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Simon Conway Morris

Phil. Trans. R. Soc. A 2011 **369**, 555-571
doi: 10.1098/rsta.2010.0276

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REVIEW

Predicting what extra-terrestrials will be like: and preparing for the worst

BY SIMON CONWAY MORRIS*

*Department of Earth Sciences, Downing Street, University of Cambridge,
Cambridge CB2 3EQ, UK*

It is difficult to imagine evolution in alien biospheres operating in any manner other than Darwinian. Yet, it is also widely assumed that alien life-forms will be just that: strange, un-nerving and probably repulsive. There are two reasons for this view. First, it is assumed that the range of habitable environments available to extra-terrestrial life is far wider than on Earth. I suggest, however, that terrestrial life is close to the physical and chemical limits of life anywhere. Second, it is a neo-Darwinian orthodoxy that evolution lacks predictability; imagining what extra-terrestrial life would look like in any detail is a futile exercise. To the contrary, I suggest that the outcomes of evolution are remarkably predictable. This, however, leads us to consider two opposites, both of which should make our blood run cold. The first, and actually extremely unlikely, is that alien biospheres will be strikingly similar to our terrestrial equivalent and that in such biospheres intelligence will inevitably emerge. The reasons for this revolve around the ubiquity of evolutionary convergence, the determinate structure of the Tree of Life and molecular inherency. But if something like a human is an inevitability, why do I also claim that the first possibility is ‘extremely unlikely’? Simply because the other possibility is actually the correct answer. Paradoxically, we and our biosphere are completely alone. So which is worse? Meeting ourselves or meeting nobody?

Keywords: extremophiles; evolutionary convergence; intelligence

1. Introduction

‘Astrobiology is the study of things that do not exist.’ This well-known statement can be dismissed as flippant cynicism, but one might suggest that in its vernacular way it is struggling to grasp what on earth (so to speak) we might expect to find. Consider the presumed alternatives: will the extra-terrestrials be utterly familiar, completely alien (whatever that is supposed to mean) or is the search a complete waste of time? What will it be? Worlds full of shoppers and celebrities, biological

*sc113@esc.cam.ac.uk

One contribution of 17 to a Discussion Meeting Issue ‘The detection of extra-terrestrial life and the consequences for science and society’.

constructions so unfamiliar that they are only brought home by accident and then inadvertently handed over for curation in a department of mineralogy or an exercise in galactic futility as one sterile world after another rolls beneath the spaceship windows while far behind our intrepid explorers the only habitable planet in the cosmos shines like a blue jewel? Even one Martian fossil, or less likely a living entity (would it, for example, be cellular?), might assist us to constrain radically our expectations. If the ‘thing’ proved to be genuinely alien, that might at least rule out the attractive idea of a local panspermia, that is from a relatively benign Noachian Mars to a considerably more risky Hadean Earth. But if the Martian life form transpires to be eerily similar, this might only show that Life with a capital ‘L’ in reality has very few options. To the mixed joy and grief of universalists, I will argue for just this likelihood in this paper. Joy, because Life is a universal; grief, because despite the principle paradoxically we are alone.

But all is not necessarily lost. Concerning the latter I should be wrong. Indeed, if the alternative stance is actually correct, then, in principle, peering from our Copernican cage, and perhaps unexpectedly, we can already identify the universals of life. Contrary to received wisdom, which views our biosphere as a commonplace but quite unlike that of even our near neighbours, no longer need we stand accused of being hobbled by a crippling lack of imagination. Far from blinkering our outlook, our local biology tells all we need to know. Down to Earth, even if for some workers it will be with a bump. No sentient forms weaving their existence in vast interstellar dust clouds, farewell to bizarre filamentous species greedily soaking up the intense magnetic fields of a crushingly oppressive neutron star and on even Earth-like planets no forms that we might as well call conceptualized pancakes [1].

