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Fine-Tuning in Living Systems

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Abstract: We give an overview of an interdisciplinary meeting held last year in Windsor to discuss the evidence for fine-tuning in living systems. Many of the papers presented there appear in this volume, so this serves as an introduction to them. We also briefly review a meeting held the previous year in Cambridge to assess the evidence for fine-tuning in physics and cosmology.

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Introduction

The papers in this volume result from a special workshop held at St George's House, Windsor Castle, during 1st–3rd September 2002 on the topic of "Fine Tuning in Living Systems". This was the second in a series of workshops, hosted by Cambridge University and Queen Mary, University of London, to assess whether so-called 'anthropic' arguments are necessary in order to explain the emergence of life in the universe. Is this emergence inevitable or does it require various forms of fine-tuning (i.e. special physical, biological and astronomical initial conditions)? The meetings were sponsored by the Templeton Foundation out of funds awarded to Robert Crittenden, Martin Rees and Neil Turok at Cambridge and Bernard Carr at London for a project entitled "Fundamental Physics, Cosmology and the Problem of our Existence". This is part of Templeton's initiative to support a research programme examining the question "Is there evidence of universal purpose in the cosmos?"

The first meeting, summarized in more detail below, took place in August 2001 in Cambridge and focused on "Fine Tuning in Physics and Cosmology". Cosmologists are used to addressing the problem of whether the present state of the universe is primarily due to special initial conditions or to generic features of gravitational evolution. Ideally, one seeks explanations which do not require special choices of the universe's initial state and are therefore not finely tuned in any way but such a quest is only partially successful. Whilst modern theories like 'inflation' are able to provide natural explanations for some features of the universe which were once thought to require special initial conditions, other apparent fine-tunings remain. For example, the cosmological constant must be tuned to 120 decimal places and there are also many mysterious 'coincidences' involving the physical constants that appear to be necessary for life, or any form of information processing, to exist.

One issue examined at Cambridge was whether current ideas of fundamental physics (e.g. superstring theory) would ultimately yield unique values for all the physical constants or whether the basic physics governing our universe had 'contingent' aspects – in the sense that the mass of the electron, the length of the periodic table, the strength of chemical bonds etc. could have been different. The question is still open, though there is a strengthening view that variety is more likely than uniqueness. Moreover, most of the 'counterfactual' universes – governed by different physics – would fail to provide even the most generic necessary conditions for life: thermodynamic disequilibrium, the presence of matter rather than pure radiation, some atoms other than hydrogen, enough time for complex chemical reactions to occur and so forth.

In the Windsor meeting we hoped to go one stage further and examine *biological* aspects of the anthropic principle. In this context, the issue of fine-tuning is not so explicit. However, biology also aims to provide an explanation for particular sorts of organised complexity that does not simply appeal to ready-made organisms. Is natural selection sufficient to explain this complexity, as some have suggested, or are additional considerations required? Would a small change in the course of natural history have brought about a completely different world, as some have also suggested, or is the average behaviour robust and insensitive, like that of many other chaotic systems with which we are familiar.

We also wished to address the question of whether life requires 'fine-tuning' in its chemical properties and whether we can specify sufficient rather than merely necessary conditions for life. To answer such questions, we need to know which features of life as we know it here on Earth are contingent and which are inevitable consequences of chemical constraints. All life on Earth uses a specific DNA-based inheritance mechanism: is this mechanism uniquely efficient or could there be others? The combinatorial possibilities of protein chemistry would seem to allow immensely more variety than

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actually occurs, so is there something special about the actual proteins of which we are made?

If the chemistry of life is indeed very special, then the basic physics of our universe might need to be even more fine-tuned than previously suspected – only a tiny 'tweaking' of the physical constants might be sufficient to prevent the crucial molecules from existing. On the other hand, if there were many alternative chemistries for life, it would be likely that, even if the physical constants were slightly 'tweaked', there would also be many (perhaps different) ways it could form and evolve. In the latter case, biology might not impose any 'anthropic' constraints on the physical world beyond those already recognised by astronomers – namely that there must be stable conditions in the temperature range allowing complex chemistry, a periodic table etc.

