Power, Sex, Suicide

Mitochondria and the Meaning of Life

Part 1. Hopeful Monster: The Origin of the Eukaryotic Cell

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About

Dr Nick Lane is a British biochemist and writer. He was awarded the first Provost's Venture Research Prize in the Department of Genetics, Evolution and Environment at **University College London**, where he is now a Reader in Evolutionary Biochemistry. Dr Lane's research deals with evolutionary biochemistry and bioenergetics, focusing on the origin of life and the evolution of complex cells. Dr Lane was a founding member of the UCL Consortium for Mitochondrial Research, and is leading the UCL Research Frontiers Origins of Life programme. He was awarded the 2011 BMC Research Award for Genetics, Genomics, Bioinformatics and Evolution, and the 2015 Biochemical Society Award for his sustained and diverse contribution to the molecular life sciences and the public understanding of science.

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Are we alone in the universe? Ever since Copernicus showed that the earth and planets orbit the sun, science has marched us away from a deeply held anthropocentric view of the universe to a humbling and insignificant outpost. From a statistical point of view, the existence of life elsewhere in the universe seems to be overwhelmingly probable, but on the same basis it must be so distant as to be meaningless to us. The chances of meeting it would be infinitesimal.

In recent decades, the tide has begun to turn. The shift coincides with the mounting scientific respectability afforded to studies on the origin of life. Once a taboo subject, dismissed as ungodly and unscientific speculation, the origin of life is now seen as a solvable scientific conundrum, and is being inched in upon from both the past and the future. Starting at the beginning of time and moving forwards, cosmologists and geologists are trying to infer the likely conditions on the early earth that might have given rise to life, from the vaporizing impacts of asteroids and the hell-fire forces of vulcanism, to the chemistry of inorganic molecules and the self-organizing properties of matter. Starting in the present and moving backwards in time, molecular biologists are comparing the detailed genetic sequences of microbes in an attempt to construct a universal tree of life, right down to its roots. Despite continuing controversies about exactly how and when life began on earth, it no longer seems as improbable as we once imagined, and probably happened much faster than we thought. The estimates of 'molecular clocks' push back the origin of life to a time uncomfortably close to the period of heavy bombardment that cratered the moon and earth 4000 million years ago. If it really did happen so quickly in our boiling and battered cauldron, why not everywhere else?

This picture of life evolving amidst the fire and brimstone of primordial earth gains credence from the remarkable capacity of bacteria to thrive, or at least survive, in excessively hostile conditions today. The discovery, in the late 1970s, of vibrant bacterial colonies in the high pressures and searing temperatures of sulphurous hydrothermal vents at the bottom of the oceans (known as 'black smokers') came as a shock. The complacent belief that all life on earth ultimately depended on the energy of the sun, channelled through the photosynthesis of organic compounds by bacteria, algae and plants, was overturned at a stroke. Since then, a series of shocking discoveries has revolutionized our perception of life's orbit. Self-sufficient (autotrophic) bacteria live in countless numbers in the 'deep-hot biosphere', buried up to several miles deep in the rocks of the earth's crust. There they scrape a living from the minerals themselves, growing so slowly that a single generation may take a million years to reproduce – but they are undoubtedly alive (rather than dead or latent). Their total biomass is calculated to be similar to the total bacterial biomass of the entire sunlit surface world. Other bacteria survive radiation at the genetically crippling doses found in outer space, and thrive in nuclear power stations or sterilized tins of meat. Still others flourish in the dry valleys of Antarctica, or freeze for millions of years in the Siberian permafrost, or tolerate acid baths and alkaline lakes strong enough to dissolve rubber boots. It is hard to imagine that such tough bacteria would fail to survive on Mars if seeded there, or could not hitch a lift on comets blasted across deep space. And if they could survive there, why should they not evolve there? When handled with the adept publicity of NASA, ever eager to scrutinise Mars and the deepest reaches of space for signs of life, the remarkable feats of bacteria have fostered the rise and rise of the nascent science of astrobiology.

