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Simon Conway Morris
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I Looking for Easter Island

I am a bipedal hominid, of average cranial capacity, write my manuscripts with a fountain pen, and loathe jogging. Thanks to years of work by innumerable biologists I, or anyone else, can tell you to a fair degree of accuracy when the ability to walk upright began, the rate at which our brain increased to its present and seemingly astonishing size, and the origin of the five-fingered forelimb whose present versatility allows me to hold a pen, not to mention the fishy origin of those lungs that make such a noise as the joggers pass me early in the morning on Cambridge's Midsummer Common.

It is obvious that the entire fabric of evolution is imprinted on and through our bodies, from the architecture of our bony skeleton, to the proteins carrying the oxygen surging through our arteries, and our eyes that even unaided can see at least two million years into the past – the amount of time it has taken for the light to travel from the Andromeda Galaxy. In every case – whether for hand or brain – we can trace an ancestry that extends backwards for hundreds of millions, if not billions, of years. Yet, for all that, both the processes and the implications of organic evolution remain controversial. Now at first sight this is rather odd, because it is not immediately clear what is being called into question. Certainly not the fact of evolution, at least as a historical narrative: very crudely, first bacteria, then dinosaurs, now humans. More specifically in terms of process, Darwin's formulation of the mechanisms of evolution is not only straightforward, but seemingly irrefutable. Organisms live in a real world, and evolve to fit their environment by a process of continuous adaptation. This is achieved by a constant winnowing through the operation of natural selection that scrutinizes the available variation to confer reproductive success on those that, by one yardstick or another, are fitter in the struggle for survival.

So is that all there is to say? The recipe for evolution just given is a decidedly bald summary. One intuitively senses that it is an inherently feeble response to an extraordinarily rich history that has brought forth an immense coruscation of form and diversity. Among

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living forms this ranges across many scales of complexity, from bacteria that build colonies like miniature trees[1] to immense societies of ants whose populations run into the millions and, independent of us, have stumbled across the advantages of agriculture (Chapter 8). And it is a history that is by no means confined to the complexity of colonies or the limpidity of a geometric shell. It is as much in the range, scope, and acuity of living organisms. They may be mere machines, but consider those owls whose hearing can pinpoint within a two-degree arc the rustling made by a mouse,[2] the navigational abilities of albatrosses across the seemingly trackless Southern Ocean[3] (Fig. 1.1), or even Nellie the cat that smelled Madagascar across more than two hundred miles of ocean.[4] But despite our admiration, wonder, and – if we are candid – even awe, surely we can still offer the following paraphrase: evolution happens, this bone evolved from that one, this molecule from that one. To be sure, not every transformation and transition will be elucidated, but we are confident this is because of a lack of information rather than a failure of the method.

Yet despite the reality that, as it happens, we humans evolved from apes rather than, say, lizards, let alone tulips, the interpretations surrounding the brute fact of evolution remain contentious, controversial, fractious, and acrimonious. Why should this be so? The heart of the problem, I believe, is to explain how it might be that we, a product of evolution, possess an overwhelming sense of purpose and moral identity yet arose by processes that were seemingly without meaning. If, however, we can begin to demonstrate that organic evolution contains deeper structures and potentialities, if not inevitabilities, then perhaps we can begin to move away from the dreary materialism of much current thinking with its agenda of a world now open to limitless manipulation. Nor need this counter-attack be anti-scientific: far from it. First, evolution may simply be a fact, yet it is in need of continuous interpretation. The study of evolution surely retains its fascination, not because it offers a universal explanation, even though this may appeal to fundamentalists (of all persuasions), but because evolution is both riven with ambiguities and, paradoxically, is also rich in implications. In my opinion the sure sign of the right road is a limitless prospect of deeper knowledge: what was once baffling is now clear, what seemed absurdly important is now simply childish, yet still the journey is unfinished.

