the acceleration is proportional to the mass of the sun and inversely proportional to the square of the distance, i.e. proportional to M/r^2. But the comet’s acceleration does not *equal* the quantity M/r^2. It could not possibly be, since M/r^2 does not have the units of acceleration. There must be, at the very least, a factor which converts M/r^2 to the correct units for acceleration. This is written “acceleration = GM/r^2”. What Newton’s law of *universal* gravitation says is that this conversion factor ‘G’ is the same for any gravitating bodies. So, a different comet passing by a different star in a different galaxy has exactly the same value for ‘G’. This is expected to be true across the whole of our universe (though different parts of the multiverse are another matter). Consequently, G is referred to as a “universal constant”. Naturally people have asked whether the so-called universal constants, G in particular, might actually vary from place to place, or vary in time.

This would make an interesting digression, but it is not essential for the purposes of this exposition. Here it will be assumed for simplicity that the universal constants are just that: both universal and constant. The disappointed reader is referred to Barrow (2002) for a discussion of time varying ‘constants’. Suffice it to say that any time variation of the fundamental ‘constants’ is believed to be far smaller than the degree of fine-tuning. Hence, the assumption of time invariant universal constants remains a good basis on which to proceed.

If the laws of physics are the engines of physics, the universal constants are the fuel which powers the engines. The numerical values of the universal constants are what must be fed into the equations which express the laws in order to make definite quantitative predictions. The engines of physics are staggeringly efficient. The standard model of particle physics contains just 26 universal constants. To this must be added between 4 and 11 more parameters which are required to describe the large scale structure of cosmology. Hence, only 30 to 37 numbers are sufficient to fuel the laws of physics and have them produce our universe. All these constants will be described in the next chapter. It is possible that the 11 cosmological parameters might eventually be derived from microscopic physics, i.e. from the 26 parameters of the standard model of particle physics or their equivalent. This exposition will use just 10 of the universal constants, which is sufficient to define almost all aspects of our universe. These are the 10 numbers listed at the start of this chapter. In fact, most familiar things depend only upon 4 of the universal constants. It is remarkable that the properties of the whole universe can, at least in principle, be deduced from such a small set of numbers.

§1.3 Illustration of the Cosmic Coincidences

Before turning to some illustrations of the cosmic coincidences, note that these do not only involve physics on the cosmological or astronomical scale. To a physicist, an atom or an animal is also part of the universe. Many of the cosmic coincidences relate to the atomic or sub-atomic level. Hence, the universal constants include the masses of the elementary particles. The simplified set of constants used here (see chapter 2) will include the masses of the three particles which comprise ordinary, baryonic, matter: the neutron, the proton and the electron. These provide a simple example of a cosmic coincidence. The masses of the neutron, the proton and the electron are 939.565, 938.272 and 0.511 respectively (in particle physicists’ traditional units, MeV/c^2). It is striking that the electron is so much lighter than the nucleons[1]. The relevance of this to the structure of the universe is discussed later (chapter 10). For now, notice how close the neutron and proton masses are. They differ by just 0.14%. This in itself is not terribly surprising. They are very similar particles, apart from the fact that the proton possesses electric charge whilst the neutron is, as the name suggests, electrically neutral.

The odd thing about the nucleon masses is that the proton is the lighter particle. When I first came across this fact I recall feeling that it was just wrong somehow. The temptation is to regard the proton as a neutron with added charge. The electrostatic field due to the proton’s charge has a positive energy associated with it and hence a corresponding

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[1] ‘Nucleon’ is the generic term for a proton or a neutron.

equivalent mass (in accordance with $E = mc^2$). If the proton were just a neutron with added charge, it would therefore have the greater mass. What I did not realise at the time was just how disastrous this would be.

