

Copyright Notice

Staff and students of this University are reminded that copyright subsists in this extract and the work from which it was taken. This Digital Copy has been made under the terms of a CLA Licence which allows you to:

- Access and download a copy
- Print out a copy

This Digital Copy and any digital or printed copy supplied to or made by you under the terms of this Licence are for use in connection with this module or course of study. You may retain such copies after the end of the course, but strictly for your own personal use.

All copies (including electronic copies) shall include this Copyright Notice and shall be destroyed and/or deleted if and when required by the University.

Except as provided for by copyright law, no further copying, storage or distribution (including by e-mail) is permitted without the consent of the copyright holder.

The author (which term includes artists and other visual creators) has moral rights in the work and neither staff nor students may cause, or permit, the distortion, mutilation or other modification of the work, or any other derogatory treatment of it, which would be prejudicial to the honour or reputation of the author.

Title of extract: **Anthropic Reasoning – Principled and Unprincipled**

Name of Author: **Rees, M.**

Title/Author of book/edition (if applicable): **Before the Beginning. Rees, M.**

Name of Visual Creator or other acknowledgement (if applicable):

Journal details –title/Vol/Year (if applicable):

Publisher: **Simon & Schuster Ltd**

Pages scanned: **253 - 269**

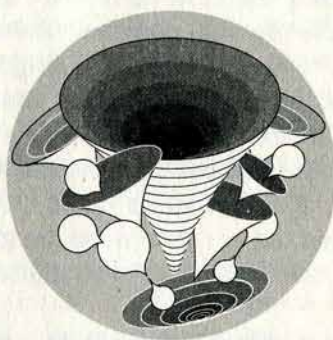
Course of Study (Module name and number): **Introduction to Cultural Astronomy and Astrology AHAN7002**

Name of Designated Person

authorising scanning: *E.L. Harris*

Date authorised: 04.05.17.

Moodle/Powerpoint



15

ANTHROPIC REASONING – PRINCIPLED AND UNPRINCIPLED

The universe knew we were coming.

Freeman Dyson

OUR CARBON-BASED BIOSPHERE HAS slowly evolved on a planet orbiting a stable star. Given that fact, some features of our universe, some constraints on the physical laws that govern it, follow quite straightforwardly. Various striking coincidences highlighted throughout this book acquire a different perspective once we recognise that we couldn't have evolved if they hadn't been fulfilled. But they still, I believe, have a deep significance: they offer clues to what the cosmos is like on even vaster scales than we can yet (or perhaps can ever) probe.

Our universe has some features – being long-lived, stable and far

from thermal equilibrium, for instance – that are prerequisites for our existence; moreover, our emergence, as we have seen, depended crucially on apparent ‘fine tuning’ of the basic physical constants: the strengths of the fundamental forces, the masses of elementary particles and so forth.

There are various ways one can react. The most robustly dismissive attitude is that the physical constants must have *some* values, so we have no reason to be surprised at any particular value rather than another. Sciama gives a *reductio ad absurdum* of this viewpoint. Suppose you walk into a room and find a million cards laid out on an enormous table. Suppose you find that these cards are numbered progressively 1, 2, 3 and so on up to 1 000 000. Would you think they had been laid out at random, on the grounds that any particular ordering would have the same probability as any other? Obviously you would not.

This judgement doesn’t depend on our knowledge that people may have reasons for dealing cards in a special order: there is an objective mathematical basis for saying this particular ordering is special. It is definable by a very short set of instructions: ‘start with one, and then add one each time’. In contrast, a long and complicated program would be needed to tell a computer how to print out most sequences – indeed a purely random sequence can’t be encapsulated by any program shorter than itself (that is, essentially, what ‘random’ means). Obviously the order implied by the cosmic coincidences doesn’t stare us quite so plainly in the face as the ordering of cards. But this example counters the dismissive view that, whatever pattern we find, we should just accept it as chance rather than seeking an explanation.

