LIFE ASCENDING

‘Lane is that particularly rare breed: a scientist who can not only offer a bird’s-eye view of an entire field but also tell you about his own very interesting ideas.’ Carl Zimmer, *Science*

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‘A writer who is not afraid to think big – and think hard’ Frank Wilczek, 2004 Nobel Laureate in Physics

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The Ten Great Inventions of Evolution

NICK LANE

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For my mother and father
Now I am a parent I appreciate all you have done for me more than ever

INTRODUCTION

The Ten Great Inventions of Evolution

Set against the consuming blackness of space, the earth is a beguiling blue-green ball. Barely two dozen people have ever experienced the emotion of seeing our planet from the moon and beyond, yet the fragile beauty of the pictures they sent back home is engraved in the minds of a generation. Nothing compares. Petty human squabbles over borders and oil and creed vanish in the knowledge that this living marble surrounded by infinite emptiness is our shared home, and more, a home we share with, and owe to, the most wonderful inventions of life.

Life itself transformed our planet from the battered and fiery rock that once orbited a young star, to the living beacon that is our world seen from space. Life itself turned our planet blue and green, as tiny photosynthetic bacteria cleansed the oceans of air and sea, and filled them with oxygen. Powered by this new and potent source of energy, life erupted. Flowers bloom and beckon, intricate corals hide darting gold fish, vast monsters lurk in black depths, trees reach for the sky, animals buzz and lumber and see. And in the midst of it all, we are moved by the untold mysteries of this creation, we cosmic assemblies of molecules that feel and think and marvel and wonder at how we came to be here.

For the first time in the history of our planet, we know. This is no certain knowledge, no stone tablet of truth, but the ripening fruits of mankind's greatest quest, to know and understand the living world around us and within us. We have understood in outline since Darwin, of course, whose *Origin of Species* was published 150 years ago. Since Darwin our knowledge of the past has been fleshed out not only with fossils filling in gaps, but with an understanding of the intimate structure of the gene – an understanding that now underpins every stitch in the rich tapestry of life. And yet it is only in the last decades that we have moved from theory and abstract knowledge to a vibrant and detailed picture of life, written in languages that we have only recently begun to translate, and which hold the keys not only to the living world around us but also to the most remote past.

The story that unfurls is more dramatic, more compelling, more intricate than any creation myth. Yet like any creation myth, it is a tale of transformations, of sudden and spectacular changes, eruptions of innovation that transfigured our planet, overwriting past revolutions with new layers of complexity. The tranquil beauty of our planet from space belies the real history of this place, full of strife and ingenuity and change. How ironic that our own petty squabbles reflect our planet's turbulent past, and that we alone, despoilers of the Earth, can rise above it to see the beautiful unity of the whole.

Much of this planetary upheaval was catalysed by two handfuls of evolutionary innovations, inventions that changed the world and ultimately made possible our own lives. I must clarify what I mean by invention, for I don't want to imply a deliberate inventor. The Oxford English Dictionary defines an invention as: 'The original contrivance or production of a new method or means of doing something, previously unknown; origination, introduction.' Evolution has no foresight, and does not plan for the future. There is no inventor, no intelligent design. Nonetheless, natural selection subjects all traits to the most exacting tests, and the best designs win out. It is a natural laboratory that belittles the human theatre, scrutinising trillions of tiny differences simultaneously, each and every generation. Design is all around us, the product of blind but ingenious processes. Evolutionists often talk informally of inventions, and there is no better word to convey the astonishing creativity of nature. To gain an insight into how all this came about is the shared goal of scientists, whatever their religious beliefs, along with anyone else who cares about how we came to be here.

This book is about the greatest inventions of evolution, how each one transformed the living world, and how we humans have learned to read this past with an ingenuity that rivals nature herself. It is a celebration of life's marvellous inventiveness, and of our own. It is, indeed, the long story of how we came to be here – the milestones along the epic journey from the origin of life to our own lives and deaths. It is a book grand in scope. We shall span the length and breadth of life, from its very origins in deep-sea vents to human consciousness, from tiny bacteria to giant dinosaurs. We shall span the sciences, from geology and chemistry to neuroimaging, from quantum physics to planetary science. And we shall span the range of human achievement, from the most celebrated scientists in history to researchers as yet little known, if destined one day, perhaps, to be famous.

My list of inventions is subjective, of course, and could have been different; but I did apply four criteria which I think restrict the choice considerably to a few seminal events in life's history.