The reason is that a positively charged proton and a negatively charged electron can potentially combine to form an electrically neutral neutron[2]. In stable matter, this is prevented by the mass of the neutron (M_N) being greater than the sum of the masses of the proton (M_P) and the electron (m_e). Using the above data we see that 939.565 > 938.272 + 0.511 (MeV/c^2). If this were not true, if instead the universe had $M_N < M_P + m_e$, then atomic nuclei would capture atomic electrons and all matter would collapse into a bunch of neutrons. We are saved from this catastrophe by the conservation of mass together with the fact that $M_N > M_P + m_e$. But see what a close miss this was. The neutron – proton mass difference is only 1.293 MeV/c^2, compared with the electron mass of 0.511 MeV/c^2. Had the neutron mass been less than 938.783 MeV/c^2, rather than 939.565 MeV/c^2, a difference of only 0.083%, then all atomic matter would have been unstable and life as we know it would have been impossible. Note that the capture of an atomic electron by a nuclear proton to form a neutron is not a mere hypothetical possibility. It is the actual, observed, decay mode of certain unstable nuclei and tends to occur whenever the difference in the binding energies of the two nuclei is sufficient to offset the greater neutron mass.

This is an instance of cosmic coincidence. The neutron mass is said to be ‘fine tuned’ since a variation of only 0.083% is sufficient for a sterile universe consisting only of neutrons to emerge. Since we have no *a priori* reason to expect M_N, M_P and m_e to take any particular values, it appears to be mere coincidence that they happen to obey $M_N > M_P + m_e$ and are thus consistent with the existence of stable atoms.

So far, this is a “one-sided” coincidence in the sense that the mass of the neutron is required only to *exceed* a certain value. Electron-proton capture could not happen if the neutron were 100 times more massive. So a ‘downward fine-tuning’ of the neutron mass has been demonstrated, but not an ‘upward fine-tuning’. A more impressive coincidence would be if the neutron mass were required to lie within some narrow range of values, $M_N^{LB} < M_N < M_N^{UB}$. Actually it is, as is shown next.

Thank heavens that the neutron *is* heavier than the proton plus the electron – but there is a price to pay for avoiding atomic instability via electron capture. Since the neutron is heavier than the sum of the proton and electron masses, the *neutron* is unstable! The conservation of mass does not prohibit the heavier neutron decaying into a proton plus an electron[2] (so-called beta decay). The excess mass, $\Delta = M_n - (M_p + m_e)$, is balanced against the kinetic energies of the product particles (which sum to Δc^2). So, we are doomed then. However the universe cooks the books, it seems that atomic matter will always be unstable. Either atoms are unstable against electron capture if $M_N < M_P + m_e$, or the atomic nucleus is unstable against beta decay of its neutrons if $M_N > M_P + m_e$. Again, beta decay of neutrons is not a mere hypothetical possibility; it is the actual,

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[2] There is a neutrino involved as well, but we need not complicate the discussion.

observed, decay mode of both free neutrons and of certain unstable nuclei. But since $M_N > M_P + m_e$ in our universe, why are *any* atomic nuclei stable?

It *is* true that free neutrons are unstable. They have a half-life of about 15 minutes in fact. But this half-life applies only when the neutrons are free. Fortunately for us, when neutrons are combined in the nuclei of atoms they become stable. To be more precise, they become stable in small or moderately sized nuclei. In larger nuclei their intrinsic instability shows through and results in the phenomenon we know as radioactivity.

The reasons for the stability of neutrons within nuclei will be explained in chapters 8 and 9. For now we wish only to point out what a delicate balance is involved. The degree of instability of a neutron is related to the mass deficit, $\Delta = M_n - (M_p + m_e)$. For matter to be stable against electron capture by protons, the mass deficit must be greater than zero. However, if the mass deficit were too large – specifically if it were several times bigger than the electron mass – then even neutrons within nuclei would be unstable and once again atomic matter could not exist for very long. The actual value of the mass deficit is just 1.53 times the mass of the electron. Given that this is only 0.083% of the nucleon mass, the stability of atomic matter appears to rest upon the mass of the neutron lying within a very narrow window, within very roughly plus or minus 0.083% of its actual value.

This completes the illustration of fine-tuning or cosmic coincidence, noting that it is now a double-sided coincidence, i.e. of the form $M_N^{LB} < M_N < M_N^{UB}$. It is worth emphasising the mind-set that underlies the labelling of such things as a ‘coincidence’. The point is that, before we carry out experiments to measure them, the neutron, proton and electron masses could apparently take any values at all. If we do not start with the prejudice that the universe must become ‘interesting’, then who cares if the universe ends up instead as a homogeneous gas of neutrons and nothing else? Why should there be anything at all, let alone anything interesting? Of course, we would not be around to make these observations if this were true, but this is what it might look like from a “God’s eye” perspective.