Too much excitement; time to settle down. In this essay, I will address two issues. The first devolves into two related paths. What are the physico-chemical limits of life on Earth? Here, we appear to be on moderately firm ground. Second, given the likely range of planetary environments, such as a 100 km deep ocean or an atmosphere substantially denser than that of Venus, what fraction of any potentially habitable biosphere is actually occupied? Is the terrestrial ‘habitation box’ only a small proportion of all of biological occupancy space or, alternatively, has life here more or less reached the limits of what is possible anywhere? The other issue, discussed in the second half of this paper, addresses the historicity of the evolutionary process and again devolves into two paths. The first examines the predictability of the process as against arguments for radical contingency. The second strand is to enquire whether prior constraints, such as so-called ‘deep homology’ [2], govern the outcomes of evolution. In the context of this paper, the most important is the likelihood or otherwise of the emergence of intelligence. In passing, I should note that what will remain unexamined is the credibility of non-carbaquist forms of life (e.g. [3–5]), or even a biosphere beneath our feet (or above our heads) based on entirely unexpected biochemistries (e.g. [6,7]). While this might seem at best an evasion of an issue central to both the definition of the habitation box and the natures of extra-terrestrial life, apart from the exigencies of space there is an underlying philosophy proposing that despite the colossal hyper-dimensionality of potential biological space, in reality, the habitable regions are infinitesimally small and evolutionary options equally constrained.

2. Extremophiles

(a) *Terrestrial limits*

What we find here, therefore, will be a reliable guide to what we will find anywhere. Paradoxically, confidence that this may be correct comes from the dramatic increase in our knowledge of so-called extremophiles (e.g. [8]). While it is not disputed that we have only a limited understanding of their overall diversity (especially genomic), this is perhaps less relevant when we attempt to define the overall shape of the habitation box in terms of such parameters as temperature, pressure, pH, salinity and water availability (e.g. [9]; figure 1). Thus, it may be that the current thermal limit (*ca* 120°C) of microbial activity [10] may not be much exceeded. In part, this is because water at this temperature is necessarily pressurized, and the equivalent limits of microbial habitation in the Earth's crust (e.g. [11,12]) may not exceed *ca* 5 km (equivalent to *ca* 110 MPa; see also below) and an ambient temperature (depending on the local geothermal gradient) of at least 120°C.

So far as the thermal tolerance of eukaryotes is concerned, while much has been made of certain polychaetes inhabiting hydrothermal vents (e.g. [13]), both the dynamic nature of this environment and the difficulties in obtaining accurate measurements suggest that for short-term exposure the upper limit lies at about 55°C, and the ambient preference is of the order of 40–50°C [14,15]. Very few eukaryotes can tolerate higher temperatures. The record seems to be awarded to certain thermophilic fungi, far removed from the torrid hydrothermal vents but rather inhabitants of dung heaps (e.g. [16]). Curiously, when it comes to resistance to water stress, most conveniently measured as water activity (a_w), fungi again take the record with some xerophilic species exhibiting a remarkable tolerance and continuing to grow when a_w reaches an astonishingly low value of 0.647 [17]. While the environmental extremes of these and a few other multicellular organisms are impressive [18], the overall size of the habitation box for eukaryotes is unsurprisingly substantially smaller than that of life as a whole.

This is evident at the other end of the temperature spectrum. While living at temperatures around freezing is biologically unproblematic, and may involve adaptations such as insulation and a variety of molecular anti-freezes, at lower temperatures we enter a largely bacterial realm, with corresponding adaptations in such features as enzyme activity and cell-wall composition (e.g. [19]). While a lower limit of *ca* –20°C has been widely accepted, not least because as the eutectic is approached free water is no longer available, it is now clear that metabolic activity can continue to much lower temperatures. For example, adenosine triphosphate can be generated at temperatures as low as –80°C [20], and perhaps more extraordinarily, at least some aspects of protein machinery are potentially operative at almost –200°C [21]. The authors are fully aware that this is a surprising result, but find neither an artefactual nor abiotic explanation convincing. They speculate that in their experiments the water may have been in a glass-like state rather than crystalline, but are surely correct when they write this research ‘defines new territory for further study’ (p. 427). Indeed it does, not least because quite remarkably in combination with dehydration and concomitant increase in the concentration of anti-freeze proteins and glycerol,