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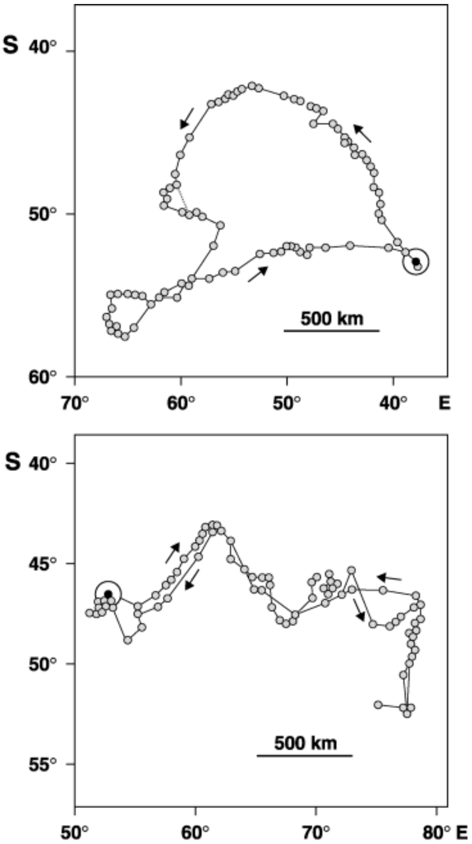

FIGURE 1.1 Two trackways, obtained by satellite monitoring, of the Wandering Albatross across the Southern Ocean. Dots indicate data intercepts, and arrows direction of travel. The upper panel is a departure from South Georgia, on its 13-day trip it passed the Falkland Islands and subsequently Tierra del Fuego. Apart from the distance covered, note the near-straight-line intercept for home. Lower panel is an excursion from Crozet Islands; note how close are the outward and return pathways. (Redrawn from fig. 4b of P. A. Prince *et al.* (1992), Satellite tracking of wandering albatrosses (*Diomedea exulans*) in the South Atlantic, *Antarctic Science*, vol. 4, pp. 31–6 (upper panel) and fig. 8A of H. Weimerskirch *et al.* (1993), Foraging strategy of Wandering Albatrosses through the breeding season: A study using satellite telemetry, *The Auk*, vol. 110, pp. 325–42 (lower panel), with permission of the authors, Cambridge University Press, and *The Auk*.)

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One such ambiguity is how life itself may have originated. As we shall see (in Chapter 4) there is no reason to doubt that it occurred by natural means, but despite the necessary simplicity of the process, the details remain strangely elusive. Life itself is underpinned by a rather simple array of building blocks. Most notable are the four (or more accurately five) nucleotides (that is molecules, such as adenine, consisting of a ring of carbon atoms with an attached nitrogen, a phosphate, and a sugar) that comprise the DNA (and RNA). The other key building blocks are twenty-odd amino acids that when arranged in chains form the polypeptides and ultimately the proteins. Yet, from this, by various elaborations, has arisen the immense diversity of life. At first sight this would seem to encapsulate the entire process of evolution, yet it soon becomes clear that we hardly understand in any detail the links between the molecular substrate and the nature of the organism. To be sure, there is some crude correlation between the total number of genes and the complexity of the organism, but when we learn that the 'worm' of molecular biologists (the nematode *Caenorhabditis elegans*), which has a relatively simple body plan with a fixed number of cells, has more genes than the 'fly' (the fruit-fly *Drosophila*) with its complex form and behaviour, then there should be pause for thought (see Chapter 9).

One response is to reconsider what we mean by 'the gene'. In particular, it is time to move away from a crippling atomistic portrayal and rethink our views. As has been pointed out by numerous workers, the concept of the gene is without meaning unless it is put into the context of what it is coding *for*, not least an extremely sophisticated biochemistry. Nor are these the only complications. It is well known that significant quantities of DNA, at least in the eukaryotic cell (that is a cell with a defined nucleus and organelles such as mitochondria), are never employed in the process of coding. Pejoratively labelled as 'junk DNA' or 'parasitic DNA', it may be just that, silent and surplus DNA churned out by repeated rounds of duplication of genetic material, like an assembly line commandeered by lunatic robots.[5] Such a view fits well with the notion that evolution is a process of blind stupidity, a meaningless trek from primordial pond to glassy oceans dying beneath a swollen Sun.