Physicists have a mental picture of this as follows. Imagine there is some “universe creation machine”. For the sake of argument we assume that the laws of physics themselves are fixed. However, we can use our universe creation machine to make a variety of completely different universes according to the numerical values we choose for the universal constants. To make this graphic, imagine the universe creation machine has a number of dials on it, one for each universal constant. We can dial-in whatever combination of values for the neutron, proton and electron masses, and all the other universal constants, that we wish. And, hey presto, out pops the universe we have ordered. Who or what was it, though, that set the dials for this particular universe of ours?

Consider for a moment that the values of the universal constants were set entirely arbitrarily. Then the fact that the mass of the neutron happens to lie within the very narrow window, roughly $\pm 0.083\%$ wide, which leads to atomic stability can only be regarded as a remarkable coincidence. Just how likely this coincidence is to have come about by chance depends upon a more detailed definition of what is meant by an “entirely arbitrary” choice of the universal constants. If they may take any value with equal probability, up to infinity, then the probability of lying within any finite range is zero! This is not helpful. Let us say instead that the neutron mass could have been anywhere from millions of times less to double its actual value, with equal probability of any value in this range. The probability of atomic matter being stable is then 0.083%. This *is* rather coincidental. This view of the situation is typical of all the cosmic coincidences. Many of them are more deeply buried in difficult physics. Many of them are less impressive, requiring only a much larger target to be hit, i.e. they have a much wider ‘window’ of coincidence. In the course of this exposition it will be shown that many of the universal constants appear to be similarly fine-tuned, to varying degrees. The word ‘coincidence’ applies, of course, only if the values of the universal constants are considered to have been chosen at random. The traditional role of science is to replace coincidence with explanation.

There is an alternative school of thought. This holds that all the universal constants are derivable in terms of pure mathematics. This has long been the dream of theoretical physicists. From this perspective, the values of the universal constants are believed to be completely constrained by the internal consistency of the physical laws. The whole programme of considering potential variations of the constants, even small variations, is intrinsically meaningless and misleading from this point of view. This is an attractive idea. But disappointingly, the development of the standard model of particle physics in the 1960s and 1970s singularly failed to reduce the number of independent universal constants. At one time there was hope that string theory might provide the means by which the universal constants could be deduced mathematically. Hope now seems to be fading that this will be realised (References).

§1.4 The Hard Line Position on the Cosmic Coincidences

There is a broad spectrum of opinion within the scientific community regarding how impressive the cosmic coincidences really are. It is the prime objective of this exposition to attempt to address this question. One of the difficulties is the appropriate probability measure. It has been seen, above, that it is not trivial to attach a probability to the neutron mass lying in a range $\pm 0.083\%$ about its value in this universe. Even if it is assumed (arbitrarily) that the probability distribution is flat, it is still necessary to assume some finite range of possible values. Alternatively, a non-flat probability distribution could be assumed, becoming zero at sufficiently large or small values. However, in this case the form of probability distribution must carry an assumption regarding the mean value and the width of the distribution (e.g. its standard deviation). In short, a probability cannot be assigned without additional assumptions of some sort.

One possible ‘additional assumption’ is that Planck dimensions provide an absolute scale. Planck dimensions are defined through three particularly fundamental universal constants, G, c and $\hbar$. These are Newton’s universal constant of gravitation, the speed of light, and Planck's constant[3] respectively. Quantities with dimension of space, time and mass formed from these three constants known as the Planck scale. They are $L_P = 1.62 \times 10^{-35}$ m; $t_P 5.39 \times 10^{-44}$ s; $M_{Planck} = 2.18 \times 10^{-8}$ kg (see chapter 2 for details). One means of gauging the probability of, say, the mass of a given particle is to regard the Planck mass as the natural unit, and hence anything far smaller to be contrived and unlikely. For example, the mass of a fundamental particle might be assumed to have equal probability of lying anywhere between (virtually) zero and several times the Planck mass. This immediately leads to all the fundamental particles being regarded as highly improbable because they all have masses which are far, far smaller than the Planck mass. But whether there is anything truly significant in this observation depends upon whether the Planck scale really is fundamental. This is perhaps more debatable than the current fashion allows.