A more reasonable reaction to the coincidences is to invoke a kind of ‘selection effect’. Fishermen aren’t surprised (to use an old metaphor of Eddington’s) to catch no fish smaller than the holes in their nets. Nor are optical astronomers surprised that the objects they detect are very hot (since otherwise they wouldn’t be shining). Likewise it may seem irrational to be surprised that our universe has any particular property if we wouldn’t exist otherwise.

But even that doesn’t seem quite enough. To say that we wouldn’t be here if things were otherwise need not quench our curiosity and surprise that our universe is as it is. The Canadian philosopher John Leslie has given a nice analogy. Suppose you are facing execution by a fifty-man firing squad. The bullets are fired, and you find that

all have missed their target. Had they not done so, you would not survive to ponder the matter. But, realising you were alive, you would legitimately be perplexed and wonder why.

It seems noteworthy, at the very least, that the physical laws governing our universe have allowed so much interesting complexity to emerge in it, especially as we can so readily imagine stillborn universes where nothing could evolve. If a 'cosmic being' turned knobs to vary the constants of physics and constructed a whole ensemble of universes, then clearly only one would be like our own, and we wouldn't feel 'at home' in most of them – that much is obvious. However, what is less trivial, and may be deeply significant, is that only a narrow range of hypothetical universes would allow *any* complexity to emerge.

This line of thought has a long lineage: its basis is often called the 'anthropic principle'. This name is an unfortunate one. 'Principles' in cosmology have often connoted assumptions unsupported by evidence, but without which the subject can make no progress.¹ The use of such phrases has hampered cosmologists in getting their subject accepted as an empirical one. I prefer the less pretentious phrase 'anthropic reasoning'.

The modern interest in anthropic reasoning was triggered by Brandon Carter, another student of Sciama, and one of my exact contemporaries at Cambridge. He was the first person to understand fully the internal structure and significance of the rotating black holes described by Roy Kerr's famous solution of Einstein's equations (see Chapter 5); he went on to contribute further ideas on black holes and (latterly) on cosmic strings. In 1970, Carter wrote a long manuscript discussing the 'coincidences' in the values of the basic physical constants, and pointing out some new ones – for instance, the formation of planetary systems around stars may require a particular relationship between the strength of gravity and various numbers derived from atomic physics. This was never published, though a shorter version appeared in print several years later. Carter's manuscript was, however, widely discussed, and he has been an influential participant in the ensuing debates.

Carter distinguished between 'weak' and 'strong' anthropic reasoning. What he called the 'weak anthropic principle' was essentially an allowance for observational selection: we shouldn't take Copernican modesty too far, but had to accept that creatures like us couldn't view the universe at all points in space and time, so that our perspective

was bound to be in some sense special. Even this 'weak principle' allows some inferences which are interesting and by no means obvious. A good example was Dicke's demonstration (described in the previous chapter) that Dirac was wrong to be puzzled about the coincidences between two large numbers – one measuring the size of our observable universe, the other the strength of gravity. Dicke pointed out that we were not observing the universe at a random time in its history: we were living in an era when some but not all stars had died and straightforward stellar physics demands that Dirac's 'coincidence' automatically holds during that era.

Carter's '*strong* anthropic principle' was more controversial and speculative: this is the idea that the fundamental laws in any universe must actually be such as to permit observers to exist. Such a claim has teleological overtones; few have ever taken it seriously. It does, however, find an echo in some interpretations of quantum theory.

THE 'PARTICIPATORY' VIEW

Niels Bohr averred that anyone who was *not* astonished by quantum theory hadn't fully taken it in. Philosophical debates about this theory remain as lively as ever. The most common viewpoint, the so-called 'Copenhagen interpretation' espoused by Bohr and his followers, envisages that every system is governed by a 'wave function', whose behaviour is exactly determined by Schrödinger's famous equation until an observer chooses to make a particular measurement. This leads to what is called 'collapse of the wave function'. Information *complementary* to what is actually measured (for instance, the exact speed of a particle if we measure its position, or vice versa) is then irretrievably lost.

