Power, Sex, Suicide

Mitochondria and the Meaning of Life

Part 4. Power Laws: Size and the Ramp of Ascending Complexity

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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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Size is a dominating bias in biology. By and large, we are mostly interested in the largest life-forms – the plants, animals and fungi that we can actually see. Our interest in bacteria or viruses tends to be anthropocentric, a morbid curiosity, probing into the horrors of the diseases that they cause, and the more gruesome the better. Necrotizing bacteria that chew up whole limbs in a matter of days can hardly but attract more attention than the myriad microscopic plankton that exert such a profound influence on our planet's climate and atmosphere. Textbooks on microbiology tend to focus disproportionately on pathogens, despite the fact that only a tiny proportion of microbes actually cause disease. When we search for signs of life in space, we are really seeking extraterrestrial intelligence: we want proper aliens with twisting tentacles, not microscopic bacteria.

In the last few chapters, we have considered the origins of biological complexity: why it was that bacteria gave rise to our own remotest ancestors, the first eukaryotes – morphologically complex cells with nuclei and organelles such as mitochondria. I have argued that the fundamental mechanism of energy generation in cells made symbiosis necessary for the evolution of complexity: eukaryotic cells almost certainly could not have evolved by natural selection alone. Generating energy using mitochondria inside the cell made this leap possible. While symbiosis is commonplace in eukaryotic cells, however, endosymbiosis in bacteria (in which one bacterium lives inside another) is far less common. It seems that bacterial endosymbiosis gave rise to the complex eukaryotic cell on just one occasion, perhaps by way of the improbable train of events discussed in Part 1.

Yet once the first eukaryotes had evolved, we can legitimately talk about a ramp of ascending complexity: the progression from single cells to human beings certainly looks like a ramp, more than a little dizzying, even if we are deceived by appearances. Now a larger question looms: what drove the eukaryotes to acquire greater size and complexity? One answer that was popular in Darwin's day, and which enabled many biologists to reconcile evolution and religion, is that life innately becomes more complex. According to this line of reasoning, evolution leads to greater complexity in the same way that an embryo develops into an adult – it follows instructions, ordained by God, in which each step approaches closer to Heaven. Many of our turns of phrase, such as 'higher organisms' and the 'ascent of man', hark back to this philosophy, and are in common currency today despite the admonitions of evolutionists right back to Darwin himself. Such metaphors are powerful and poetic, but can be profoundly misleading. Another visually striking metaphor, that electrons orbit the nucleus of an atom in the same way that planets orbit the sun, long concealed the fantastic mysteries of quantum mechanics. The idea that evolution is akin to embryonic development conceals the fact that evolution has no foresight: it cannot operate as a program (whereas the development of an embryo is necessarily programmed by the genes). So complexity can't have evolved with the distant goal of approaching closer to God, but only as an immediate payback for an immediate advantage.

If the evolution of complexity was not programmed, are we to believe that it occurred merely by chance, or was it an inevitable outcome of the workings of natural selection? The fact that bacteria never showed the least tendency to become more complex (morphologically) argues against the possibility that natural selection inevitably favours complexity. Numerous other examples show that natural selection is as likely to favour simplicity as complexity. On the other hand, we have seen that bacteria are stymied by their respiration problem, but eukaryotes are not. Did complexity perhaps evolve in eukaryotes just because it could? Ridding himself of higher religious connotations, Steven Jay Gould once compared complexity with the random meanderings of drunkard: if a wall blocks his passage on one side of the pavement, then the drunkard is more likely to end up in the gutter, simply because there is nowhere else for him to go. In the case of complexity, the metaphorical wall is the base of life: it is not possible to be any simpler than a bacterium (at least as an independent organism), so life's random walk could only have been towards greater complexity. A related view is that life became more complex because evolutionary success was more likely to be found in the exploitation of new niches – an idea known as the 'pioneering' theory. Given that the simplest niches were already occupied by bacteria, the only direction in which life could evolve was towards greater complexity.

Both these arguments imply there was no intrinsic advantage to complexity – in other words, there was no trait inherent to the eukaryotes that encouraged the evolution of greater complexity – it was simply a response to the possibilities offered by the environment. I don't doubt for a moment that both of these theories account for certain trends in evolution, but I do find it hard to swallow that the entire edifice of complex life on Earth was erected by what amounts to evolutionary drift. The trouble with drift is its lack of direction, and I can't help but feel there is something inherently directed about eukaryotic evolution. The great chain of being may be an illusion, but it is a compelling one, one that held mankind in its sway for 2000 years (since the ancient Greeks). Just as we must account for the apparent evolution of 'purpose' in biology (the heart as a pump, etc), so too we must account for the apparent trajectory towards greater complexity. Can a random walk, stopping off at vacant niches on the way, really produce something that even looks like a ramp of complexity? To twist Steven Jay Gould's analogy, how come so many meandering drunkards didn't end up in the gutter, but actually succeeded in crossing the road?

One possible solution, inherent to eukaryotic cells but not to bacteria, is sex. That there is a link between sex and complexity has been argued persuasively by Mark Ridley in Mendel's Demon. The trouble with asexual reproduction, says Ridley, is that it is not good at eliminating copying errors and harmful mutations in genes. The larger the genome, the greater the probability of a catastrophic error. The recombination of genes in sexual reproduction may lower this risk of error, and so raise the number of genes an organism can tolerate before undergoing a mutational meltdown (although this has never been proved). Clearly, however, the more genes an organism accumulates, the greater its possible complexity, so the invention of sex in eukaryotes might have opened the gates to complexity. While there is almost certainly some truth in this argument, there are also problems with the idea that sex stands at the gateway to complexity, as Ridley himself concedes. In particular, the number of genes in bacteria is well below the theoretical asexual limit, even if they relied on asexual reproduction alone, which they do not (lateral gene transfer in bacteria helps restore genetic integrity). Ridley acknowledges that the data are ambivalent, and the asexual limit to gene number may fall somewhere between fruit flies and human beings – if so the gates of complexity could hardly have been thrown open by the evolution of sex. Something else must have been the gatekeeper.