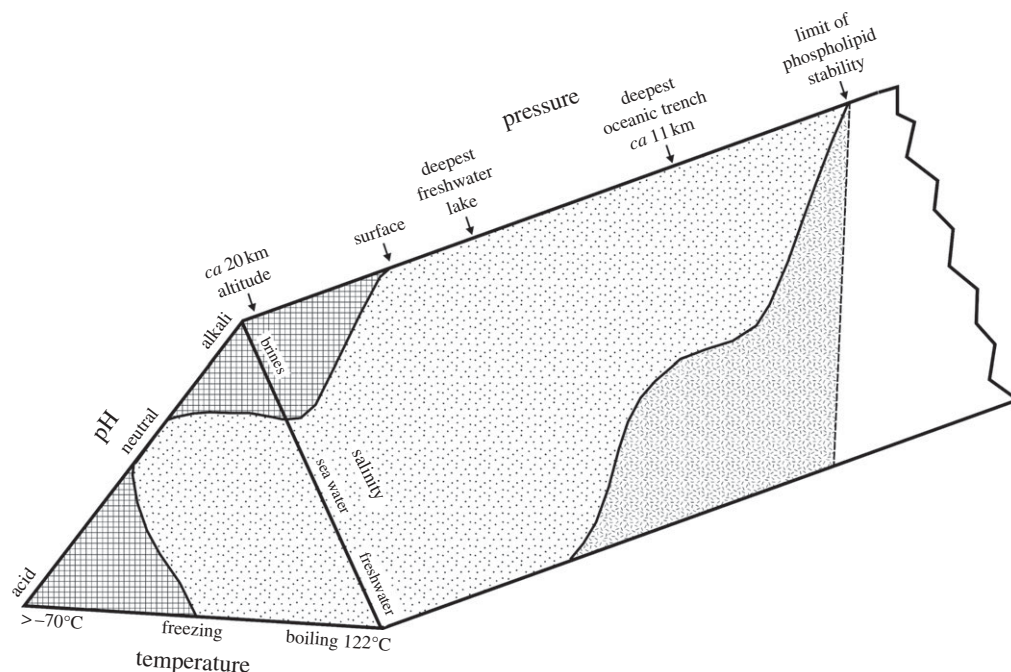


Figure 1. Diagrammatic sketch of the carbaquist habitation box with respect to some principal parameters (pH, pressure, salinity, temperature). All scales are approximate. Collectively, terrestrial life occupies all regions of the habitation box, albeit with a greater extension of tolerances by the prokaryotic extremophiles. The only regions that appear not to have a terrestrial counterpart are very deep freshwater oceans (although the likelihood of such bodies remaining fresh given crustal/mantle exchange seems doubtful). Area with dots, eukaryotes + prokaryotes; area with checks, prokaryotes; area with stipple, potential non-terrestrial environments.

at very low temperatures (*ca* -76°C) the body water of an Arctic beetle larva vitrifies and some individuals might survive to yet lower temperatures [22]. In fact, for life as a whole, there may be no lower limit in as much as at increasingly lower temperatures normal growth then yields to physiological maintenance, and ultimately dormancy where ‘coincidentally’ rates of DNA and protein repair are equal to those of macromolecular deterioration [23]. Here, perhaps, immortality resides.

Another aspect of water is its solute content, and here halophiles (e.g. [24]) add another important dimension to the definition of the habitation box. Although the concepts of chaotropic and kosmotropic interactions, defined as to whether dissolved ions tend to disrupt (chaotropy) or reinforce (kosmotropy) the adjacent water structure, are not regarded as chemically useful ([25]; see also [26]), they provide a useful short-hand for life in different sorts of brine. Thus, with respect to chaotropicity, where the weakening of electrostatic interactions unsurprisingly has deleterious biological consequences, it is evident that magnesian brines are especially problematic; above about 2.3M concentration, they may be uninhabitable [27]. What, perhaps, is of special importance is that modelling of the bilayer lipid membranes (that typically define a cell wall) is especially

vulnerable to large anions, such as Cl^- , that deeply penetrate the bilayer [28]. In passing, one should also note that it is not coincidental that the fungi that are extreme xerophiles (see above) are also chaotropophiles. And among the extreme environments in which these fungi survive is one far removed from most astrobiological scenarios, that is blue Stilton cheese.

(b) *Beyond the Earth*

Whether or not the example just provided serves as a viable link to an extra-terrestrial biosphere might be best mediated over a glass of port, why not the Taylor '63? It is, however, a logical step to export the terrestrial habitation box to different planetary settings and explore what, if any, congruence can be identified, that is whether the terrestrial environmental parameters have any overlap with the inferred conditions on a planet or moon. So far as our Solar System is concerned, with the possible exception of Mars the parameters are poorly constrained, but even in the context of that planet, its early history is hardly encouraging, not least with regard to salinity [29]. Just such an approach, of using terrestrial analogues to explore the potential habitation space, was employed by Marion *et al.* [30] in the context of Europa. While the extreme cold of the surface and the intense impinging radiation suggest an environment well beyond tolerance of the hardiest organism, the strong likelihood of a deep ocean (possibly circulating [31] and with a complex chemistry [32]) residing beneath a dynamic ice shell (with thermal diapirism [33]) arguably makes this moon the priority target in the search for extra-terrestrial life. Yet neglecting the huge challenges in sampling even the cryosphere of Europa, our search for European life might still end in disappointment. Perhaps most problematic is the possibility of the extreme salinity of the ocean [34], although optimists will draw attention to potential sites of habitation in postulated hydrothermal zones in the ocean floor or 100 km above them within interstitial habitats of the ice crust.