Another important issue concerns the environment in which our form of life orginated and whether alternative ones (be they planet-based, chemistry-based, physics-based, AI-based or complexity-based) are viable. Recently the growth of research into 'life' in computers has provided a new route into the study of the necessary and sufficient conditions for complex self-organisation. This offers novel ways to evaluate the specialness and sensitivity of the environments needed to initiate life. It also emphasizes that tackling the problem of life is an essentially *interdisciplinary* task, requiring input from physicists, mathematicians and computer scientists, as well as biologists.

All these issues are crucial to exobiology because the likelihood of life arising elsewhere in the universe hinges upon whether special conditions are needed and its possible forms depend upon whether there are alternatives to simple carbon-based organisms. The detection of even the most rudimentary lifeforms (of independent origin) beyond the Earth would clarify the issue of whether there is something very special about these specific molecules, or whether alien life (even if still carbon-based) could utilise quite different chemistry. Indeed, scientists trying to understand the origin of life on Earth need to ask whether it was just a fluke that one particular molecule triumphed. For this reason, it seems most appropriate that many of the talks are being published in this issue of the "International Journal of Astrobiology".

A Summary of the Cambridge Meeting

The existence of life (or at least our particular form of it) requires the formation of a hierarchy of structures – planets, stars and galaxies – and several speakers at Cambridge highlighted how each of these seems to require rather special conditions. As regards planets, the discovery of about a hundred extra-solar planetary systems in recent years suggests that our solar system is far from unique. However, most of these are very different from ours in that they have Jupiter-mass planets in (often eccentric) orbits which would preclude the existence of an Earth-like planet in an orbit where liquid water could exist. Moreover, as Carl Murray emphasized, the Earth seems to have been fortunate in having the Moon to serve as a climate regulator. If the Moon were absent or much smaller, the spin axis of the Earth would change chaotically – leading to catastrophic weather variations that could exclude the emergence of life.

As regards stars, Virginia Trimble drew attention to a famous fine-tuning in nuclear physics which involves the generation of carbon (another prerequisite for our form of life) in the helium-burning phase of red giant stars. Carbon synthesis occurs via a reaction in which two alpha particles unite to form a beryllium nucleus that then combines with another alpha particle to form carbon. However, as the late Fred Hoyle first pointed out, the beryllium would decay before interacting with another alpha particle were it not for the existence of a remarkably finely-tuned resonance in this interaction. Heinz Oberhummer has studied this resonance in detail and showed how the amount of oxygen and carbon produced in red giant stars varies with the strength and range of the nucleon interactions. His work indicates that these must be tuned to at least 0.5% if one is to produce both these elements to the extent required for life.

For stars to exist at all, the universe must allow galaxies to arise and galaxy formation depends on various cosmological parameters, such as the density of the matter in the universe, the amplitude of the initial density fluctuations, the photon-to-baryon ratio and the cosmological constant (an extra term Einstein introduced into his field equations for cosmological reasons and which may cause the universe to accelerate). As Martin Rees emphasized, even small deviations from the observed values of such parameters would exclude the formation of structures like galaxies and their subsequent fragmentation into stars. Bernard Carr and Anthony Aquirre discussed several other cosmological constraints which involve fine-tunings between the strengths of the various interactions.

The Cambridge meeting concluded that there is no doubt that the 'biophilic' character of our universe depends on apparent fine-tuning of various key parameters in physics and cosmology. As Craig Hogan emphasized, even slight changes in some of these numbers would lead to a universe that would be 'sterile' in that it could not fulfil even the most basic requirements for life. However, there was less of a consensus on how this should be interpreted. One issue, raised by Brandon Carter and particularly relevant to astrobiology, concerns what qualifies as an 'observer'. Other issues were the relevance of consciousness, discussed by Don Page, and the epistemological status of the anthropic principle, discussed by Bill Stoeger.

The key question is whether some fundamental theory will eventually determine all the constants uniquely or whether some of them are 'cosmic environmental accidents' with their values being determined by phase transitions during the cooling that occurred after the big bang. In the first case, the fine-tunings must just be regarded as coincidental. In the second case, there may be room to explore more interesting possibilities. In particular, there could be many big bangs and not just one. Indeed many theories of the early universe lead naturally to the inference of a 'multiverse'. If there are many big bangs, and if they cool down in individualistic ways

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(a distinctive extra requirement), ending up with different ingredients and governed by different low energy physics, then the apparent fine-tuning in our universe can be explained as a kind of observational selection effect: 'biophilic' universes may be a tiny subset of the ensemble but we should not be surprised to find ourselves in one of them.

