

# 4

## HOW EVOLUTION WORKS

*In which we explore some of the many mechanisms of evolutionary change.*

The engine that drives the evolutionary train forward is Darwinian – or natural – selection. It is fuelled by the continual changes made by living organisms in their efforts to complete full and successful lives, so that their genes are represented in successive generations. This chapter explores some (only some – a full list would make a book of its own) of the many ways by which this happens, thereby providing the material for selection. At every stage of evolution innovation creates more opportunities for cooperation, and emergent forms in the shapes of new organisms and fresh collaborations.

Offspring are subtly different from their parents, and all offspring are subject to the process of natural selection at every stage in their lives. At first, it was thought that the main source of variation was the spontaneous change to DNA that occurred as the result of faulty copying, or that were brought about by external factors such as radiation. Collectively, these changes were called mutations.

Since then, there have been major advances in understanding the interactions between organisms and their environments and the exchanges that take place spontaneously between different sections of DNA. Some of these are now being exploited in medicine by gene therapists. For example, the replacement or repair of faulty genes in embryos, or modifying the patient's own blood cells to become more efficient cancer fighters would have once been considered miracles. The new discoveries have brought a far wider appreciation of the sources of, and the persistence

of, mutations. In this chapter, we explore a range of these sources of change. Remember, a single gene may have different effects, depending on the other genes in its immediate environment. Nothing so much reinforces da Vinci's insistence that everything is connected to everything else as apparently random changes that are not random after all.

To the surprise – and even alarm – of his contemporaries, Darwin included our own species, *Homo sapiens*, in his discoveries of evolutionary change. In this chapter, therefore, all the phenomena described may also apply to us. To this rich biological inheritance for humans, however, must be added our evolution as a social species, our artistic nature and our capacity for empathy for others. Biological evolutionary pressures, such as our long generation time and its implication for extended parental care, contribute to the social changes.

The accumulation of small mutations leading to new species was attractive to the gradualist point of view of evolution, first espoused by Darwin himself. It was a view that held sway in the first half of the twentieth century. Its great flaw, as Richard Goldschmidt (1940) saw, was that it did not provide a mechanism for macro-evolution – evolution *beyond* the family level of classification – although it did explain very nicely how families might arise. We all of us recognise the members of the family of parrots but, with all due deference to psittacophiles, on first observation one parrot looks very like another. Few people would have difficulty believing that a palm cockatoo and a sulphur-crested cockatoo are related, but a crested pigeon is something else entirely. How do you get a pigeon? It is counterintuitive that chihuahuas and borzois are the same species of dog, but chimpanzees, gorillas, baboons and monkeys are easily recognised as a group.

Goldschmidt (1940) suggested that the genetic system might make a number of simultaneous changes in a single generation to produce what, unfortunately, became called 'hopeful monsters'. In vain, Goldschmidt pointed out that he did not mean that the individual monster 'hoping' for its own survival would be fully adapted to its environment but that all of its variants would be subject to the pressures of selection. Unfortunately, the reductionist 'either/or' attitude prevailed. No-one was prepared to countenance the idea that one might have both mechanisms – mutation *and* shuffling of genetic material without mutation – at the same time.

In humans, social acceptance is strongly influenced by extreme variation, for facial distortions in particular. Mutations, such as albinism or dwarfism were often treated to the kind of extreme discrimination well understood

by many modern human minorities. ‘Freak shows’ at circuses or public display in asylums have been the sad fate of so many in the past. All these responses contribute to human social evolutionary pressures so the concept of the ‘hopeful monster’ was doomed. Now we know, however, that genes often act in teams and the laborious, one at a time, accumulation of single mutations is only part of the story (see Chouard 2010).