An example of a hard line position on the cosmic coincidences is provided by an argument due to Smolin (1997) which is quoted in full below. Smolin sets out to estimate the probability that the universe would contain stars that live for billions of years if the universal constants were chosen randomly. He is implicitly assuming flat probability distributions between zero and the Planck scale:-

"*The lifetime of stars depends on the ratio of the proton mass to the Planck mass. That they live more than a billion years requires that this ratio be less than* 10^{-19}. *The probability for this to occur randomly is one part in* 10^{19}. *We saw that for there to be many nuclei, the neutron must have about the same mass as the proton, while the electron must have a mass on the order of a thousand times smaller. The accuracy to which the neutron's mass must approximate that of the proton is a few electron masses. This means that the masses of the electron and neutron must come out to within an accuracy of about* 10^{-22} *in Planck units. The same is true also for the neutrinos. The probability for this to happen in three rolls of the dice is about* 10^{-22} *cubed, which equals* 10^{-66}. *If we put this together with the probability that the proton mass comes out as no larger than it is, we get a probability of one part in* 10^{85}.

We have to take into account also the cosmological constant, for if it is too large the universe will not live long enough for stars to form. In order for the universe to live at least until the time of the formation of the galaxies, the cosmological constant must be less than 10^{-60}. *The probability to get this number randomly is then one part in* 10^{60}. *Putting this together with the previous results, we now have a probability of one part in* 10^{145}.

We have yet to mention the nongravitational interactions. If we start with their strengths, then we may again compute the probabilities by taking ratios. Taking again the strongest, which is the strong nuclear interaction, as the measure, the weak and electromagnetic interactions are each about one part in 100. This multiplies the above probabilities by 10^{-4}, *which gives us one part in* 10^{149}. *Finally, we have to take into account the ranges of*

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[3] Historically, $\hbar$ was defined as Planck's original constant, h, divided by 2π. However, since it almost invariably occurs as $\hbar$ we adopt the definition, for textual convenience, of referring to $\hbar$ as Planck's constant.

the forces. The largest range is that of electricity, which is at least the radius of the universe. The ratio of the radius of the nuclei, which is the range of the two nuclear interactions, to the radius of the universe, is at most 10^{-40}*. The probability to get two such tiny ratios randomly is one part in* 10^{80}*. It we combine this with our previous result, we reach the conclusion that the probability for the world to have turned out as ours, with stars lasting billions of years, and thus with nuclear and atomic physics more or less like ours – were the parameters of the standard model picked randomly – is at most one part in* 10^{229}*.*"

This has been chosen as an illustration of the hard-line "coincidencist" position. The claim that a universe with long lived stars has only a 1-in-10^{229} chance of occurring is startling. One of the objectives of this exposition is to assess whether the above argument is fair. We shall return to it in chapter 12. But if it were fair, how could we explain that the universe has occurred at all, against such odds?

Finally we come to what has become a widespread view amongst physicists in regard to explaining the cosmic coincidences: the multiverse (References). It comes in many variants, but the common theme is that our observable universe is merely one of a rather nauseatingly large number of universes within some multiverse. In one variant, these universes all exist in different parts of the same four dimensional spacetime. They are just elsewhere – and causally disconnected. Another variant has the other universes occupying different M-branes in some higher dimensional space (Reference). Yet another identifies the multiverse with that familiar from the Everett 'many worlds' interpretation of quantum mechanics (Reference). We will say a little more about these ideas in chapter 3. The basic idea of most of them appears to be the most flagrant violation of Occam's razor imaginable. The argument seems to be that, if you want to realise a universe whose probability of occurrence on a random basis is very small, say 10^{-N} for some large N, then all you have to do is to arrange for more than 10^{N} universes to be created at random, and the chances are that you will get one. Possibly my prejudice is showing, but as a theory it fails to impress. One can 'explain' literally anything on this basis. In which case the idea is not refutable and hence not scientific (see Smolin 2006a). This is not to say that this class of ideas cannot be made scientific. But to do so requires more details to be specified. One's scientific neck must be stuck out so as to be potentially falsifiable. Moreover, there appears to be insufficient respect shown for the exceedingly small probabilities involved. It seems to me that, even if a huge number of universes is conceded, there must also be some directing mechanism for the eventual production of 'interesting' universes. In this respect, Smolin's (1997) idea is attractive. He contends that universes evolve in a manner analogous to biological evolution. In this way a credible means of 'climbing Mount Improbable[4]' is provided.

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[4] Richard Dawkins (date?)