The particle physicists at the Cambridge meeting expressed various views on how likely such tunings are to result from some fundamental theory. As John Donoghue emphasized, 'fine-tuning' arises in different contexts in particle physics and some of these – such as the smallness of the strong charge-parity (CP) violation – may have no anthropic relevance. However, at least some physical parameters would appear to be contingent. For example, Frank Wilczek, who first posited the existence of a light particle called the 'axion' in order to explain the lack of CP violation in strong interactions, pointed out that the density of these particles would now be much larger than the baryonic density unless an angle associated with the initial conditions of the axion field were tiny. Such a large axion density would be incompatible with the formation of galaxies and so is anthropically disallowed. The only reasonable explanation for axions and baryons having comparable densities is to invoke an early inflationary phase, in which the universe expanded exponentially fast due to the effect of a cosmological constant. The axion angle would then have different values in different places and we would necessarily live in a region where this angle was small.

Most physicists would probably prefer the constants to be determined by more conventional physics. So how likely is this? The current favourite candidate for a fundamental theory is the string model. This posits that space-time is either 10-dimensional (superstring theory) or 11-dimensional (M-theory), with four-dimensional physics emerging from the compactification of the extra dimensions. Unlike the Standard Model of particle physics, which does not incorporate gravity and contains several dozen free parameters, M-theory should in principle predict all the fundamental constants, as stressed by Malcolm Perry. However, the situation is not clear-cut since M-theory allows more than one vacuum state and perhaps a huge number: the constants may be uniquely determined within each vacuum but could be different across the states themselves.

A new twist arises if the (so-called) constants vary in time even in our universe. This is expected in many unification theories since the constants should be related to the size of the compact internal dimensions, which would be expected to change during at least part of the universe's history. This theme was taken further by John Barrow, who is part of a team that recently claim to have found evidence for a variation in the fine structure constant of about seven parts in a million. This comes from studying spectral lines in gas so far away that it is being viewed as it was several billion years ago. If the fine structure constant does vary, then this could make atom-based life impossible unless the universe is nearly 'flat' and the cosmological curvature is very tiny.

One reason many cosmologists now take the multiverse seriously is that the 'many worlds' interpretation of quantum mechanics seems to be the only sensible context in which to discuss 'quantum cosmology' – the branch of physics that describes what happened near the big bang. As emphasized by Jim Hartle, quantum theory allows many mutually incompatible histories but it only makes sense to consider the initial conditions that led to the classical behaviour that we observe today. (With complete ignorance of the initial conditions, the quantum fluctuations could be arbitrarily large and the emergence of a classical world would be impossible.) Within this restriction, quantum cosmology allows many different worlds or 'branches', all with different values of the constants.

Nevertheless, the cosmologists present had widely different views on how the different worlds might arise. Andrei Linde and Alex Vilenkin invoked 'eternal' inflation, in which the universe is eternally self-reproducing. This version of inflation predicts that there may be an infinite number of exponentially large domains, all with different laws of low-energy physics. On the other hand, Stephen Hawking objected to the eternal-inflation model on the grounds that it extends to the infinite past and thus violates his 'no boundary' proposal for the origin of the universe. This proposal requires that the universe start at a finite time and it avoids the initial singularity by requiring time to become imaginary there (i.e. the metric starts off Euclidean rather than Lorentzian). Although such models are 'closed', Neil Turok argued that 'open' inflationary models are equally plausible.

The conference also focused on more radical deviations from standard physics. Richard Gott speculated on how the existence of closed timelike curves in general relativity could allow the universe to create itself. Max Tegmark discussed anthropic constraints on the dimensionality of space and time: three spatial dimensions are required for the stability of planetary orbits and more than one time dimension would destroy causality. He also raised the issue of whether it is sufficient to consider universes with different values of the coupling constants, or whether one should contemplate universes with different physical laws or even different mathematical foundations. Lee Smolin invoked a form of natural selection, in which the formation of black holes generates new universes with slightly mutated constants. In this way, after many generations, the parameter distribution will peak around those values for which black-hole formation is maximized. This proposal is ultra-speculative, since we have no well-motivated theory for the 'heredity' mechanism. However, it has the virtue of being testable since one can calculate how many black holes would form if the parameters were different.