The first criterion is that the invention had to revolutionise the living world, and so the planet as a whole. I mentioned photosynthesis already, which turned the Earth into the supercharged, oxygen-rich planet we know (without which animals are impossible). Other changes are less obvious, but almost equally pervasive. Two inventions with the most widespread consequences are movement, which allowed animals to range around in search of food, and sight, which transformed the character and behaviour of all living organisms. It may well be that the swift evolution of eyes, some 540 million years ago, contributed in no small measure to the sudden appearance of proper animals in the fossil record, known as the Cambrian explosion. I discuss the Earth-moving consequences of each invention in the introductions to individual chapters.

My second criterion is that the invention had to be of surpassing importance today. The best examples are sex and death. Sex has been described as the ultimate existential absurdity, and that is to ignore the Kama Sutra's worth of contorted mental postures, from angst to ecstasy, and focus only on the peculiar mechanics of sex between cells. Why so many creatures, even plants, indulge in sex when they could just quietly clone copies of themselves is a conundrum that we are now very close to answering. But if sex is the ultimate existential absurdity, then death must be the ultimate non-existential absurdity. Why do we grow old and die, suffering along the way the most harrowing and dreadful diseases? This most modern preoccupation is not dictated by thermodynamics, the laws of mounting chaos and corruption, for not all living things age, and even those that do can flip a switch and stop. We shall see that evolution has extended the lifespan of animals by an order of magnitude, time and again. The anti-ageing pill should not be a myth.

The third criterion is that each invention had to be a direct outcome of evolution by natural selection, rather than, for example, cultural evolution. I am a biochemist, and I have nothing original to say about language or society. And yet the substrate for all we have achieved, all that is human, is consciousness. It is hard to picture any form of shared language or society that is not underpinned by shared values, perceptions or feelings, wordless feelings like love, happiness, sadness, fear, longing, hope, belief. If the human mind evolved, we must explain how nerves firing in the brain can give rise to the sense of immaterial spirit, to the subjective intensity of feelings. For me, this is a biological problem, if still a vexed one, as I endeavour to justify in Chapter 9. So consciousness is 'in' as one of the great inventions; language and society are out, as more the products of cultural evolution.

My final criterion is that the invention had to be iconic in some way. The supposed perfection of the eye is perhaps the archetypal challenge, dating back to Darwin and before. Since then the eye has been addressed many times, in many ways, but the explosion of genetic insights in the last decade offers a new resolution, an unexpected ancestry. The spiralling double helix of DNA is the greatest icon of our information age. The origin of complex cells (the 'eukaryotic' cell) is another iconic subject, albeit better known among scientists than the lay public. This milestone has been one of the most hotly contested matters among evolutionists over the last four decades, and is crucially important to the question of how widespread complex life might be across the universe. Each chapter deals in its way with iconic issues such as these. At the outset, I discussed my list with a friend, who proposed 'the gut' as emblematic of animals, in place of movement. The idea falters in its status as an icon: to my mind at least the power of muscle is iconic – think only of the glories of flight – the gut, without powered movement, is but a sea squirt, a swaying pillar of intestines tied to a rock. Not iconic.

Beyond these more formal criteria, each invention had to catch my own imagination. These are the inventions that I, as a passionately curious human being, most wanted to understand myself. Some I have written about before, and wanted to address again in a broader setting; others, like DNA, exert a kind of fatal attraction for all inquisitive minds. The unravelling of clues buried deep in its structure is one of the great scientific detective stories of the last half-century, and yet somehow remains little known even among scientists. I can only hope I have succeeded in conveying some of my own thrill in the chase. Hot blood is another example, an area of furious controversy, for there is still little consensus about whether the dinosaurs were active hot-blooded killers, or slothsome giant lizards, whether the hot-blooded birds evolved directly from close cousins of *T. rex*, or had nothing to do with dinosaurs. What better chance to review the evidence myself!

So we have a list. We start with the origin of life itself, and end with our own deaths and prospects for immortality, by way of such pinnacles as DNA, photosynthesis, complex cells, sex, movement, sight, hot blood and consciousness.

But before we start, I must say a few words about the leitmotiv of this introduction: the new 'languages' that afford such insights into the depths of evolutionary history. Until recently, there have been two broad paths into the past: fossils and genes. Both have enormous power to breathe life into the past, but each has its flaws. The supposed 'gaps' in the fossil record are oversung, and many have been laboriously filled in over the 150 years since Darwin worried about them. The trouble is that fossils, through the very conditions that favour their preservation, cannot and do not hold an undistorted mirror to the past. The fact that we can glean so much from them is remarkable. Likewise, comparing the details of gene sequences enables us to build genealogical trees, which show precisely how we are related to other organisms. Unfortunately, genes ultimately diverge to the point that they no longer have anything in common: beyond a certain point, the past, as read by genes, becomes garbled. But there are powerful methods that go beyond genes and fossils, far back into the deepest past, and this book is in part a celebration of their acuity.