Quantum theory undeniably works; most physicists apply it confidently but unreflectively. As John Polkinghorne has put it, 'the average quantum mechanic is no more philosophical than the average motor mechanic'. But the 'Copenhagen interpretation' makes many of us uneasy. It implies a sharp and artificial-seeming disjunction between the object being measured and the observer (or experimenter); on the other hand everything – observer and experiment alike – should equally be subject to quantum laws.

Some have exalted the observer's role even further, claiming that an observation is needed to 'bring the world into being'. Universes would then be 'real' only if they contained observers: the status of a universe would depend fundamentally on whether it could harbour a conscious observer of any kind (whether or not it resembles carbon-based life). This 'participatory' view has been espoused by John Wheeler, who wrote,

The system of shared experience which we call the world is viewed as building itself out of elementary quantum phenomena, elementary acts of observer-participancy. In other words, the questions that the participants put – and the answers they get – by their observing devices, plus their communication of their findings, take part in creating the impressions which we call the system: that whole great system which to a superficial look is time and space, particles and fields.

The 'participatory universe' seems hard to accept – hard, even, to take seriously. What sort of observer must be invoked to 'bring the universe into being': a mouse? a human? or a PhD physicist? I'm reluctant, however, to be too dismissive, because Wheeler has earned the right to be heeded. Early in his career, back in the 1930s, he collaborated with Niels Bohr on the theory of nuclear fission. Richard Feynman was one of his first PhD students (graduating in 1942) and Wheeler has ever since been an inspiration to successive generations of physicists. In the 1950s, he explored what quantum uncertainty might imply for the nature of space and time. He invented the concept of 'space-time foam' – the idea that on the Planck scale space and time themselves, and even the dimensionality of the world, fluctuate randomly. He introduced 'geons' – hypothetical entities that behave like particles, but are composed of nothing but curved empty space. Wheeler's bold conjectures prefigured the current ideas of chaotic cosmology and wormholes at the Planck time. He coined the term 'black hole' and was the primary inspiration behind the resurgence of American research in relativity in the 1960s. His gaze is still focused on the conceptual frontiers of cosmology – the 'flaming ramparts of the world', as he calls them.

The paradoxes of quantum mechanics, and the nature of consciousness, are manifestly two of the deepest mysteries of all. It

is striking that John Wheeler and Roger Penrose, the most original and influential living theorists about space and time, have both, in their later years, advocated the dissident view that these mysteries are linked.

Whatever one thinks about Wheeler's concept of quantum mechanics, it shifts the perspective of anthropic arguments by making them less anthropocentric. Rather than asking what conditions were necessary for *our* evolution, we can ask what distinguishes a 'still-born' universe from one that would be 'cognisable', in the sense that it permitted some kind of conscious entity or 'observer' to evolve within it. One must not be too anthropomorphic nor too restrictive in envisaging the requirements for the emergence of a conscious observer. Maybe neither stars, nor even atoms, are absolutely necessary. Science-fiction writers have familiarised us with many bizarre alternatives. However, some departure from thermal equilibrium would seem essential. A universe that recollapsed too promptly to a big crunch would, for instance, never become 'cognisable' during its brief existence. A force like gravity may also be essential, in order that structures should emerge (as described in Chapter 7); but it must be weak and slow-acting, as in our own universe.

Another approach to quantum mechanics is the 'many-worlds' theory, proposed by Hugh Everett in the 1950s. The basic idea here is presaged in Olaf Stapledon's classic work of science fiction *Star Maker*:

Whenever a creature was faced with several possible courses of action, it took them all, thereby creating many . . . distinct histories of the cosmos. Since in every evolutionary sequence of the cosmos there were many creatures and each was constantly faced with many possible courses, and the combinations of all their courses were innumerable, an infinity of distinct universes exfoliated from every moment of every temporal sequence.

The 'many-worlds' approach envisages our entire universe as a single quantum system. It appeals especially to cosmologists, for whom the Copenhagen picture is plainly unsatisfactory, since there cannot then be an observer external to the system when that 'system' is the entire universe. A newer variant due to David Deutsch replaces the idea of branching universes by an infinite

ensemble of universes, evolving in parallel and displaying greater variety as time goes on.