A Summary of the Windsor Meeting

The Windsor workshop was intended to be an interdisciplinary meeting, involving biologists, physicists, astronomers, mathematicans, cognitive scientists and evolutionary psychologists. It was divided into five sessions, each focusing on a specific theme and comprising four talks, followed

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by a general discussion. The successive themes were: (1) the evolution of biological fine-tuning; (2) chemical and physical aspects of life; (3) exobiology and astronomy; (4) artifical life and self-organization; (5) special features of human life. Since this was an interdisciplinary meeting, speakers avoided being too technical. However, about half the talks – mainly those with greater relevance to astrobiology – have been expanded into the papers presented in this volume. In order to set these into the broader context of the meeting, we now give a brief overview of all the talks.

The evolution of biological fine-tuning

The first session focused on the evolution of biological fine-tuning and considered the necessary and sufficient conditions life. Does natural selection suffice to explain biological fine-tuning or is evolution sensitive to historical accidents? How special were the initial conditions needed to evolve life and were there independent evolutionary histories on Earth? None of the talks in this session appear as papers – possibly because the biological significance of the term 'fine-tuning' was too vague (even at the end of the workshop) for the contributors to want to put their thoughts in writing. Nevertheless, the ideas covered are very relevant to the overall theme of the meeting.

Stanislav Leibler spoke on "Robustness versus fine-tuning in biological networks". He gave examples of recent studies of natural and artificial genetic and biochemical networks. In particular, he described some underlying principles uncovered in these networks, such as robustness, precision and noise-resistance.

Pier Luisi discussed "Determinism and contingency in the formation of specific macromolecular sequences". Following the pioneering work of Stanley Miller, prebiotic chemists have been able to make a rich chart of low molecular weight compounds produced under prebiotic conditions. However, even if chemists could be given all known low molecular weight compounds, they would be unable to make life in the laboratory. The bottleneck of the transition to life from inanimate matter lies in macromolecular chemistry. The problem is to explain not just the origin of random polymers of polypeptides and/or nucleic acids (although we cannot even do that) but also the origin of co-polymeric chains having specific sequences capable of chemical recognition, catalysis and self-replication. It should be stressed that the lengths of polypeptides or polynucleotides are only a tiny fraction of what is theoretically possible. These chains have been selected not because they are thermodynamically special (they are no more stable than their billions of constituent isomers) but because they are the products of contingency and evolution, the environmental conditions also being due to contingency. This contrasts with the view that life is an inevitable, deterministically directed series of events. Our lack of understanding of how these chains were selected is the main problem in reproducing cellular life in the laboratory and removing this stumbling block may determine the best research strategy. Some of these ideas are presented in Phil.Trans.R.Soc.Lond. A (2003) 361, 1141–1147.

Jotun Hein described "The invasion of evolution into functional biology". We are presently experiencing an explosion of biological knowledge but it is uncertain to what extent this will lead to a complete understanding of life. If larger biological systems (cells, tissues, organs, organisms) can be fully modelled, some would regard this as 'the end of biology'. One startling feature of present research is the recent invasion of evolutionary biology into structural biology. This is surprising in view of the traditional indifference to evolution from medical and molecular biology. The invasion has manifested itself at three different levels. (1) There is the fundamental unity of life-forms on Earth, these having a common architecture and metabolizing a small subset of possible molecules. But how necessary is this and how different could lifeforms be elsewhere? This challenging problem could be tackled during the coming decade from three areas of research: astrobiology, the design of self-replicating systems, and the modification of the simplest autotrophic systems. (2) There is the comparison *between* species used to transfer knowledge obtainable in one organism to another, called homology modelling. This can be applied to a variety of problems and a refined version of this obtains information by observing evolutionary paths. This has mainly been applied to protein structure, RNA structure and genome annotation but it could potentially be applied in a much broader context. The basic idea is that the evolution of sequences is dependent on their structure and function, so the latter can be inferred from the former. (3) There is evolution *within* species: Population Genetic Variation and Functional Variants. This can be viewed as short-term molecular evolution, but has a series of specific characteristics. Being members of a population, it is suddenly possible to make probability statements about relationships of individuals and use genetic variation-phenotype correlations to identify genes responsible for particular characteristics. But there are fundamental constraints on how far this can be used, stemming from the underlying process generating genetic variation, and the present explosion in variation will bring this kind of analysis to the forefront. A key feature of these studies – often traced back to what is called Coalescent Theory – is the interpretation of data via the genealogy relating sequences or individuals. This raises various interesting questions: How many individuals in ancestral populations contributed to our present population? Given a set of sequences from a population with known evolutionary parameters, how many recombinations occurred in their common evolutionary history? How many generations do we have to go back in order to find the ancestors that did not contribute to a particular individual's genetic make-up? Addressing these questions requires a joint effort from statisticians, mathematicians and bioscientists.