One of the more important and common ways that one species might split into two is genetic drift. Imagine a population of mice living on a peninsula that is attached to the mainland by a narrow neck of land. Every mouse shares the same genetic heritage with every other mouse on the peninsula and on the adjacent mainland. Each male mouse therefore has the potential to interbreed with every female mouse. There is always the possibility of the flow of genetic information back and forth, as A breeds with B, and B breeds with C, and C with A and so on. Now imagine a minor catastrophe – the sea erodes away the link with the mainland. It separates the mouse population into two, one on the mainland and the other on the newly formed island. Now gene transfer through the whole population cannot occur. Mainland and island mice can never get together. Each separate population is then subject to different environmental conditions that, over a number of generations, affect its genetic heritage and become reflected in its members. The two populations begin to diverge and embark on their own evolutionary adventures. Eventually they will become distinct subspecies and, finally, distinct species – especially if the island lacks the predators that are found on the mainland. The popular holiday resort of Lord Howe Island is a good example; its isolation has permitted the evolution of many species that can only be found there.

The same is true of the separation of human populations in the last ice age. Cut off in the frozen north, Siberian adaptations include increased activity of two genes that burn fat for heat rather than energy and others that are implicated in the metabolism of fats from meat and dairy products (Cardona et al. 2014). Outer manifestations include eyes with epicanthic folds to shield them from the icy wind, and facial sinuses with thick fat pads to protect them from freezing conditions.

Islands are marvellous evolutionary laboratories. The extinct dodo, a flightless bird that once lived on Mauritius and stood a metre tall, showed what pigeons were capable of becoming, given enough time and the absence of predators (Quammen 1996). Even quite large isolated islands,

such as New Zealand, had their own unique inhabitants. The giant moas, flightless birds almost 4 metres high, persisted until the arrival of Māori, about 600 years ago. Sadly, both the dodo and the moa were hunted to extinction.

These examples, to which we can add the giant turtles of the Galapagos and the Komodo dragons (giant lizards) of Indonesia, represent one response to isolation. Another is dwarfism. The limited resources on islands sometimes result in dwarfism as an evolutionary outcome. Limited resources create a selection pressure towards achieving reproductive ability at the smallest size consistent with long-term survival. Humans are not exempt from these pressures. Recently, on the island of Flores, the discovery of bones of *Homo floresiensis* prompted a rethink of human history. These small hominins were just over a metre tall. They lived alongside dwarf elephants, which had also undergone a similar process (Aiello 2010). The small humans were nicknamed ‘hobbits’ after JRR Tolkien’s creations.

Another opportunity for variation is offered by increasing the amount of DNA in the nucleus of the cell. Doubling or tripling the number of copies, up to 12 times, is not uncommon. The more DNA an organism possesses, the greater are the chances that it will vary between generations and the greater are the opportunities for mutation to occur. The phenomenon is called polyploidy and often occurs in nature. It is frequently observed in our domestic crops after the thousands of years of selective breeding they have undergone. The common black and white Australian mudlark appears to be a tetraploid (doubled) version of the much smaller diploid African and Asian common pied flycatcher. The common dandelion (*Taraxacum*) is also tetraploid. Doubling of individual chromosomes is common among humans, but usually leads to genetic disorders of varying severity.

The genetic program is a dynamic system, bits of which are continually changing places and interacting, creating new patterns. Nothing illustrates this better than the jumping genes (transposons) discovered by Barbara McClintock in the 1940s and 50s. ‘Transposition mutagenesis’ allows genes to be transferred from one chromosome to another, thus interrupting or modifying the functions of their new neighbouring genes. McClintock was an example of a paradigm shifter who was ridiculed by her contemporaries. The importance of her work was finally acknowledged with the Nobel Prize in 1982 (Keller 1983).

Meiotic drive is the name for another interesting phenomenon that illustrates the dynamic character of the genome (Sandler and Novitski 1957). It is a complicated mechanism that is sometimes encountered in some species during cell division. It results in genes from the male or female gamete being over-represented in the fertilised egg. In other words, contrary to classical Mendelian genetics, where the 50:50 ratio of gene distribution is to be expected, it is skewed in favour of certain genes. It is as if, here, we have an example of evolution evolving, bootstrapping itself, by increasing the chances of the 'favoured' gene being represented in successive populations.