So, beyond the brute fact that evolution happens, the mechanisms and the consequences remain the subject of the liveliest debate and not infrequently acrimony. But, contrary to the desires and beliefs

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of creation 'science', the reality of evolution as a historical process is not in dispute. And whatever the divergences of opinion, which as often as not have a tacit ideological agenda concerning the origins of human uniqueness, there is a uniform consensus that vitalism was safely buried many years ago, and the slight shaking of the earth above the grave marking the resting place of teleology is certainly an optical illusion. But is it an illusion? Perhaps as the roots and the branches of the Tree of Life are more fully explored our perspectives will begin to shift. Evolution is manifestly true, but that does not necessarily mean we should take it for granted: the end results, be it the immense complexity of a biochemical system or the fluid grace of a living organism, are genuinely awe-inspiring. Could it be that attempts to reinstall or reinject notions of awe and wonder are not simply delusions of some deracinated super-ape, but rather reopen the portals to our finding a metaphysic for evolution? And this in turn might at last allow a conversation with religious sensibilities rather than the more characteristic response of either howling abuse or lofty condescension.

INHERENCY: WHERE IS THE GROUND PLAN IN EVOLUTION?

Although much of this book will be concerned with retelling the minutiae of biological detail in support of the general thesis of the ubiquity of evolutionary convergence and, what is more important, its implications, here is a brief overview of what strike me as the basic tensions in evolution. The first is what, for want of a better name, I might term 'inherency'. A hard-boiled reductionist will dismiss this as a non-problem, but I am not so sure. Perhaps the first obvious clue was the result, surprising at the time, of the minimal genetic difference between ourselves and the chimps. In terms of structural genes the much-quoted difference amounts, it is said, to about 0.4%. If there were any residual doubt of the closeness between *Homo* and *Pan*, then other indicators of similarity, such as the fact that the string of amino acids that make up the protein haemoglobin is identical in number and sequence, are surely a sufficient indicator of our evolutionary proximity. This, of course, confirms the obvious: we and the chimps share an ancestor, probably between about 6 and 12 million years ago, and indeed there is much we have in common. But in other respects we are poles apart. I'm told that chimps driving cars (or at least go-karts) have the time of their lives, but we are neither likely to see a chimp designing a car, nor for that matter mixing the driest of Martinis, let alone being haunted by existentialist doubts.

This problem of inherency, however, is far more prevalent and pervasive than the local quirk that chimps and humans are genomically almost identical, but otherwise separated by an immense gulf of differences. Let us look, for example, at a much deeper stage in our evolution, effectively at the time of the ancestors of the fish. Enter the moderately undistinguished animal known as the lancelet worm or amphioxus (*Branchiostoma* and its relatives, Fig. 1.2). By general agreement this beast is the nearest living approximation to the stage in evolution that preceded the fish, which in turn clambered on to land, moved to using the egg, grew fur, and in one lineage developed into socially alert arborealists. All these changes and shifts must have been accompanied by genetic changes, but if we look back to amphioxus we see a genetic architecture in place that seemingly has no obvious counterpart in its anatomy. To give just one example: the central nervous system of amphioxus is really rather simple. It consists of an elongate nerve cord stretching back along the body, above the precursor of the vertebral column (our backbone, consisting of a row of vertebrae) and a so-called brain. The brain can only be described as a disappointment. It is little more than an anterior swelling (it is called the cerebral vesicle) and has no obvious sign in terms of its morphology of even the beginnings of the characteristic threefold division seen in the vertebrate brain of hind-, mid- and fore-sections. Yet the molecular evidence,[6] which is also backed up by some exquisitely fine studies of microanatomy,[7] suggests that, cryptically, the brain of amphioxus has regions equivalent to the tripartite division seen in the vertebrates.

The clear implication of this is that folded within the seemingly simple brain of amphioxus is what can almost be described as a template for the equivalent organ of the vertebrates: in some sense amphioxus carries the inherent potential for intelligence. Quite how the more complex brain emerges is yet to be established. The evidence that a key development in the molecular architecture of the vertebrates was episodes of gene duplication,[8] that is, doubling up of a gene, could well give one clue. This is because the 'surplus' gene is then potentially available for some new function. It could alternatively be claimed that amphioxus is secondarily simplified (the condition sometimes referred to as *regressive*), but it retained genes for