The success of life in hostile conditions has tempted some astrobiologists to view living organisms as an emergent property of the universal laws of physics. These laws seem to favour the evolution of life in the universe that we see around us: had the constants of nature been ever-so-slightly different, the stars could not have formed, or would have burnt out long ago, or never generated the nurturing warmth of the sun's rays. Perhaps we live in a multiverse, in which each universe is subject to different constants and we, inevitably, live in what Martin Rees calls a biophilic universe, one of a small set in which the fundamental constants favour life. Or perhaps, by an unknown quirk of particle physics, or a breathtaking freak of chance, or by the hand of a benevolent Creator, who put in place the biophilic laws, we are lucky enough to live in a true universe that does favour life. Either way, our universe apparently kindles life. Some thinkers go even further, and see the eventual evolution of humanity, and in particular of human consciousness, as an inevitable outcome of the universal laws, which is to say the precise weightings of the fundamental constants of physics. This amounts to a modern version of the clockwork universe of Leibniz and Newton, parodied by Voltaire as 'All is for the best in the best of all possible worlds.' Some physicists and cosmologists with a leaning towards biology find a spiritual grandeur in this view of the universe as the midwife of intelligence. Such insights into the innermost workings of nature are celebrated as a 'window' into the mind of God.

Most biologists are more cautious, or less religious. Evolutionary biology holds more cautionary tales than just about any other science, and the erratic meanderings of life, throwing up weird and improbable successes, and demolishing whole phyla by turns, seems to owe more to the contingencies of history than to the laws of physics. In his famous book Wonderful Life, Steven Jay Gould wondered what might happen if the film of life were to be replayed over and over again from the beginning: would history repeat itself, leading inexorably each time to the evolutionary pinnacle of mankind, or would we be faced with a new, strange and exotic world each time? In the latter case, of course, 'we' would not have evolved to see it. Gould has been criticised for not paying due respect to the power of convergent evolution, which is the tendency of organisms to develop similarities in physical appearance and performance, regardless of their ancestry, so that anything which flies will develop similar-looking wings; anything that sees will develop similar-looking eyes. This criticism was propounded most passionately and persuasively by Simon Conway Morris, in his book Life's Solution. Conway Morris, ironically, was one of the heroes of Gould's book, Wonderful Life, but he opposes that book's sweeping conclusion. Play back the film of life, says Conway Morris, and life will flow down the same channels time and time again. It will do so because there are only so many possible engineering solutions to the same problems, and life will always tend to find the same solutions, whatever they may be. All of this boils down to a tension between contingency and convergence. To what extent is evolution ruled by the chance of contingency, versus the necessity of convergence? For Gould all is contingent; for Conway Morris, the question is, would an intelligent biped still have four fingers and a thumb?

Conway Morris's point about convergent evolution is important in terms of the evolution of intelligence here or anywhere else in the universe. It would be disappointing to discover that no form of higher intelligence had ever managed to evolve elsewhere in the universe. Why? Because very different organisms should converge on intelligence as a good solution to a common problem. Intelligence is a valuable evolutionary commodity, opening new niches for those clever enough to occupy them. We should not think only of ourselves in this sense: some degree of intelligence, and in my view conscious self-awareness, is widespread among animals, from dolphins to bears to gorillas. Humanity evolved quickly to fill the 'highest' niche, and a number of contingent factors no doubt facilitated this rise; but who is to say that, given a vacated niche and a few tens of millions of years, the kind of foraging bears that break into cars and dustbins could not evolve to fill it? Or why not the majestic and intelligent giant squid? Perhaps it was little more than chance and contingency that led to the rise of Homo sapiens, rather than any of the other extinct lines of Homo, but the power of convergence always favoured the niche. While we are the proud possessors of uniquely well-developed minds, there is nothing particularly improbable about the evolution of intelligence itself. Higher intelligence could evolve here again, and by the same token anywhere else in the universe. Life will keep converging on the best solutions.

The power of convergence is illustrated by the evolution of 'good tricks' like flight and sight. Life has converged on the same solutions repeatedly. While repeated evolution does not imply inevitability, it does change our perception of probability. Despite the obviously difficult engineering challenges involved, flight evolved independently no less than four times, in the insects, the pterosaurs (such as pterodactyls), the birds and the bats. In each case, regardless of their different ancestries, flying creatures developed rather similar-looking wings, which act as aerofoils – and we too have paralleled this design feature in aeroplanes. Similarly, eyes have evolved independently many times, each time following a limited set of design specifications: the familiar 'camera eye' of mammals and (independently) the squid; and the compound eyes of insects and extinct groups such as trilobites. Again, we too have invented cameras that work along similar principles. Dolphins and bats developed sonar navigation systems independently, and we invented our own sonar system before we knew that dolphins and bats took soundings in this way. All these systems are exquisitely complex and beautifully adapted to needs, but the fact that each has evolved independently on several occasions implies that the odds against their evolution were not so very great.