ANTHROPIC SELECTION OF UNIVERSES

The physical constants seem to have fixed values throughout our universe. Maybe they could be different in others. Brandon Carter and I first heard such speculations floated in some public lectures in Cambridge in the early 1960s, given by Charles Pantin, a biology professor. He said that:

the properties of the material universe are uniquely suitable for the evolution of living creatures. If we could know that our own universe was only one of an indefinite number with varying properties we could perhaps invoke a solution analogous to the principle of natural selection, that only in certain universes, which happen to include ours, are the conditions suitable for the existence of life, and unless that condition is fulfilled there will be no observers to note the fact.

If there were nothing beyond our universe, its properties indeed seem fine-tuned, or even providential. But suppose Pantin's conjecture could be fleshed out – suppose there really were other universes. If the 'constants' took different values in each, there would then be no need for surprise that some universes allowed creatures like us to exist. And we obviously find ourselves in one of that particular subset. If you go to a clothes shop with a large stock, it isn't surprising to find a suit that fits you.

Scientists commonly pay obeisance to 'Ockham's razor' – the celebrated injunction by William of Ockham, in the early 14th century, which (translated from his Latin) means 'don't multiply entities more than is absolutely necessary'. Nothing, perhaps, could seem to violate this more drastically than postulating an infinite array of universes! Nor does it, at first sight, seem properly 'scientific' to invoke regions that are unobservable, and perhaps always will be. The concept of an ensemble of universes of which ours is just one member (and not necessarily a typical one) is, needless to say, not yet in sharp theoretical focus. But it helps to explain basic (and previously

mysterious) features of our universe, such as why it is so big, and why it is expanding. In the broader perspective of a 'multiverse', anthropic reasoning acquires genuine explanatory force.

A MULTIVERSE?

The 'many-worlds' version of quantum mechanics offers one approach to the 'multiverse' concept. The idea of 'eternal inflation' described in Chapter 10, though still very speculative, suggests another context in which other universes could exist.

The fundamental forces – gravity, nuclear, and electromagnetic – all 'froze out' with their present values and distinctive properties as our universe cooled down. Likewise the masses of the elementary particles. When the inflationary era ended, space itself (the 'vacuum') underwent a drastic change. As Chapter 10 describes, inflation may lead to separate universes – separate domains within a multiverse – which cooled down differently, ending up governed by different laws.

Complex evolution would occur only in 'oases' where the constants had propitious values. Our oasis must then be at least 10 billion light-years across because the physical laws seem the same everywhere we can observe. But the 'desert' beyond it would come into view in the remote future, when, maybe 10^{12} years or more from now, light from the edges of our domain has had time to reach us. This time delay is, to be sure, an impediment to empirical tests but such statements, though plainly not yet testable, are certainly not vacuous: they are akin to the conjectures of early explorers about what lurked beyond the frontiers of the then-known world, or Barrow and Tipler's speculation that 'the universe will recollapse 10^{15} years from now'.

The other universes may even be completely disjoint from ours, so that they will never come within the horizon of our remotest descendants. We may be part of an infinite and eternal multiverse within which new domains 'sprout' into universes whose horizons never overlap – ironically, the steady-state concept can then be revived, but applied to the multiverse rather than its constituent universes. New universes could be triggered by the big crunch (if our own universe eventually recollapses), or even within black holes. Alex Vilenkin prefers to envisage the universes as 'nucleating'

separately and spontaneously, each thereafter inflating into its own separate space.

What these speculative viewpoints have in common is that all envisage our big bang as one event in a grander structure; the entire history of our universe is just an episode in the infinite multiverse. Earlier chapters have given a flavour of what other universes might be like.

The multiverse could encompass all possible values of fundamental constants, as well as universes that follow life cycles of very different durations: some, like ours, may expand for much more than 10 billion years; others may be 'stillborn' because they recollapse after a brief existence, or because the physical laws governing them aren't rich enough to permit complex consequences. In some there could be no gravity: or gravity could be overwhelmed by the repulsive effect of a cosmological constant (λ), as it would have been during the early inflation phase of our own universe. In others, gravity could be so strong that it crushes anything large enough to evolve into a complex organism. Some could always be so dense that everything stayed close to equilibrium, with the same temperature everywhere. Some could even have different numbers of dimensions from our own.