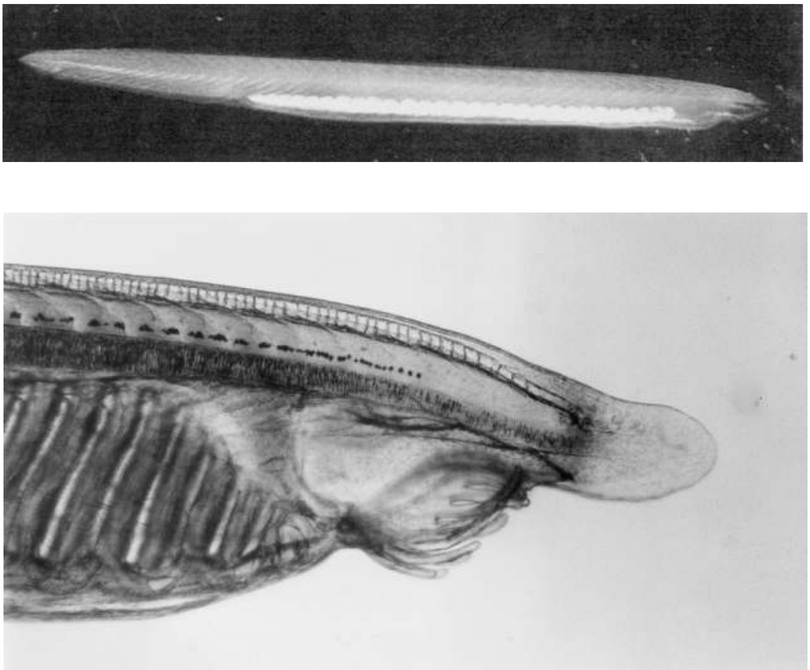

FIGURE 1.2 The amphioxus animal. Upper, entire animal. The anterior end is to the right, with the 'brain' located towards upper side. Prominent white units are gonads. Lower, detail of anterior with prominent feeding (buccal) tentacles and more posteriorly gill bars. The notochord is the longitudinal structure slightly above the mid-line, with closely spaced vertical lines. The nerve cord lies above the notochord, with minimal enlargement at the anterior. (Courtesy of Dale Stokes, Scripps Institution of Oceanography (upper) and Thurston Lacalli, University of Victoria, British Columbia (lower).)

vital functions, although ones no longer specifically connected to the coding for a complex brain. Unfortunately the rather limited information on the earliest amphioxus-like animals, from the Cambrian period (*c*. 545–500 Ma (million years) ago)[9] does not extend to seeing their brains. In general, however, the genomic evidence suggests that the living amphioxus is not in some sense degenerate but is genuinely primitive.

Revealing the foundations of the molecular architecture that underpins our brains and sentience gives us not only a feeling of emergence, but underlines how little we really know about why and how organic complexity arises. Nor is this example of the amphioxus brain

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and its molecular inherency in any way unusual. Equally instructive examples can be culled from the most primitive animals, such as the sponges and *Hydra* (the latter is a relative of the sea-anemones and corals), in which genes (or proteins) that are essential for complex activities in more advanced animals are already present. Doubtless they have their functions, but what these are and how they have been redeployed, co-opted, or realigned in more advanced animals is for the most part still unknown. The unravelling of these evolutionary stories is going to be one of the most fascinating episodes in recent biological history, but what will almost certainly be more extraordinary is how much of organic complexity will be seen to be latent in more primitive organisms. Or perhaps not that extraordinary: it is sometimes forgotten that the main principle of evolution, beyond selection and adaptation, is not the drawing of new plans but relying on the tried and trusted building blocks of organic architecture.

THE NAVIGATION OF PROTEIN HYPERSPACE

Life, then, is full of inherencies. We might legitimately enquire whether there is anything in the human condition that could prefigure some future level of complexity that with the virtue of hindsight will, no doubt, seem to have been inevitable, but to us remains unimaginable. Yet whatever privileges exist for untrammelled speculation, there is a story to be told which will occupy the rest of this book. My critics will, I imagine, complain at its eclectic, if not unorthodox, nature; and given that the topics covered will include such matters as extraterrestrial amino acids and ants pursuing warfare it is advisable to try to explain the underlying thread of the argument. Here we can do no better than to look at a stimulating and thoughtful essay written by Temple Smith and Harold Morowitz,[10] which is an exploration of the tension between the predictabilities of physical systems and the seemingly contingent muddle that we call history. In brief, and their paper contains many other insights, they remind us of the simplicity of the basic building blocks of life, by which is meant such molecules as amino acids (which go to build the proteins, perhaps familiar as collagen or haemoglobin), or sugars (which when joined together can form carbohydrates). In the case of amino acids, however, even with the rather modest total of the 20 available variants and taking a relatively simple protein – consisting, say, of 100 such building blocks – it is immediately apparent that the potential number of combinations in

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which this protein could be assembled is absolutely gigantic. Specifically it is 20^{100}, which is equivalent to 10^{130}.