Richard Durbin discussed "Discreteness in life and mechanism design". The physical world is continuous at biological scales, but life is to a great extent based on discrete units that can interact in essentially arbitrary ways. Examples include base-pairs, protein molecules, and patterning domains in nerve cells, individuals and species. He claimed that this is an

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evolutionary result that frees life from fine-tuning constraints at lower scales and thus a fundamental property of life. It allows behaviours to arise from interactive adaptation, as in game theory, and these can be very rich. Mechanism design is a field of economics that is essentially reverse game theory: the design of 'rule and reward' systems to achieve optimal outcomes when independent agents are interacting, e.g. new auction systems. Perhaps life is limited by the mechanisms that can be designed by evolution from what it has at hand and its ability to create new units.

Chemical and physical aspects of life

The second session focused on the origin and persistence of life. How does one define life, how did it start and what are its chemical and physical characteristics? What are the basic rules and principles that govern its development?

Graham Cairns-Smith, whose paper appears in this issue, spoke on ''Early evolution and the unity of biochemistry''. The central features of biochemistry, common to all free life-forms on Earth, are so complex and well organized that they look as if they were products of evolution through natural selection. However, at some stage (before the last common ancestor) this evolution was effectively frozen. By looking at the structure of the biochemical pathways, he suggests in general terms how this happened. There are hints as to which of the 'molecules of life' came first and intimations of a different genetic system in our ancestry. He concludes that the origin of primitive genes and replicating structures may be crystal growth in inorganic molecules rather than organic chemistry.

Harold Morowitz's talk was entitled ''From the periodic table of the elements to the chart of intermediary metabolism''. The Pauli Exclusion Principle is a selection rule that leads to the emergence of chemistry (the periodic table and covalent bonding) from quantum mechanics. He conjectured about the necessity of another rule or set of rules to go from the periodic table to the chart of intermediary metabolism. Assuming that the earliest metabolism was that of chemo-autotrophs, his approach is to construct the entire autotrophic chart and seek regularities. These include universal inputs of nitrogen and sulphur and chemiosmotic and substrate-level energy processing. Other rules, such as conservation of chirality, are associated with pyridoxal phosphate. The ubiquity of tetrapyrroles in oxidation reduction reactions is another example. The goal is a set of laws of biochemistry not derivable from physics as envisioned by Bohr and Elsasser.

Eric Chaisson described ''An energetic approach to complexity writ large'' and his paper appears here under the title ''Unifying concept for astrobiology''. He outlines an energetics approach which merges physical, biological and cultural evolution into a unified whole. Topics covered include the expanding cosmos, chance and necessity, energy flow, non-equilibrium thermodynamics, life and complexity. By introducing a new quantitative measure of complexity – normalized energy flow – he shows how life and the hierarchy of complex structures in the universe depend upon the cosmic expansion and associated energy flows. He thereby places astrobiology in a broader cosmological setting. This program introduces no new science but just tries to explain what we know about Nature with what we have at hand.