Now we come to one of the most important creators of genomic novelty, that of horizontal gene transfer. The original Darwinian view, one that persisted until the middle of the last century, was that vertical transmission of genes, from parent to offspring, was the only game in town. This provided the metaphor of the evolutionary tree or bush. We know now that it is certainly not the only game and that it never was. The whole of life other than bacterial is based on an initial collaborative event in which three or four independent sets of genes from bacteria-like organisms merged their identities in a single cell. This is horizontal transfer, not branching. The evolutionary tree, with one main trunk and lots of side branches is therefore not an accurate metaphor for evolution, at either the cellular or the primate levels of classification.

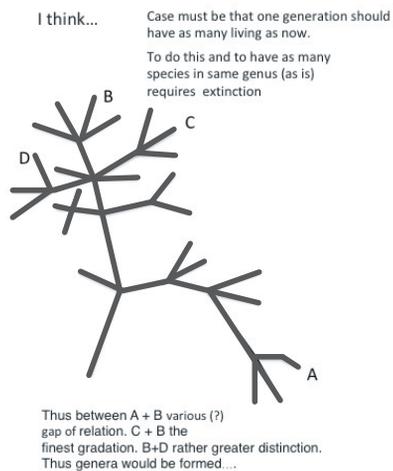
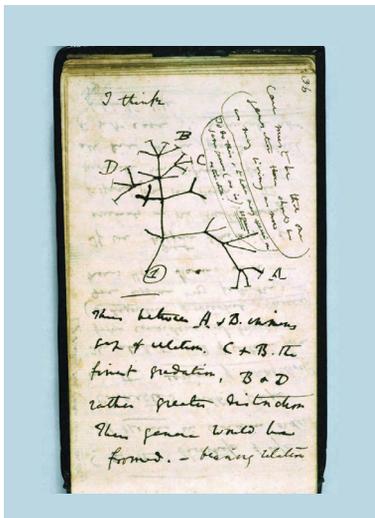


Figure 9. Darwin's very first evolutionary map.

Darwin did not think of a tree in the first place. His sketch of a possible evolutionary pattern is more of a map (Figure 9). The evolutionary bush, with many main stems and lots of twigs, is better, but still unsatisfactory. Best of all would be a three-dimensional representation of an evolutionary network that shows how adjacent and even more distant branches of the evolutionary bush are joined by horizontal connections.

The first great act of horizontal gene transfer to produce modern cells had proved to be an enormous evolutionary success. On the principle that what worked once can work again, which seems to pervade the evolutionary story, it is not surprising to discover that horizontal gene transfer from one cell to another still occurs commonly among ancient cells and, for example, is responsible for the development of resistance to antibiotics in pathogenic bacteria.

Viruses also have a role. They are not cells, but some may once have been cells. Now they are packages of DNA or RNA that depend on cells to reproduce. It is hardly surprising, therefore, that viral inclusions in different genomes are common. This is never so clear as when viruses cross from animals to humans. A recent and dangerous example is Severe Acute Respiratory Syndrome (SARS), a virulent, invasive respiratory disease that startled the world in 2002–04 with an overall death rate of about 15 per cent, although some sections of the community suffered death rates as high as 50 per cent. It required full international collaboration to identify the source of the virus as the Chinese horseshoe bat. The bats infected civets, a wild, cat-like animal related to stoats and weasels. When they were brought together in Chinese food markets, the viruses transferred to humans. At the time of writing, we are in the grip of a pandemic, COVID-19, due to another virus that has made a similar jump.

If the host cells survive the viral attack, some viral nucleic acid sequences may persist in the cell, silent at first but, with time, they may be incorporated into the genome. In this event, they augment the genome and have the potential to become involved in natural selection. In humans it is currently thought that about 8 per cent of our genome is of viral origin. The fact that foreign gene insertion into a genome is a relatively easy outcome to achieve is demonstrated by the work in many laboratories, such as those striving for blue roses, or enhanced vegetable oil yields in rape plants, and the many other transgenic food crops now available. Another application is therapeutic gene transfer. Genes can be

added to human cells or removed from them. Leukemia is one condition that responds to the replacement of malfunctioning genes by healthy units from the patient's own genetic repertoire.