Let me give a single example, one of my own favourites, which never found the opportunity for a mention in the book proper. It concerns a protein (a catalyst, or enzyme, called citrate synthase) which is so central to life that it is found in all living organisms, from bacteria to man. This enzyme has been compared in two different species of bacteria, one living in superhot hydrothermal vents, the other in the frozen Antarctic. The gene sequences that encode these enzymes are different; they have diverged to the point that they are now quite distinct. We know that they *did* diverge from a common ancestor, for we see a spectrum of intermediates in bacteria living in more temperate conditions. But from the gene sequences alone there is little more we can say. They diverged, surely because their living conditions are so different, but this is abstract theoretical knowledge, dry and two-dimensional.

But now look at the molecular structure of these two enzymes, pierced by an intense beam of X-rays and deciphered through the wonderful advances in crystallography. The two structures are superimposable, so similar to each other that each fold and crevice, each niche and protrusion, is faithfully replicated in the other, in all three dimensions. An untutored eye could not distinguish between them. In other words, despite a large number of building blocks being replaced over time, the overall shape and structure of the molecule – and thus its function – has been preserved throughout evolution, as if it were a cathedral built in stone, and rebuilt from within using bricks, without losing its grand architecture. And then came another revelation. Which building blocks got switched and why? In the superhot vent bacteria, the enzyme is as rigid as possible. The building blocks bind tightly to each other, through internal bonds that work like cement, retaining the structure despite the buffeting of energy from the boiling vents. It is a cathedral built to withstand perpetual earthquakes. In the ice, the picture is reversed. Now the building blocks are flexible, allowing movement despite the frost. It's as if the cathedral were rebuilt with ball-bearings, rather than bricks. Compare their activity at 6°C, and the frosty enzyme is twenty-nine times as fast; but try at 100°C, and it falls to pieces.

The picture that emerges is colourful and three-dimensional. The changes in gene sequence now have meaning: they preserve the structure of the enzyme and its function, despite the need to operate under totally different conditions. We can now see what actually happened over evolution, and why. It is no longer merely intimation, but real insight.

Similarly vivid insights into what actually happened can be gained from other clever tools now available. Comparative genomics, for one, allows us to compare not just genes, but full genomes, thousands of genes at once, in hundreds of different species. Again, this has only been possible in the last few years, as whole genome sequences have proliferated. Then proteomics allows us to capture the spectrum of proteins working within a cell at any one time, and to grasp how this spectrum is controlled by a small number of regulatory genes that have been preserved down the aeons of evolution. Computational biology enables us to identify particular shapes and structures, motifs, which persist in proteins despite changes in genes. Isotopic analyses of rocks or fossils allow us to reconstruct past changes in the atmosphere and climate. Imaging techniques let us to see the function of neurons in the brain while we think, or to reconstruct the three-dimensional structure of microscopic fossils embedded in rocks without disturbing them. And so on.

None of these techniques is new. What *is* new is their sophistication, speed and availability. Like the Human Genome Project, which accelerated to a crescendo well ahead of schedule, the pace at which data are accumulating is dizzying. Much of this information is written not in the classical tongues of population genetics and palaeontology, but in the language of molecules, the level at which change actually occurs in nature. With these new techniques, a new breed of evolutionist is emerging, able to capture the workings of evolution in real time. The picture so painted is breathtaking in its wealth of detail and its compass, ranging from the subatomic to the planetary scale. And that is why I said that, for the first time in history, we know. Much of our growing body of knowledge is provisional, to be sure, but it is vibrant and meaningful. It is a joy to be alive at this time, when we know so much, and yet can still look forward to so much more.

1

THE ORIGIN OF LIFE

From Out the Turning Globe

Night followed day in swift succession. On earth at that time a day lasted for only five or six hours. The planet spun madly on its axis. The moon hung heavy and threatening in the sky, far closer, and so looking much bigger, than today. Stars rarely shone, for the atmosphere was full of smog and dust, but spectacular shooting stars regularly threaded the night sky. The sun, when it could be seen at all through the dull red smog, was watery and weak, lacking the vigour of its prime. Humans could not survive here. Our eyes would not bulge and burst, as they may on Mars; but our lungs could find no breath of oxygen. We'd fight for a desperate minute, and asphyxiate.