Geoffrey West's talk was entitled ''Towards a quantitative unifying theory of biological structure, function and organization''. Life is the most complex physical phenomenon in the universe, manifesting an extraordinary diversity of form and function over an enormous range of scales, from the largest animals and plants to the smallest microbes and subcellular units. Yet many of its most fundamental and complex phenomena scale with size in a surprisingly simple fashion. For example, metabolic rate (the power needed to sustain life) scales as the 3/4-power of mass over 27 orders of magnitude, ranging from molecular and intra-cellular levels up through the smallest unicellular bacteria to the largest multicellular organisms. Similarly, time-scales (such as life-span and inverse growth-rate) and length-scales (such as genome length and mitochondria interspacing) scale with exponents which are typically integral multiples of 1/4. The universality and simplicity of these scaling relationships strongly suggest that fundamental universal principles underly much of the generic structure, function and organisation of biological phenomena. He proposes that these principles are based on the observation that life at all scales is sustained, and ultimately constrained, by space-filling, fractal-like hierarchical branching networks (both real and virtual) which are optimised by the forces of natural selection. Such principles can explain universal quarter-power scaling and lead to a general quantitative understanding of many diverse biological systems. These include the cardiovascular, respiratory and plant vascular systems, growth, aging and mortality, minimum and maximum sizes of mammals, mitochondrial density, ecosystems and the nature of evolution, including thermodynamic considerations and the concept of a universal molecular clock.

Exobiology and astronomy

The third session focused on life in the universe and emphasized the link between biology and astronomy. We heard first about searches for life in the Solar System and then about the prospects of finding intelligent life in the Galaxy (the goal of the SETI project). This session also highlighted the importance of the rapidly advancing field of astrobiology.

Freeman Dyson talked about ''Looking for life in unlikely places'', arguing that planets may not be the best places to seek it. His paper is included here under the same title and proposes a new method to search for extraterrestrial life adapted to cold environments far from the Sun. To keep warm, any such life-form must be like a sunflower, growing lenses or mirrors to focus sunlight onto its vital parts. Since any light reflected or re-radiated will be focused by the lenses or mirrors into a narrow beam pointing back towards the Sun, one could search for such life-forms by scanning the sky with telescopes pointing directly away from the Sun and looking for bright patches against a dark background. Sunflowers that adapted successfully to a vacuum environment

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could spread widely over small objects with icy surfaces in the outer regions of the Solar System. The further away the creatures are from the Sun, the more powerful this retro-reflection search method becomes. The guiding principle of the search is that detectability is more important than probability. We should look for whatever is detectable, whether or not we consider it to be probable.

Seth Shostak spoke on "Searching for cosmic company" and his paper appears here with the title "Searching for Sentience: SETI today". It has been more than four decades since the pioneering SETI search began and we have still not turned up evidence for other sentience in the universe. Is this a consequence of disinterest by evolution in promoting mere biology to intelligence or have our searches been either too incomplete or too lacking in sophistication to uncover the extraterrestrials? His paper takes a new look at these issues – highlighting new search strategies, stressing the importance of experiments at optical (rather than microwave) wavelengths, and describing a new purpose-built radio telescope. He reviews the outlook for clever confrères among the stars and discusses why SETI may be about to enter its true Golden Age.

Lynn Rothschild addressed the question "Is evolution predictable?" and a written version of her talk will appear elsewhere. Astrobiology – the study of the evolution, distribution and future of life in the universe – has provided an integrated approach to understanding questions about life. But could evolution be directed by laws similar to those of other sciences? If the origin and evolution of life were an unpredictable oddity, based on quirks of contingency, astrobiology would be fascinating but capricious. However, what we know about the origin and evolution of life on Earth suggests that there are certain rules, if not quite laws, that lend predictive power to the enterprise. While it is acknowledged that 'laws' cannot be derived from an historical science, the fact that biological history must also follow the dictates of physical and chemical laws – in conjunction with the principles of natural selection and the constraints of genetics and developmental biology – allows a surprising amount of predictive power. Critical is the apparent prevalence of organic chemistry and the uniformity of the laws of chemistry and physics in the universe. The widespread occurrence of convergent or parallel evolution suggests that under certain conditions similar evolutionary trajectories are arrived at independently. In particular, the evolution of autotrophy, herbivory and carnivory always seem likely. This introduces a predictive element into the search for life elsewhere in the universe.