The same group of optimists might be usefully seconded to consider as an alternative the potential habitation zone within the cloud layer of Venus (e.g. [35–37]). Here, too, the challenges, not least the extreme dryness and acidity, are considerable, but the evidence for atmospheric disequilibrium, UV absorption and particles of microbial size encourage speculation as to the possibility of a sulphur-based ecosystem [38,39]. If Europa remains a best hope, the case for exploration of the Venusian atmosphere cannot be far behind [40]. And although more neglected, an analogous case could be made for a Jovian habitat ([41]; see also [42]).

(c) *Beyond the Solar System*

Applying the terrestrial habitation box to any other planetary body in the Solar System, and after Europa and Venus Titan seems to be the most obvious candidate (e.g. [43]), would no doubt be informative. A more fundamental question, however, is whether because of locally contingent circumstances terrestrial life just happens to occupy some fraction, perhaps very small, of the total carbaquist habitation box. As we have already seen, however, in the case of minimum temperatures, pH range, salinities and desiccation (a_w), arguably the defined limits for all carbaquists have been reached by life on Earth, and with somewhat less certainty this applies also to hyperthermophiles. In principle,

however, the possible range of survivable pressures could extend significantly this particular parameter of the habitation box. This extension, however, is much more likely to be in the direction of the hyper-piezophiles (sometimes known as barophiles). This is because in terms of much lower pressure, micro-organisms have been recovered from at least 20 km altitude [44], with claims of viability extending to twice this height [45], or even higher [46]. Apart from an emphasis on avoiding inadvertent contamination of the probes (balloons, rockets, etc.) the investigators have stressed the extreme nature of this environment, notably in terms of UV flux, very low pressure and desiccation; even at 20 km elevation, it is doubtful there can be a functioning ecosystem [47].

In the opposite direction, that is at elevated pressures, one intriguing possibility to consider are planets with massive oceans, possibly hundreds of kilometres deep. The phase diagram of liquid water and the various ice polymorphs, of which interestingly only the familiar ice I is buoyant [48], help to delimit exobiological possibilities in such ocean planets. In such a setting, the representative environments are mostly remote from the terrestrial habitation box, so it is largely speculative what (if any) biological systems might exist, especially as there are concomitant changes in physical parameters ranging from free energies, enthalpy, heat capacity, viscosity and the speed of sound [49]. While claims exist for microbial viability to gigapascal pressures, including residence in ice VI (this would be equivalent to oceanic depths of *ca* 160 km [50]), these results have met with some scepticism [51].

So far as biological functions at somewhat lower pressures, but still up to a crushingly high *ca* 800 MPa, there is a diverse literature. A significant proportion of it, however, arises from a food biotechnology bent on destroying microbial populations or suspending enzymatic reactions that lead to taste or colour deterioration. Useful overviews of the pressure sensitivity of biological systems are available (e.g. [52–56]), but any attempt at a summary comes with important provisos. These include the fact that there are a range of experimental systems and may address a specific molecular system or an entire cell. Pressure, temperature and pH can have complex inter-relationships, and so too many experiments employ surface-dwelling organisms, and especially in the case of food technology, the experimental times used are short. It is certainly the case that some enzymes can remain active to very high pressures (e.g. [57,58]). So too short oligonucleotide strands show extraordinary resilience under even higher pressures, with the molecule acting like a spring ([59]; see also [60]). The somewhat analogous case of collagen, with its diagnostic triple-helix structure, might also explain its remarkable stability to elevated pressures [61].