The earth was named badly. 'Sea' would have been better. Even today, oceans cover two-thirds of our planet, dominating views from space. Back then, the earth was virtually all water, with a few small volcanic islands poking through the turbulent waves. In thrall to that looming moon, the tides were colossal, ranging perhaps hundreds of feet. Impacts of asteroids and comets were less common than they had been earlier, when the largest of them flung off the moon; but even in this period of relative tranquillity, the oceans regularly boiled and churned. From underneath, too, they seethed. The crust was riddled with cracks, magma welled and coiled, and volcanoes made the underworld a constant presence. It was a world out of equilibrium, a world of restless activity, a feverish infant of a planet.

It was a world on which life emerged, 3,800 million years ago, perhaps animated by something of the restlessness of the planet itself. We know because a few grains of rock from that bygone age have survived the restless aeons to this very day. Inside them are trapped the tiniest specks of carbon, which bear in their atomic composition the nearly unmistakable imprint of life itself. If that seems a flimsy pretext for a monumental claim, perhaps it is; there isn't a full consensus among experts. But strip away a few more skins from the onion of time and, by 3,400 million years ago, the signs of life are unequivocal. The world was heaving with bacteria then, bacteria that left their mark not just in carbon signatures but in microfossils of many diverse forms and in those domed cathedrals of bacterial life, the metre-high stromatolites. Bacteria dominated our planet for another 2,500 million years before the first truly complex organisms appeared in the fossil record. And some say they still do, for the gloss of plants and animals doesn't match the bacteria for biomass.

What was it about the early earth that first breathed life into inorganic elements? Are we unique, or exceedingly rare, or was our planet but one in a million billion hatcheries scattered across the universe? According to the anthropic principle it scarcely matters. If the probability of life in the universe is one in a million billion, then in a million billion planets there is a chance approaching 1 that life should emerge somewhere. And because we find ourselves on a living planet, obviously we must live on that one. However exceedingly rare life might be, in an infinite universe there is always a probability of life emerging on one planet, and we must live on that planet.

If you find overly clever statistics unsatisfying, as I do, here is another unsatisfying answer, put forward by no lesser statesmen of science than Fred Hoyle and later Francis Crick. Life started somewhere else and 'infected' our planet, either by chance or by the machinations of some god-like extraterrestrial intelligence. Perhaps it did – who would go to the stake to say that it didn't? – but most scientists would back away from such reasoning, with good reason. It is tantamount to an assertion that science cannot answer the question, before we've even bothered to look into whether science can, in fact, answer it. The usual reason given for seeking salvation elsewhere in the universe is time: there has not been enough time, on earth, for the stupefying complexity of life to evolve.

But who says? The Nobel laureate Christian de Duve, equally eminent, argues altogether more thrillingly that the determinism of chemistry means that life had to emerge quickly. In essence, he says, chemical reactions must happen rapidly or not at all; if any reaction takes a millennium to complete, then the chances are that all the reactants will simply dissipate or break down in the meantime, unless they are continually replenished by other, faster, reactions. The origin of life was certainly a matter of chemistry, so the same logic applies: the basic reactions of life must have taken place spontaneously and quickly. So life, for de Duve, is far more likely to evolve in 10,000 years than 10 billion.

We can never know how life really started on earth. Even if we succeed in producing bacteria or bugs that crawl out from swirling chemicals in a test tube, we will never know if that is how life actually started on our planet, merely that such things are possible, and perhaps more likely than we once thought. But science is not about exceptions, it's about rules; and the rules that govern the emergence of life on our own planet should apply throughout the universe. The quest for the origin of life is not an attempt to reconstruct what happened at 6.30 a.m. on Thursday morning in the year 3,851 million BC, but for the general rules that must govern the emergence of any life, anywhere in the universe, and especially on our planet, the only example we know. While the story we'll trace is almost certainly not correct in every particular, it is, I think, broadly plausible. I want to show that the origin of life is not the great mystery it is sometimes made out to be, but that life emerges, perhaps almost inevitably, from the turning of our globe.

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Science is not just about rules, of course; it's also about the experiments that elucidate the rules. Our story begins in 1953, then, an *annus mirabilis* marked by the coronation of Queen Elizabeth II, the ascent of Everest, the death of Stalin, the elucidation of DNA, and, not least, the Miller–Urey experiment, the symbolic origin of origin of life research. Stanley Miller was at that time a headstrong doctoral student in the lab of Nobel laureate Harold Urey; he died perhaps a touch embittered in 2007, still fighting for views that he had upheld doughtily for half a century. But whatever the fate of his own particular ideas,