Paul Davies' talk touched on two themes – "Did terrestrial life originate on Mars?" and "Is life really written into the laws of physics?" – and his written contribution "How bio-friendly is the universe?" merges these. Although he does not favour panspermia, he believes that life can spread between neighbouring planets via rocky ejecta (transpermia). Indeed, he argues that it may have evolved first on Mars before transferring to Earth. If life is widespread, some form of biological determinism must be at work (i.e. life must be almost inevitable under Earth-like conditions). Indeed it is often glibly stated, especially by astrobiologists, that life is 'written into the laws of nature'. Christian de Duve, for example, describes life as a 'cosmic imperative'. To a physicist, however, this claim looks decidely odd. How can a specific state of matter be encoded in physical laws? Yet life is so complex that, superficially it seems, the probability of it arising by chance from a random mix of molecular building blocks is infinitesimal. Might there exist 'organizing principles' that fast-track matter to life against the odds? By viewing life as an information processing system, Davies transfers the emphasis in the search for a cosmic imperative from chemistry to information theory and computation. Recently, our understanding of the concept of information has been transformed by the race to build a quantum computer. In the quantum realm, the rules of information processing are different, so he asks whether a theory of quantum computation might cast light on the mystery of biogenesis.

Artificial life and self-organization

The fourth session was mathematical in emphasis and covered artificial life, chaos theory and the spontaneous generation of order, and cosmological considerations.

John Conway spoke on "Fine-tuning in artificial life". Fine tuning of the universe seems to be required for real life to come into existence but a curious analogy also makes fine-tuning important in the study of 'artificial life'. The rules of the 'Game of Life' were in fact found by a two-year process of tuning the birth and death rules, and this turned out to be very important for the proof of its computational and constructional universality. The analogy is not a close one but it might still have something to tell us about the evolution of real life.

Margaret Boden's talk on "Artificial life and metabolism" here appears under the title "Alien life: How would we know?" A few A-life researchers believe that life could exist in computer-memory. Whether that is really possible is not straightforward, because there is no universally agreed definition of 'life'. She argues that the concept of life involves three different types of metabolism. The first (and weakest) involves the basic intake and consumption of energy; this does indeed allow virtual, non-corporeal creatures inside computers to be alive. The second requires the collection, storage, spending, budgeting and transforming of energy, i.e. an 'economy' of energy for each individual system; this excludes artificial life but allows some non-biochemical robots to be classified as alive. The third requires the use and budgeting of energy for bodily construction and maintenance, i.e. the autonomous use of matter and energy in building, growing, developing and maintaining the bodily fabric of a (self-organized) unitary physical system; the energy exchanges involved are necessarily complex, so we can expect many richly interlocking 'finely tuned' biochemical cycles. A computer cannot exhibit this third type of metabolism, so alien organisms cannot exist in cyberspace. Whether A-Life workers could synthesize a new form of life, based on alien biochemistry, is another question. But if they did so by

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nanotechnology, we might not regard it as real (autonomous) life. Although we can define 'life' however we like, our definition should include evolution because evolution and metabolism together offer huge explanatory power. The only advantage of adopting a weaker form of metabolism is that it allows virtual life and that is not sufficiently persuasive.

Stuart Kauffman addressed the theme "Models of the organization, logic and dynamics of genetic regulatory networks: spontaneous order for selection's tuning" and his paper appears under the title "Understanding genetic regulatory networks". Now that we have identified the key molecules at the DNA level, we need to understand the integrated dynamical behaviour which controls their interactions and this is a daunting task. Over the past three decades, models of genetic regulatory networks have been based on random Boolean networks but these are now being extended to classes of continuous or piecewise linear equations. Recent studies have demonstrated that such networks exhibit three phases: ordered, chaotic and a phase transition 'edge of chaos' regime. Substantial work suggests that real cells lie in the ordered regime, where self-organizing properties not only mirror many features of real cells and ontogeny but also provide the building blocks for selection's further sifting. He discusses these models and the current evidence that cells lie in the ordered regime.

Frank Tipler's talk on "Intelligent life in cosmology" appears here under the same title. There are two steps in his intriguing analysis. He first argues that intelligent life must be rare. This is based on the Fermi paradox (the lack of evidence for extraterrestrials) and the fact that ubiquitous life would use up all available resources very quickly. His second step is to argue that the quantum mechanical principle of unitarity requires that at least one intelligent species must have evolved early in the expansion of the universe and that furthermore this must survive until the end of time. He also claims that the recently discovered acceleration of the universe implies that intelligent life, though rare, may have evolved several times within the observable universe.