Important as these and similar results are, there is little evidence of microbial viability significantly in excess of the tolerances seen in terrestrial piezophiles. Indeed there appear to be two particularly significant constraints to viability at greatly elevated pressures. As many authors have stressed, other than their vulnerability to chaotropic solutions, one of the weakest links of the bilayer cell phospholipid membranes is that very high pressures compromise their fluidity (e.g. [62]). Unsurprisingly, piezophilic organisms show adaptational strategies, notably greater employment of unsaturated fatty acids ([63]; see also [64]). It is, however, a complex area, because of both the nature of lipid chemistry and compounding factors such as temperature and osmotic pressure. Nevertheless, phase diagrams of lipid behaviour and the transitions to gel-like states [62] suggest

that viability may not extend that far beyond known limits. Given that at least in terms of carbaquist life it is likely that lipid membranes are universal, this suggests that viability may not extend much beyond the deepest oceanic trenches (*ca* 11 km) or equivalent pressure zone within the crust of the Earth (*ca* 5 km). But the viability of lipids is not the only problem. Another potential constraint of the habitation box is the behaviour under different temperature and pressure regimes of hydration water essential to biomolecular function [65]. Not only is the optimal zone remarkably narrow, with that for temperature being curiously coincidental in both micro-organisms and homeotherms (*ca* 36–44°C), but the phase diagram for hydration water is circumscribed and little larger than the terrestrial habitation box.

In conclusion, while we need to remain aware that the versatility and efficiency of life provokes constant surprise, there do appear to be arguments that any form of extra-terrestrial carbaquist life could only modestly extend the physico-chemical parameters available for occupation. Although space does not allow any consideration here, it is also worth remarking that there are also diverse strands of evidence to suggest that at least some biological systems, ranging from enzymes such as carbonic anhydrase and rubisco (e.g. [66]) to anatomical configurations, such as teeth (e.g. [67,68]), are as good as they will ever be able to get.

3. Evolution

(a) *Organizational principles*

Even if it is agreed that the carbaquist habitation box can be little larger than that of the Earth, the vast majority of biologists would still insist that alien life is as described, that is genuinely alien. The history of terrestrial life, it would be argued, can provide few useful clues, and emphatically no predictability. As I have made clear elsewhere [69–72], I argue that contrary to received neo-Darwinian wisdom, life on Earth at any level of organization—from molecular to societal—will provide a remarkably good guide as to what ought to be ‘out there’. But is this correct? The most obvious stumbling blocks to this approach are threefold. First, given advanced life on Earth could not have occurred without a whole series of major transitions, not least those revolving around eukaryosis, multicellularity and homeotic genes, how fortuitous are these events? Second, given the emphasis on historical processes, what role do contingent events play? Most obvious in this context are mass extinctions, but the dynamism of this planet in terms of physical (environmental shifts) and biological (say, epidemics) factors suggests to most biologists that evolution is more like living permanently in a pinball machine. And finally we need to ask from the perspective of the first two points whether any functional solution is excluded because of one or other re-routing of the history of life forever foreclosing an option that was in principle perfectly viable but denied by history. Certainly, the extraordinary diversity of life would persuade most observers that the endpoints of any evolutionary trajectory are fortuitous. Where is the predictability in a tulip, or a tapeworm? In fact, flowers have evolved more than once [69], and a dinoflagellate has transformed itself into what for all intents and purposes is a tapeworm [71,72]. It is also important to stress that biological systems may look radically different but are in fact surprisingly

similar in operation. Of such ‘skin-deep’ differences, the operation of the octopus arm [73,74] or the locomotion of insects both in terms of biomechanics [75] and neurobiology (e.g. [76]) are telling examples.

What follows with respect to evolutionary predictability can only be an abstract of a developing programme, and may seem to fly in the face of received neo-Darwinian thinking. That this programme is in accord with the principal Darwinian mechanisms is not in dispute, but the agenda argues that the entire evolutionary process is governed by deeper constraints. While these might appear largely self-evident, the impact on current Darwinian thinking is decidedly muted. Among the principles involved are those that revolve around self-organization and inherency. With respect to the former concept, there is, for example, reason to suspect that some aspects of protein assembly are effectively spontaneous so that structures like the α -helix are necessarily universal ([77]; see also [78]).