If so, then convergence outweighs contingency, or necessity overcomes chance. As Richard Dawkins concluded, in The Ancestors Tale, "I am tempted by Conway Morris's belief that we should stop thinking of convergent evolution as a colourful rarity to be remarked and marvelled at when we find it. Perhaps we should come to see it as the norm, exceptions to which are occasions for surprise." So if the film of life is played back over and over again, we may not be here to see it ourselves, but intelligent bipeds ought to be able to gaze up at flying creatures, and ponder the meaning of the heavens.

If the origin of life amidst the fire and brimstone of early Earth was not as improbable as we once thought (more on this in Part 2), and most of the major innovations of life on earth all evolved repeatedly, then it is reasonable to believe that enlightened intelligent beings will evolve elsewhere in our universe. This sounds reasonable enough, but there is a nagging doubt. On earth, all of this engineering flamboyance evolved in the last 600 million years, barely a sixth of the time in which life has existed. Before that, stretching back for perhaps more than 3000 million years, there was little to see but bacteria and a few primitive organisms like algae. Was there was some other brake on evolution, some other contingency that needed to be overcome before life could really get going?

The most obvious brake, in a world dominated by simple single-celled organisms, is the evolution of large multicellular creatures, in which lots of cells collaborate together to form a single body. But if we apply the same yardstick of repeatability, then the odds against multicellularity do not seem particularly high. Multicellular organisms probably evolved independently quite a few times. Animals and plants certainly evolved large size independently; so too (probably) did the fungi. Similarly, multicellular colonies may have evolved more than once among the algae – the red, brown and green algae are ancient lineages, which diverged more than a billion years ago, at a time when single-celled forms were predominant. There is nothing about their organization or genetic ancestry to suggest that multicellularity arose only once among the algae. Indeed, many are so simple that they are better viewed as large colonies of similar cells, rather than true multicellular organisms.

At its most basic level a multicellular colony is simply a group of cells that divided but failed to separate properly. The difference between a colony and a true multicellular organism is the degree of specialization (differentiation) among genetically identical cells. In ourselves, for example, brain cells and kidney cells share the same genes but are specialized for different tasks, switching on and off whichever genes are necessary. At a simpler level, there are numerous examples of colonies, even bacterial colonies, in which some differentiation between cells is normal. Such a hazy boundary between a colony and a multicellular organism can confound our interpretation of bacterial colonies, which some specialists argue are better interpreted as multicellular organisms, even if most ordinary people would view them as little more than slime. But the important point is that the evolution of multicellular organisms does not appear to have presented a serious obstacle to the inventive flow of life. If life got stuck in a rut, it wasn't because it was so hard to get cells to cooperate together.

In Part 1, I shall argue that there was one event in the history of life that was genuinely unlikely, which was responsible for the long delay before life took off in all its extravagance. If the film of life were played back over and over again, it seems to me likely that it would get stuck in the same rut virtually every time: we would be faced with a planet full of bacteria and little else. The event that made all the difference here was the evolution of the eukaryotic cell, the first complex cells that harbour a nucleus. An esoteric term like ‘eukaryotic cell’ might seem a quibbling exception, but the fact is that all true multicellular organisms on earth, including ourselves, are built only from eukaryotic cells: all plants, animals, fungi and algae are eukaryotes. Most specialists agree the eukaryotic cell evolved only once. Certainly, all known eukaryotes are related – all of us share exactly the same genetic ancestry. If we apply the same rules of probability, then the origin of the eukaryotic cell looks far more improbable than the evolution of multicellular organisms, or flight, sight and intelligence. It looks like genuine contingency, as unpredictable as an asteroid impact.

What has all this to do with mitochondria, you may be wondering? The answer stems from the surprising finding all eukaryotes either have, or once had, mitochondria. Until quite recently, mitochondria had seemed almost incidental to the evolution of eukaryotes, a nicety rather than a necessity. The really important development, after which eukaryotes are named, was the evolution of the nucleus. But now this is perceived differently. Recent research suggests that the acquisition of mitochondria was far important than simply plugging an efficient power-supply into an already complicated cell, with a nucleus brimming with genes – it was the single event that made the evolution of complex eukaryotic cells possible at all. If the mitochondrial merger had not happened then we would not be here today, nor would any other form of intelligent or genuinely multicellular life. So the question of contingency boils down to a practical matter: how did mitochondria evolve?

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