Special features of human life

The final session considered special features of human life and returned to the issue which is perhaps most relevant to the agenda of the Templeton Foundation. It focused on the evolutionary role of such human attributes as altruism, language, art and culture. How special is human life and what are the implications of this for the nature of life elsewhere in the universe?

Simon Conway Morris spoke on "The navigation of biological hyperspace" and his paper has the same title. Ever since Darwin, most biologists have invoked 'chance and necessity' but with their emphasis very much on the former. That accords with the difficulty of finding general biological rules, let alone laws. Their science is made of exceptions and physicists do not like it. Biologists (and physicists) sometimes forget, however, that the combinatorial immensities of biological 'hyperspace', at whatever level (proteins to societies), make arriving at any viable destination exceedingly improbable unless the route is already well known (which in principle is impossible, given that evolution has no foreknowledge). Biologists, being pragmatic, are happy to accept what is made available, without asking awkward questions. However, while such pragmatism is entirely justified on a day-to-day basis, such a world picture potentially overlooks the possibility of finding a deeper structure to biology. He argues that the ubiquity of evolutionary convergence may point to such a structure and this has important implications for extra-terrestrial lifeforms.

Geoffrey Miller described "The role of fitness indicators in fine-tuning complex adaptations, and in the evolution of human and extra-terrestrial intelligence". His talk explored the possible roles of 'fitness indicators' in (1) evolution generally, (2) the evolution of human creative intelligence and language, and (3) the evolution of extraterrestrial intelligence. His paper does not appear here but many of the ideas are covered in his book "The Mating Mind". Fitness indicators are traits that evolve to signal the genetic quality and phenotypic condition of one organism to another organism (e.g. to a potential mate, rival, or predator). One example is the peacock's tail: peacocks that happen to be highly mutated, inbred, starving, sickly and/or stupid cannot afford to grow or maintain large, heavy, symmetric, colourful tails. This is why peahens kept paying attention to peacock tails when choosing mates and why tails kept growing ever more spectacular. Fitness indicators are not limited to such courtship displays, but constitute the vast majority of all animal signals, including aggressive threats, status badges, and anti-predator displays. In recent years, biologists have begun to realize that fitness indicators play major overlooked roles in evolution: (1) they act as a *genetic filter* for each species, eliminating harmful mutations and fine-tuning complex adaptive design in ways that are faster and more effective than natural selection on survival traits; (2) they allow lineages to escape from local evolutionary optima; and (3) they drive speciation and generate biodiversity. Thus, many uniquely human mental abilities, such as language and abstract creative intelligence, may have evolved originally as fitness indicators through mutual mate choice and other forms of social and sexual selection. Our indicators took a cognitive turn, displaying our genetic quality by advertising our neurophysiological efficiency rather than our tail-growing ability. Moreover, the adaptive logic of fitness indicators applies universally: any exobiological systems capable of self-replication, self-organizing development, and discriminative social interaction should evolve fitness indicators. Those indicators may sometimes take the same cognitive turn that humans did, resulting in various forms of extraterrestrial intelligence. This perspective suggests that exobiological systems may commonly evolve social intelligence, language-like communication, and creativity, but that the emergence of progressive techno-scientific cultures may be a very rare side-effect of selection for cognitive fitness indicators.

Bob Aunger talked about "Complex culture as a unique feature of human life". He took it for granted that

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culture evolved in certain brainy creatures as a means of disseminating useful information among conspecifics. But only one species on Earth exhibits complex (or cumulative) culture and this is made possible by the use of language and machines. These two features are unique to human culture and both depend on the psychological ability to plan a sequence of events – either the production of a syntactic sentence or the production of a complex artifact. Constructing sentences and machines also depends on evolved manipulative abilities which other brainy creatures (such as cetaceans and chimps) do not have in combination: a specialized vocal apparatus and dexterous limbs. Although this combination of attributes – and hence complex culture – is rare, these psychological and physical abilities have enabled us to massively modify the environment, with many consequences for other life-forms and the planet as a whole. Whether the combination of intelligent foresight and manipulative ability will keep us 'fine tuned' to the needs of the environment as human culture and technology continue to evolve is an open question.

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