Even a universe that was, like ours, long-lived and stable, could contain just inert particles of dark matter, either because the physics precludes ordinary atoms from ever existing, or because atoms all annihilate with exactly equal numbers of antiatoms. Even if protons and hydrogen atoms exist, the nuclear forces may not be strong enough to hold the nuclei of heavy atoms together: there would then be no periodic table, and no chemistry.

SMOLIN'S SPECULATION

Natural selection of 'favoured' universes seems the stuff of science fiction. However the American cosmologist Lee Smolin conjectures that the multiverse could display the effects of heredity and selection. When a black hole collapses, he speculates that another universe sprouts from its interior, creating a new expanse of space and time disjoint from our own. Small universes, in which there was too little space or time to form many black holes, would not leave many

progeny. Nor, he argues, would even a large universe if its physics prohibited stars from ever terminating as black holes.

Smolin then adds a new twist – the physical laws governing the daughter universe may differ from those in its parent, *but only slightly*. Since the number of progeny a universe has depends on the laws prevailing within it, there is a selection pressure. Many generations, or many iterations, would lead to a 'takeover' by the universes that generate the most numerous progeny. These would be the ones governed by laws that allowed the largest number of black holes to form.

The mechanisms that might 'imprint' the basic laws and constants in a new universe are obviously far beyond anything that we understand. But Smolin's idea, though far out on the speculative fringe, has the virtue of making a testable prediction: if our own universe is an outcome of such 'selection', it should be maximally efficient at spawning new universes – in other words, black holes must form more readily in it than they would in a different universe. This prediction can be addressed and checked by astronomers, using observations and physical ideas that are relatively conventional.

If we imagine tinkering with our universe by changing the electron mass, the strength of gravity and other variables, then any change, any 'turning of the knobs' from their actual setting, should, if Smolin is right, either make the universe smaller or reduce the propensity of stars to terminate as black holes. So to test his conjecture we need to know, for instance, how an adjustment of the constants would affect the chance that a heavy star ends up as a black hole, rather than throwing off so much mass during its lifetime that it can end up as a white dwarf (below Chandrasekhar's limiting mass, described in Chapter 4) or a neutron star. We also need to know whether the same adjustment would alter the processes of star formation, perhaps tilting the balance between high-mass stars (which might end as black holes) and low-mass stars (which will end as white dwarfs).

Star formation is something that astrophysicists will have to understand better before they can model the 'ecology' and recycling processes within even our own Milky Way, and before they can interpret the pictures of remote newly forming galaxies that the Space Telescope is giving us. Protostars are now condensing within dense clouds of gas and dust in, for example, the Orion Nebula, only 1500 light-years away. The detailed flow patterns that lead to protostars are hard to compute, but plainly depend on complicated

interactions between gravity and pressure (which depends on the gas temperature); magnetic fields are also important; so is dust mixed with the gas, which emits infrared radiation and helps the clouds to cool and reduce their pressure. But how would stars have formed in a young galaxy at an earlier cosmic epoch? There would then have been no chemical elements other than hydrogen and helium (and therefore nothing that could make dust); probably no magnetic fields; and the primordial radiation, now at 2.7 degrees, would have been warmer, and might stop the clouds getting as cold as they are today.

Astrophysicists are still flummoxed about these questions, and this lack of understanding impedes all attempts to understand how galaxies evolve. It also impedes any test of Smolin's speculations. We can be confident that many black holes are indeed forming via stellar deaths or via the accumulation of huge masses in galactic centres. Our universe is therefore certainly not 'sterile' by Smolin's criterion. But, as to whether it is anywhere near 'optimal' for black-hole formation, we must suspend judgement.