I do think there was an inherent tendency for eukaryotes to grow larger and more complex, but the reason relates to energy rather than sex. The efficiency of energy metabolism may have been the driving force behind the rampant ascent of eukaryotes to diversity and complexity. The same principles underpin energetic efficiency in all eukaryotic cells, giving an impetus to the evolution of larger size in both unicellular and multicellular organisms, whether plants, animals or fungi. Rather than being a random walk through vacant niches, or a march driven by the imperative of sex, the trajectory of eukaryotic evolution is better explained as an inherent tendency to become larger, with an immediate payback for an immediate advantage – the economy of scale. As animals become larger, their metabolic rate falls, giving them a lower cost of living.

I am here conflating size with complexity. Even if it is true that greater size is favoured by a lower cost of living, is there really a connection between size and complexity? Complexity is not an easy term to define, and in attempting to do so we are inevitably biased towards ourselves: we tend to think of complex beings in terms of their intellect, behaviour, emotions, language, and so on, rather than, for example, a complex life-cycle, as in an insect with its drastic morphological transitions, from caterpillar to butterfly. In particular, I am not alone in my bias towards larger size: for most of us, I suspect, a tree appears more complex than a blade of grass, even though, in terms of photosynthetic machinery, grasses might be said to be more highly evolved. We insist that multicellular creatures are more complex than bacteria, even though the biochemistry of bacteria (as a group) is far more sophisticated than anything we eukaryotes can muster. We are even inclined to see patterns in the fossil record implying an evolutionary trend towards greater size (and presumably complexity), known as Cope's Rule. While accepted with little question for a century, several systematic studies in the 1990s suggested that the trend is nought but an illusion: different species are equally likely to become smaller as they are larger. We are so mesmerized by our fellow large creatures that we easily overlook the smaller ones.

So do we conflate size with complexity, or is it fair to say that larger organisms are in general more complex? Any increment in size brings along a new set of problems, many of which are related to the troublesome ratio of surface area to volume that we discussed in the previous chapter. Some of these issues were highlighted by the great mathematical geneticist JBS Haldane, in a delightful 1927 essay entitled On Being the Right Size. Haldane considered the example of a microscopic worm, which has a smooth skin across which oxygen can diffuse, a straight gut for absorbing food, and a simple kidney for excretion. If its size were increased tenfold in each dimension, its mass would rise by 103, or 1000-fold. If all the worm's cells retained the same metabolic rate it would need to take up a thousand times more oxygen and food, and excrete a thousand times more waste. The trouble is that if its shape didn't change, then its surface area (which is a two-dimensional sheet) would increase by a factor of 102, or 100-fold. To match the heightened requirements, each square millimetre of gut or skin would need to take up 10 times more food or oxygen every minute, while its kidneys would need to excrete 10 times as much waste.

At some point a limit must be reached, beyond which larger size can be attained only by way of specific adaptations. For example, specialised gills or lungs increase the surface area for taking up oxygen (a man has a hundred square metres of lung), while the absorptive area of the gut is increased by folding. All these refinements require greater morphological, and supporting genetic, complexity. Accordingly, larger organisms tend to have a larger number of specialised cell types (anything up to 200 in humans, depending on the definition we use), and more genes. As Haldane put it: “The higher animals are not larger than the lower because they are more complicated. They are more complicated because they are larger. Comparative anatomy is largely the story of the struggle to increase surface area in proportion to volume.”

As if the purely geometric obstacles to large size were not intractable enough, there are other disadvantages to being big. Large animals struggle to fly, burrow, penetrate thick vegetation, or walk on boggy ground. The consequences of a fall for large animals can be catastrophic, as the air resistance during a fall is proportional to the surface area (which is smaller, relative to body mass, for large animals). If we drop a mouse down a mineshaft, it will be briefly stunned, before scampering away. If we drop a man, he will break; if we drop a horse, according to Haldane, it will ‘splash’ (though I’m not sure how he knew). Life looks bleak for giants; why bother getting bigger? Again, Haldane offers a few reasonable answers: larger size gives greater strength, which aids in the struggle for a mate, or in the battle between predator and prey; larger size can optimise the function of organs, such as the eyes, which are built from sensory cells of fixed size (so more cells means larger eyes and better vision); larger size reduces the problems of water tension, which can be lethal for insects (often forcing them to drink using a proboscis); and larger size retains heat (and for that matter water) better, which explains why small mammals and birds are rarely found anywhere near the poles.

These answers make good sense, but they betray a mammal-centric view of life: none begins to explain why something as large as a mammal should have evolved in the first place. The question I’m interested in answering is not whether large mammals are better adapted than small mammals, but why it was that small cells gave rise to large cells, then larger organisms, and finally to highly dynamic, energetic creatures like ourselves; in essence, why anything exists that we can see at all. If being larger demands greater complexity, which has an immediate cost – a need for new genes, better organization, more energy – was there any immediate payback, some advantage to being bigger for its own sake, which could counter-balance the costly new organization? In this Part, we’ll consider the possibility that the ‘power laws’ of biological scaling may have underpinned the apparent trajectory towards greater complexity that seems to have characterized the rise of the eukaryotes, while forever defying the bacteria.

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