Such principles may apply in other interesting contexts. Thus, it seems likely that all life is fundamentally cellular, even if amoeboid plasmodia and the green alga *Acetabularia* are reminders that not all the world is built like *Escherichia coli*, yeast or *Paramecium*. Any cell depends on a lipid membrane, and in their simplest form, these probably are also self-assembled. Such a solution is, of course, ideal for containing the metabolic activities without outside interference, but suffers the penalty that enclosed in a hydrophobic and impermeable membrane, the products necessary for the continuing metabolism (and replication) are excluded. The solution, of course, is to evolve a variety of transporters and channels that ensure useful and hazardous material can pass in the appropriate direction. Subsequently, of course, the evolution of such ‘pores’ as the sodium channel (which evidently evolved from a calcium predecessor) will play a key role in the evolution of the nervous system (but significantly has convergently evolved in both the bacteria (e.g. [79,80]) and protistan heliozoans [81] and diatoms [82]). But how to evolve any sort of channel in the first place? It transpires that by employing only two amino acids (leucine and serine) they will spontaneously form a helix, and if three such helices are brought together, they can function as a rudimentary channel ([83]; see also [84]). So too given the nature of the periodic table, one might suggest that both specific cation (e.g. K^+ , Ca^{2+}) and anion (e.g. Cl^-) channels will be very likely to evolve given their charging and ionic radius. One could continue this line of enquiry and ask as to the likelihood of a number of other cellular components, most obviously those connected to replication, which are ‘unexpectedly’ constrained in terms of available building blocks and functionality. Nor should we forget that so far as the latter is concerned it may well be that an alternative system, say DNAs that employ hexose rather than ribose, may well be chemically stable and capable of adopting the appropriate conformation, but in its wider biochemical milieu still prove to be hopelessly maladaptive.

The possibility that much of terrestrial biochemistry reflects a universal configuration may not be wide of the mark. But thereafter so far as the patterns of evolutionary diversification are concerned, it is almost universally assumed that other than the broadest of constraints (‘think of streamlining if you want to swim fast; do not step off cliffs without wings’ and so on), as already indicated, the trajectories of evolution are fortuitous and lack any predictability. If correct, then this would apply to the emergence of intelligence and so might help to explain the Fermi paradox. However, as I argue below, intelligence is an evolutionary inevitability, yet the Fermi paradox holds.

(b) Co-option and modules

In support of this view, it is necessary to show that major transitions, of which eukaryogenesis and the rise of animals might be good examples, are only major in a *post hoc* sense and from an evolutionary perspective remain unproblematic. Such a view is supported by three lines of evidence. The first, that of self-organization, has already been briefly addressed. Second, much that looks new in evolution is at one level trivial because much of the spade work has already been done. By this, I mean that the prior availability of molecular systems and the all-important role of gene duplication underpin a good part of life's potential for versatility. Think of evolution more like a factory floor, with components scattered around (and sometimes stored in surprising places). The trick is to have the right set of 'plans' to hand. Much, therefore, at the molecular level is already available. This concept of inherency is linked to the familiar evolutionary topic of co-option, of which a much-cited example would be the eye crystallins (e.g. [85]). Here, various proteins, often enzymes and associated with stress functions such as heat shock, find new employment in the lens and cornea. The extent and versatility of this co-option, however, becomes apparent from the gelsolins found in the eyes of some teleosts. Here, like other crystallins they confer transparency, but the gelsolin proteins have a diversity of other functions, including involvement with actin [86]. And it may be that the extent and importance of molecular inherency remains underestimated. For example, in terms of the evolution of the nervous system in a planarian flatworm, not only is there extensive overlap between the genes of this 'primitive' flatworm and a human, but as importantly, some 30 per cent of these genes are also known [87] in the nerve-less plants (*Arabidopsis*) and fungi (yeast). As significantly in terms of major functional categories within the animal nervous system (such as brain morphogenesis or neural differentiation), representatives of genes employed in each category occur in these other kingdoms. But to speak of these as 'genes for nerves' misses the point because matters such as cell communication and vesicle formation go far beyond the nervous systems.

Of equal importance, and I believe still underplayed, is that the counterpart of molecular inherency is molecular versatility, whereby the same structure is employed in multiple contexts. The β -grasp fold (β -GF) provides a good example of what is often referred to as a 'Swiss Army Knife Syndrome' [88]. Here too, the proximal explanation for this phenomenon may be quite trivial and revolve around such matters as binding properties and conformation to particular, if very different, substrates. Even so, I suspect, the apparent opportunism of this molecular versatility may conceal deeper principles of order. In any event, these observations echo what one group (writing specifically in the context of the repeated evolution of vertebrates with effectively four eyes [89]) referred to as 'the capacious cauldron of evolution' (p. 145). This may suggest that while evolutionary transitions may indeed be profound with respect to consequences, they are not necessarily so in terms of process (and any more than in any supposedly macroevolutionary transformation).