Suppose, for instance, that a hypothetical universe was like ours except that the electric repulsive force within nuclei was slightly stronger, so they didn't fuse together to release energy and build up the elements of the periodic table. Stars would then evolve much more quickly to their final state. Low-mass stars would still become white dwarfs. But heavy stars would be more likely than in our actual universe to become black holes, because there would be no chance that nuclear energy could blow off enough material to bring them below the Chandrasekhar limit before they died. At first sight, this seems a straight disproof of Smolin. However, his conjecture could be salvaged if stars formed so differently in a medium of pure hydrogen that none were massive enough to become black holes and create progeny.

Quite apart from its relevance to other universes, astrophysicists would like to settle this issue because the first stars that formed in our expanding universe would have been made of hydrogen and helium; if these were indeed mainly of low mass, they would be candidates for baryonic dark matter (see Chapter 6). To elucidate it requires a better understanding of 'conventional' astronomical processes – an understanding that I hope we'll have within a few years – rather than exotic new concepts.²

Wheeler and Guth have speculated about artificial creation of small black holes by implosion mechanisms, which could be the seeds of new universes. Of course, anthropic arguments are superfluous if we

live in a purposely created 'daughter universe'; Paley's old 'arguments from design' might then make a comeback.

ASSESSING ANTHROPIC ARGUMENTS

Where do anthropic arguments stand today? When they were first widely discussed, in the 1970s, many people were dismissive. Such arguments plainly didn't offer scientific explanations in the proper sense: at best they seemed a stop-gap, allaying our curiosity about phenomena for which genuine physical explanations were being sought, but had yet to be found. The world would, for instance, be very different if the nuclear or electric forces were somewhat altered, but one still hopes eventually to relate these forces via some mathematical formula just as, more than a century ago, James Clerk Maxwell related electrical and magnetic forces and the speed of light. Likewise, Salam and Weinberg took a further step in incorporating weak neutrino forces into an integrated scheme. By extension, a more comprehensive theory may eventually unify all the fundamental forces.

Rather than having to be measured experimentally, the physical forces and constants may one day be mathematically calculable – just as a circle's circumference can be calculated from its diameter, though not quite so easily. Weinberg says, 'I certainly wouldn't give up attempts to make the anthropic principle unnecessary by finding a theoretical basis for the value of all the constants. It's worth trying, and we have to assume that we shall succeed, otherwise we surely shall fail.' So it would be a pity if theoretical physicists took anthropic ideas too seriously, as it might diminish their motivation for seeking unified theories!

The physicist Heinz Pagels was especially dismissive:³

Physicists and cosmologists who appeal to anthropic reasoning seem to me to be gratuitously abandoning the successful programme of conventional physical science of understanding the quantitative properties of our universe on the basis of universal physical laws. Perhaps their exasperation and frustration ... has gotten the better of them. The influence of the anthropic principle on the development of contemporary cosmological models has been sterile. It has explained nothing, and it has even had a

negative influence, as evidenced by the fact that the values of certain constants ... for which anthropic reasoning was once invoked as an explanation can now be explained by new physical laws ... I would opt for rejecting the anthropic principle as needless clutter in the conceptual repertoire of science.

This goes too far in disparaging all anthropic reasoning. After all, in its weak form – the realisation that our existence, as observers, in itself has implications for what our cosmic environment must be like – little more is involved than the routine attitude of an observer who allows for the limitations of his search techniques and equipment. Saying that our cosmic environment is 'well tuned' for our sort of life is not just a tautology. It yields genuine understanding: Dicke's explanation of Dirac's alleged 'coincidences' (see Chapter 14) is an example. There is nothing very controversial about the claim that another universe could be 'maladjusted' for life – for instance, its physical constants might preclude any chemical elements other than hydrogen. Universes that stay close to thermal equilibrium, which exist for too short a time, or (more radically) have only two spatial dimensions, would surely be less propitious than ours for complex evolution of any kind at all.

SCOPE AND LIMITS OF A 'FINAL THEORY'

The status and scope of anthropic arguments, in the long run, will depend on the character of the (still quite unknown) physical laws at the very deepest level. Weinberg hopes that a 'final theory' exists, and that we may some day discover it. Such a theory may uniquely fix the basic laws governing our universe: they could all be computed from some fundamental equations.