Another quite remarkable use of gene technology is known as CRISPR (pronounce it 'crisper') and it is an instantly memorable acronym for the uncatchy 'Clustered Regularly Interspaced Short Palindromic Repeats'. It originates as a defence mechanism found in bacteria where its function is to identify the DNA of an invading virus and inactivate it. Modified further in the laboratory, it is now being tested for use in embryos, for identifying and removing deleterious genes or introducing beneficial ones. Potential targets include diseases such as muscular dystrophy, congenital blindness, haemophilia, Huntington's disease, cystic fibrosis and a range of cancers.

A more detailed explanation of CRISPR is to be found on the Internet at: [www.wired.co.uk/article/crispr-cas9-technique-explained](http://www.wired.co.uk/article/crispr-cas9-technique-explained).

Having looked at some of the ways that a single genome can be shuffled for the next generation, what are the possibilities for two or more genomes working together? The cells of which we are all made, that are formed from collaborating bacteria-like organisms, come once again to mind. Evolution, nothing if not iterative, has tried the experiment of collaboration over and over again. At the whole organism level, wherever you look there are successful associations, such as lichens, that are an ancient partnership between fungi and ancient (blue-green) algae or modern algae, right up to the modern ruminants that could not survive without the fermenters – fungi, protozoa and bacteria – in their rumens. The result is that Gaia is made up of countless beneficial biotic associations. In addition, every known organism has at least one parasite, whether viral, bacterial or modern cell. A quick consideration of this proposition should convince you of the thesis that one of half the living world is therefore living in some sort of association with the other and that the numbers of such associations are astronomical. These associations can be graded.

At the first level, there is predation, as exhibited by lions hunting springboks. Next come the things that live on the outside of their hosts and plunder them in some way. These are the ectoparasites, such as leeches and fleas on mammals, and green- and black-fly on plants. They are 'predators' too: the difference is in the relative sizes of the food source and the predator. This is acknowledged in that we talk about the lion's 'prey'

and the flea's 'host'. Humans regard fleas as pests, not life-threatening unless they carry plague. Though, fortunately, we do not often form the prey of lions, we are often hosts to many small ectoparasites like fleas. From a springbok's point of view, a lion is more than just a pest; it is indeed a predator.

It is when the pest starts eating the prey from the *inside* that the game changes. This is true parasitism, and all sorts of genetic changes are required of the internal predator or parasite if the parasitic relationship is to exist and perhaps evolve into something mutually beneficial. This is because the host fights back, perhaps by mounting a strong immune response against its invader. That, in turn, calls for a secondary response from the parasite, and so on. This is an example, common in biology, of the phenomenon that was called 'Running the Red Queen's Race' by van Valen (1973), who borrowed the idea from a science fiction writer, Isaac Asimov, who borrowed it from Lewis Carroll's *Through the Looking Glass* (1865).

'Well, in our country,' said Alice, still panting a little, 'you'd generally get to somewhere else—if you run very fast for a long time, as we've been doing.'

'A slow sort of country!' said the Queen. 'Now, here, you see, it takes all the running you can do, to keep in the same place. If you want to get somewhere else, you must run at least twice as fast as that!'

The Red Queen hypothesis posits that organisms are in continuing ecological interaction with other organisms as they look for an evolutionary edge that will take them forward. An excellent example is the proliferation of bony armour and exoskeletons among the Cambrian animals, half a billion years ago. As the amount of carbon dioxide in the atmosphere increased, it became available for incorporation into protective armour as calcium carbonate. Potential prey became more heavily armoured; predators responded by developing more powerful jaws. Suddenly (in geological terms) a very rich fauna composed of these armorial novelties appears in the Devonian fossil record. These fossils are remarkable for the increasingly heavy armour on the one side – as in the thick carapaces of bottom-dwelling fish of the era – and the increasingly enlarging teeth and jaws – such as those of eurypterids or sea scorpions – on the other. But remember: this is not the whole story. Armoured forms are much more likely to leave a fossil record than the no doubt

many equally successful soft-bodied groups. Hiding in a small hole in a rock is, for example, a very successful strategy against a large animal with an inflexible exoskeleton. This caveat, the imperfection of the fossil record, must always be borne in mind. It also applies particularly strongly to the human fossil history. Bones can only be found in sites suitable for their preservation, so we have a skewed idea of the social and biological evolution that was so important in humans.