This is an uncomfortably large number,[11] and, as Smith and Morowitz see it, this immensity of possibilities confers an inherent unpredictability on the process of evolution. Taking the figures given above, that is the 20 available amino acids and their random inclusion in a protein composed of a total of 100 amino acids, Smith and Morowitz then apply some apparently stringent criteria to the selection of those proteins that will actually work. The specific function they have in mind for proteins is as natural catalysts, that is, to function as the organic molecules known as enzymes,[12] which serve to accelerate metabolic processes. The alternative, of course, is that a hypothetical protein will be non-functional, failing in one way or another. We know that in principle this is perfectly feasible, because there are many examples known where only a handful of changes, and sometimes even the substitution of a single amino acid for another one, will render the entire protein inoperative and thereby biologically useless. Let us then suppose that only one in a million proteins will be soluble, a necessary prerequisite for the watery milieu of a cell. Let us further suppose, and again the figure seems reasonable, that of these again only one in a million has a configuration suitable for it to be chemically active. How many potentially enzymatically active soluble proteins with an amino acid length totalling 100 could we expect to be available to life? A few thousand, perhaps even a few million? In fact, the total far exceeds the number of stars in the universe.

As Smith and Morowitz dryly note, ‘It is quite clear from such numerology that the domain of possible organisms is enormously large if not infinite’,[13] especially when we recall that many proteins are substantially longer than 100 amino acids. The only way we can begin to envisage such a protein domain is in the abstract terms of a kind of hyperspace. Mathematically this will encompass all the measurements that together serve to define the totality of this ‘protein space’. As Smith and Morowitz point out, with such an immense number of potential possibilities the number of proteins known to exist on Earth can only be an infinitesmally small fraction of this vast total. As they say, notwithstanding ‘the immensity of the dimensionality of the descriptive hyperspace’, the world we know and the evolutionary processes that define it have ‘produced a very sparsely sampled hyperspace in the actual living world’.[14]

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One inference that might be immediately drawn from this is that in principle the likelihood of any other world employing an area of ‘protein space’ that is even remotely close to that found on Earth should be vanishingly small. At this early stage of the argument we can leave aside, for the moment, the distinct likelihood that Earth-like planets are going to be in exceedingly short supply (Chapter 5), and simply remind ourselves that even as our net of exploration spreads first across the Milky Way and then from galaxy to galaxy, so each time a protein chemist steps on to the surface of a new planet only another tiny fraction of this immense ‘hyperspace’ will be documented. The combinatorial possibilities are so much more immense than all the planets with all their biospheres that most proteins will for ever be only hypothetical constructs. That, at least, is the expectation and it would seem difficult to refute. All other worlds might be expected to be truly alien, at least in so far as the occupation of protein ‘space’ is concerned. That is, at least, the assumption.

THE GAME OF LIFE

Nevertheless, despite Smith and Morowitz’s calculus of immensity, matters are probably much less alien than might at first be imagined. This is because at one level the strings of amino acids and their exact sequence are irrelevant, so long as the protein works effectively. To be sure, specific regions of a protein may be exceedingly sensitive to which amino acid is present, but we also know that various proteins have evolved independently of each other to perform a similar, if not identical, function. Such examples of molecular convergences are examined in more detail later (Chapter 10). What matters here is that these convergences emphatically do not depend on arriving at a closely similar sequence of amino acids, which given the size of protein ‘hyperspace’ would be almost a miracle. Navigation through this ‘hyperspace’ depends rather on two principal properties that, as it happens, underpin all life. The first concerns the remarkable specificities of particular sites within the protein that confer the necessary function, for example in those microbial pathogens whose existence depends on precise molecular mimicry to outwit a host’s defences. The secondary property is that the complex functions that characterize proteins depend not only, in many cases, on highly specific sites, but also on particular architectural forms that are highly recurrent.[15] As we shall see in at least some protein designs, such as those that render tissue transparent (as in an eye lens), transport or store oxygen (for

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