If the physical constants were indeed uniquely fixed by a 'final theory', it would then be a brute fact that these universal numbers happened to lie in the narrowly restricted range that permitted complexity and consciousness to emerge. The potentialities implicit in the fundamental equations – all the intricate structures in our universe – may astonish us, but this reaction would be akin to the surprise mathematicians must sometimes feel when vastly elaborate deductions follow from innocuous-looking axioms or postulates.

Consider, for instance, the Mandelbrot set. The instructions for drawing this astonishing pattern can be written in just a few lines, but it discloses layer upon layer of varied structure however much we magnify it. Anyone who has learned coordinate geometry (where the coordinates x and y denote distances along the two axes) can visualise that $x^2 + y^2 < 1$ is the inside of a circle; a real superintelligence would be needed immediately to visualise the shape of the Mandelbrot set just from reading its 'formula'! Similarly, latent in the succinct equations of a 'final theory' could be everything that has emerged in our universe, as it cooled from the initial big bang to the diffuse low-energy world we inhabit.

But the quest for a unique theory may be doomed to fail: the particles and forces in our universe could be inherently arbitrary. The way a metal bar responds to pressure or bending is important to engineers, and there are detailed tables giving the 'elastic constants' for different materials. But, to the physicist, the bulk properties of solids are *secondary* quantities determined by the underlying atomic structure. Likewise, what we call the fundamental constants – the numbers that matter to physicists – may be *secondary consequences* of the 'final theory', rather than direct manifestations of its deepest and most fundamental level. The multiverse may be governed by some unified theory, but each universe may cool down in a fashion that has 'accidental' features, ending up governed by different laws (and with different physical constants) from other members of the ensemble.

It could turn out that some constants are genuinely universal, even though others are not. Maybe those governing the microworld are unique throughout the multiverse (or at least in all universes with three spatial dimensions), and are therefore 'brute facts', but the constants important for cosmology differ from one universe to the next. Universes could then have distinctive values of ω (which fixes the density and how long their 'cycle' lasts if they recollapse), λ (which measures the energy latent in empty space) and Q (which measures how smooth a universe is, and so determines what structures emerge in it).

If some physical constants are arbitrary, then anthropic arguments can properly be deployed to account for the values they actually take in our universe – indeed this would be *the only way* to understand why they didn't have values that were very different.

Any final theory is still such a distant goal that we cannot guess which features (if any) are unique throughout the multiverse, and

which are ‘accidents’ of the way our universe cooled down. We therefore cannot yet assess how far our universe can be explained ‘anthropically’. However, just as Smolin’s speculative conjectures about natural selection of universes make ‘predictions’ that can be verified or refuted by quite conventional astrophysicists, so we may be able to fathom the nature of the final theory even before we know its specific details.

Suppose that the important physical constants take different values in other universes. Their measured values may not be typical of the entire multiverse: our universe must, as we have seen, have been special and atypical to permit our existence. But it ought not to be *unduly* special: this realisation allows us to guess which constants are ‘accidents’, and which are determined by the laws of a ‘final theory’ that prevail throughout the multiverse.⁴

Consider, for instance, the cosmological constant λ , a repulsive force that accelerates the cosmic expansion. Will the ‘final theory’ offer some deep reason why this has to be exactly zero? Or is its value an ‘accident’? We just don’t know. Anthropic constraints rule out very large values of λ because an unduly fierce cosmic repulsion would prevent galaxies from forming. Very large *negative* values would also be excluded, because the universe would then recollapse after a cycle too short to have allowed stars to evolve.

λ in our own universe may not be zero: as described in Chapter 8, the age estimates of stars could be more readily reconciled with a short Hubble time if the cosmic expansion were accelerating rather than slowing down. The λ that is favoured (tentatively) is about ten times lower than the anthropically allowed maximum – no galaxies could form in a universe where λ was more than ten times larger than the value some observers actually prefer. Thus λ may not be enormously less than its allowed maximum – our universe would not, in respect of λ , have been ‘tuned’ much more precisely than our presence requires.