But the notion of 'cauldron', or indeed 'crucible' [90], is informative because it can serve as the metaphor for the evolutionary process being ordered, following a 'spell' or chemical treatise. What guarantees the outcome is not only the appropriate ingredients (and here the material available far exceeds in potentiality that available to any sort of alchemist), but the manner in which

the appropriate combinations are employed. It is increasingly evident, be it in terms of developmental or morphological modules, that combinatorial rearrangements lead to what appears to be an almost unlimited resourcefulness. In the former context, one can think of ‘genes for eyes’ being employed in muscle development [91], while in terms of functional integration that leads to highly successful ecomorphs, a good example is provided by the cacti [92]. Once again, the point is that while evolutionary combinatorics will by definition provide a potentially large number of alternative states, the reality is that in the real world the great majority may well be non-viable. As importantly, the combinatorial possibilities may be determined by organizational rules that are not themselves immediately adaptive.

It is not, therefore, surprising that in all clades we see that at various scales evolution repeats itself, and what cladists term homoplasy is rampant. There is, however, another aspect about the way diversification within the clade proceeds that has been relatively neglected, even though this has a bearing on the developmental programmes and even more importantly the likelihood of evolution being constrained to follow particular trajectories. Thus, in any diversification it is very common, and I suspect universal, to see a juxtaposition of characters that are respectively deemed to be ‘primitive’ or ‘advanced’. The significance of this has been largely overlooked for two reasons. First, to the committed cladist, who inhabits a strange atomistic world where both evolutionary transformation and functional integration are near-irrelevancies, the combination of primitive and advanced is deeply provoking, as is evident from the repeated employment of words such as ‘puzzling’ and ‘surprising’. These adjectives apply to the investigator, not the organism. It is almost as if the organisms had not taken the trouble to read the textbooks. The real importance of this mosaic evolution, however, is that when one level of a biological evolution is achieved, one can be confident that the next set of adaptive explorations will not be a series of random excursions but multiple events in a series of surprisingly limited directions. Thus, among the sarcopterygian fish, we see multiple paths towards tetrapodomorphs, and in the theropod dinosaurs the independent evolution of flight at least three times [71]. The implications of this are, to put it mildly, interesting because they invite a recursive view of the structure of the Tree of Life where each bifurcation is largely pre-determined by the prior conditions.

If the above is correct, then it suggests that evolution is Darwinian in terms of mechanism, but the outcomes are governed by deeper principles of organization that constrain what is possible (and in my view most likely representing an infinitesimally small fraction of potentially available biological hyperspace) as against what can never evolve, in any place, at any time. Such a view hardly falls within current neo-Darwinian orthodoxy, but also falls foul of what is effectively an institutional problem. That is, each and every taxonomic group has its dedicated specialists. While this provides the essential ground truth for our investigations, it does not encourage the identification of more general biological properties. The phenomenon of evolutionary convergence, however, seems to be a useful starting point in identifying such properties that are largely independent of taxonomic position. An important corollary of this is that, as already noted, apparent differences between organisms in reality can be merely skin deep, and was the powerful metaphor employed by Donley *et al.* [93] in their functional analysis of the open-ocean predators exemplified by the

tunniform teleosts and lamnid sharks. Here, the point revolves not only around the hydrodynamic streamlining (although that too has its subtleties), but the convergent arrangement of thermogenic muscle linked to a tendinous system to transmit the power to a large vertical tail. This, and the examples given above, is a reminder that (i) the alien nature of extra-terrestrial biospheres will be as much in the eye of the visitor and (ii) a compilation of terrestrial convergences will provide a helpful *vade mecum* to place in the knapsack of any such galactic tourist.

(c) *The myth of mass extinctions*

There might still be one fatal objection to the likelihood that an alien biosphere will have much in common with ours, and this is based on the oft-repeated assertion that mass extinctions are radically contingent, largely erasing the ecological slate and allowing hitherto insignificant groups to rise to dominance. The exemplar of this, of course, is the end-Cretaceous extinction, the extirpation of the great reptiles (notably dinosaurs, mosasaurs and pterosaurs) and the ensuing ecological radiations of the birds and mammals, including of course the primates. ‘No bolide, no extinction, no us’ chimes the mantra. Yet, this can be questioned for at least two reasons. First, while from the perspective of being a Mesozoic reptile the impact of the asteroid at Chicxulub can hardly be regarded as helpful, the main driving force was more likely to have been the massive flood volcanism (as is evidently the case in many of the other mass extinctions) of the Deccan Traps of northern India (although 65 Ma ago the point of eruption was located on a mantle hot-spot presently defined as the volcanic island of Réunion).