On the other hand, if improved observations were to reveal that λ had *no* discernible effect, implying that it was perhaps 1000 times smaller than anthropic constraints required, then our universe would seem even more special, in respect of λ , than it need be. We might then suspect that the ‘final theory’ mandated an exactly zero λ throughout the multiverse.

Even those theorists who hope that most constants will be uniquely

pinned down are less optimistic about explaining λ . Steven Weinberg, for instance, suspects that λ may be the only number that is anthropically selected rather than being directly fixed by the final theory.

By applying similar arguments to other constants, we can infer what features are unique and uniform throughout the multiverse, and what variety the separate universes can display. Can *all* the microphysical constants and particle masses be different in other universes? And what about gravity? It could even – as Smolin conjectures – be natural selection, not a mere accident, that our universe (that is, the part of space-time we can observe) has the particular values of the physical constants that we measure.

OUR UNIVERSE AND OTHERS

Most universes would be less propitious for complex evolution than ours, but not necessarily all. We cannot conceive what structures might emerge in the distant future of our universe. Still less, therefore, can we envisage what might happen in a universe where there were more forces than the four we are familiar with, or where the number of dimensions was larger. Our universe could be ‘impoverished’ compared with some others, which could harbour vastly richer structures, and potentialities beyond our imaginings.

By mapping and exploring our universe, using all the techniques of astronomy, we are coming to understand – to a degree that even a decade ago would have seemed astonishing – our cosmic habitat, the laws that govern it, and how it evolved from its formative initial instants. But, even more remarkably, we have intimations of other universes, and can perhaps deduce something about them. We can infer the scope and limits of a final theory even if we are still far from reaching it – even if, indeed, it eludes our intellectual grasp for ever.

Chandrasekhar thought as long and intensely about our universe as anyone since Einstein. In one of his last lectures, he concluded:

The pursuit of science has often been compared to the scaling of mountains, high and not so high. But who amongst us can hope, even in imagination, to scale the Everest and reach its summit

when the sky is blue and the air is still, and in the stillness of the air survey the entire Himalayan range in the dazzling white of the snow stretching to infinity? None of us can hope for a comparable vision of nature and of the universe around us. But there is nothing mean or lowly in standing in the valley below and awaiting the Sun to rise over Kinchinjunga.

NOTES

- 1 The Oxford cosmologist E.A. Milne postulated, as a 'cosmological principle', that the large-scale universe (about which hardly anything was then known) was uniform enough to make the simple theoretical models applicable. Bondi and Gold went further, basing their steady-state theory on a so-called 'perfect cosmological principle' – that the universe was the same *at all times* as well as at all places. We quite quickly learned that the latter was false (see Chapters 2 and 3). In contrast, Milne's 'cosmological principle' has been vindicated more accurately than he would have dared to hope, for the part of the universe within our present horizon, Mach's principle, described in Chapter 12, has been a more fruitful concept than other 'principles', though perhaps only because it has been interpreted in so many different ways.
- 2 Before Smolin's idea (first proposed in an article in the journal *Classical and Quantum Gravity*, vol. 9, p173, (1992)) can be developed further, two issues need clearer formulation. First, does the selection process favour universes that generate black holes at the *maximum rate* (and maximum efficiency), or is the *total number produced by a universe over its lifetime* more relevant? The latter criterion would depend, more than anything else, on how big and long-lived a universe was. The second point concerns the anthropic constraint. Suppose it turned out that black holes were most readily produced in a universe where complex life could never evolve. For instance, stars might more readily form black holes if there were no nuclear energy sources, and no stable elements other than hydrogen. But there would then be no chemistry, and perhaps no complexity. Should that be so, one might reject Smolin's ideas entirely. However one could then test a modified prediction: that our universe produces more black holes than any other *in which conditions are equally propitious for complex evolution*.
- 3 This quotation is from p359 of Heinz Pagels' book *Perfect Symmetry* (Michael Joseph, 1985).
- 4 This resembles the line of argument that could have been used against Boltzmann's hypothesis that our universe was a fluctuation away from equilibrium (see Chapter 13) – our existence requires an improbable fluctuation, but the actual universe is vastly larger and constitutes an immensely more improbable fluctuation than our existence demands.