But let us suppose what seems to have been a coincidental impact tipped the balance. So, we can imagine a counterfactual world where the asteroid sails harmlessly by and the dinosaurs survive. Is this the end of the story? Not quite. By the Oligocene, the Earth was finally leaving its greenhouse state and entering an ice house world, culminating in the Plio-Pleistocene ice ages. In such an alternative world in the polar and temperate zones, warm-blooded, socially adept, large-brained tool makers presumably will be at an advantage. I speak, of course, of the once companions of the dinosaurs, the birds and mammals. The former were already diverse in the Cretaceous, and some evidence suggests that mammals had also begun to diversify at this time. I would suggest that their emergence would, sooner or later, have sealed the fate of the dinosaurs, just as in reality it did in the case of the mammalian megafaunas. More intelligent and convergently arriving at tool-making, sooner or later the capacity for hunting would emerge.

In the grand scheme of things the dinosaurs were doomed, and the end-Cretaceous extinction simply accelerated the inevitable. One can, of course, argue from another perspective and observe that since birds evolved from the dinosaurs (specifically theropods), then the more important issue is the emergence of advanced intelligence, as in the crows and parrots. In any event, I suggest that from an astrobiological point of view the importance of mass extinctions deserves a re-appraisal. That is, that rather than mass extinctions being important because of the mayhem they cause and the resulting radical re-setting of the evolutionary agenda, their importance lies in a quite different direction. This is not to dispute the historical reality of mass extinctions, nor to assume that all result from the same drivers. It is, however, to suggest that paradoxically mass extinctions are creative factors in the evolution of a biosphere and this is because they buy

evolutionary time for nothing. In the case of the K/T extinctions, the whole story was brought forward by perhaps 50 Ma. This may transpire to be non-trivial. It is conjectural, of course, whether Earth-like planets necessarily must have a protracted interval of principally microbial evolution (akin to our Precambrian), but if they do and have a time for complex multicellular life of approximately 1–2 billion years (taking the emergence of animals at *ca* 600 Ma, and a future habitability of *ca* 1000 Ma), then an average of 10 mass extinctions might buy a biosphere 500 Ma extra.

4. Conclusion

I argue, against much received neo-Darwinian wisdom, that what we see here is at least broadly, and I suspect much more precisely, what we will find on any comparable Earth-like planet. Accordingly, and with specific reference to SETI, as well as the *sine qua non* of terrestriality, the evolution of intelligence and cognitive sophistication (including numerosity), manipulative skills, tool-making and technology, not to mention the increasing appropriation of resources are all evolutionarily inevitable because all are convergent. So too the seemingly mundane, be it anatomical (such as walking) or biochemical (as with respiratory proteins), will be highly constrained. Our alien may look unfamiliar, but if she does (yes, sex is also inevitable, as will be parental imprinting, sex determination, viviparity and milk), it will be a skin-deep difference. More probably, as Bieri [1] pointed out many years ago, they will not look like thinking ‘pancakes. In all probability they will look an awful lot like us’ (p. 457).

So why should we ‘prepare for the worst’? First, if intelligent aliens exist, they will look just like us, and given our far from glorious history, this should give us pause for thought. The alternative is more paradoxical, but revolves around the observation that if I am correct in my supposition of evolutionary convergence in reflecting the outcomes of evolution on any Earth-like planet, then we should not be here. This is simply because solar systems depending on metal-rich stars would have begun to form some billions of years ahead of ours. We can juggle the figures as we see fit, but reminding ourselves that much of the nervous system has a molecular inherency that extends far deeper than animals and within this group advanced cognition has evolved independently at least five times, then let us say that only one in a thousand biospheres spawns technology and of those one in 10 000 finally leaves its solar system then this planet would still have been colonized by people who kept trilobites for pets. And what about our ancestor, that is the earliest fish [94]? Animals like *Myllokunmingia*, swimming above what is now the city of Kunming. Best on toast. But that did not happen, and it will not happen. We never had any visitors, nor is it worth setting up a reception committee in the hope that one day they might turn up. They are not there, and we are alone. So which do you prefer: neighbours with the culture of the Aztecs or a howling silence?

Warm thanks to Vivien Brown for typing numerous versions of this article, to Nick Tosca and an anonymous referee for constructive comments. The figure was kindly drafted by Sharon Capon. Also my gratitude to the organizers of this Discussion Meeting, especially Martin Dominik and John Zarnecki, along with the staff at the Royal Society, especially Catherine Lawrence and Nicola Kane. Cambridge Earth Sciences Publication ESC 1921.

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