Internal parasites are in an intimate and intense relationship with their hosts. Over generations, the parasite population exerts selection pressure on the host population, the host responds and, in turn, this exerts selection pressure on the parasite. This is not like a rally in tennis; rather, it is more like a protracted tug of war between two evenly matched teams, until a resolution is achieved. It can confer a surprisingly long-term stability on the host–parasite relationship. So much so that important evidence supporting continental drift was found among host–parasite relationships. For example, ratites make up a related group of large flightless birds. The South American rhea and tinamou, the African ostrich and the Australian emu all have parasites that are themselves closely related. The only reasonable explanation is that their ancestors were once cohabitants of the great continent of Gondwana that broke up and drifted apart.

The question that it raises is whether this family of parasites, having existed for at least 200 million years in the same family of hosts, is ever likely to develop mutually favourable symbioses. Clearly, they do not seem to harm the host species much, as host and parasite are still with us. It all depends on the nature of the relationship. The answer is no if, say, the offspring of a parasite depend on scavengers to eat the carcass of their dead host to provide them with a new home. Most parasites, however, have a vested interest in not killing their hosts for as long as possible.

Other parasite–host relationships long ago achieved equilibrium, to the stage where they cause the host no detectable harm at all. One example of a human host–parasite relationship demonstrates this point well. A study of the distribution of the parasitic protozoon, *Sarcocystis*, in Paris, France, found that more than 90 per cent of those tested had been infected by this protozoan parasite at some time and probably still were. It is thought that the Parisians owe this to their fondness for steak tartare, thinly sliced raw beef. In healthy people, the parasite remains dormant; only in cases of immunodeficiency does it show symptoms. So perhaps what we call a mutually beneficial symbiosis is the end point of long mutual struggle.

If so, it is a struggle that has succeeded over and over again. If a parasite – or anything – causes behavioural changes in an animal, they can, in turn, initiate evolutionary change by bringing that animal into contact with aspects of its environment it never before encountered.

Offspring can also vary by ‘remembering’ at a genetic level some of the events that occurred in the lives of their parents after their genetic cards had been shuffled and dealt and they have begun their own development. This statement would have been heresy until the last decade of the twentieth century and one would have been immolated in the righteous fires lit by the Darwinists of that time for uttering it. It is, of course, a form of Lamarckism, the ‘inheritance of acquired characters’, of characteristics acquired by an organism responding to pressures from the environment during its lifetime. Rechristened *epigenesis*, it has shed much of the opprobrium once heaped upon poor old Lamarck’s head.

The justification for all the fury levelled at Lamarck was a concept called the Weismann barrier, named for the famous early evolutionary thinker, August Weismann. Weismann argued that reproductive cells were separated from body cells by physical and physiological barriers that could not be crossed. It followed, therefore, that events that occurred outside the reproductive cells could not contribute to inheritance. It sat at the heart of early twentieth century evolutionary orthodoxy. Even in 1942, however, Julian Huxley had qualms about the Weismann barrier and, in his great book that ushered in neo-Darwinism, he wrote ‘the distinction between soma and germ plasm is not always so sharp as Weismann supposed’.

‘Weismanism’ is a fine demonstration of academic insularity, for even if the Weisman barrier were present it could only be in higher animals. Weismann had trained as a medical doctor and his anthropocentric prejudices were showing. Botanists were having none of the Weissman barrier. The plant kingdom represents more than 90 per cent of evolving life and botanists knew that, in plants, reproductive cells developed from somatic or body cells. The man who finally demolished the Weismann barrier and opened this can of zoological worms was Steele (1981), another paradigm shifter who suffered opprobrium for his view of the world. He showed that, in mice, changes in the parent’s immune system may be manifested in the immune system of the offspring, ‘pre-adapting’ them in the event that they meet the phenomenon that brought about the change in their parents. What’s good for the parents is good for the offspring and the likelihood of the offspring encountering the same challenges as the parents is high if they remain in the same environment.

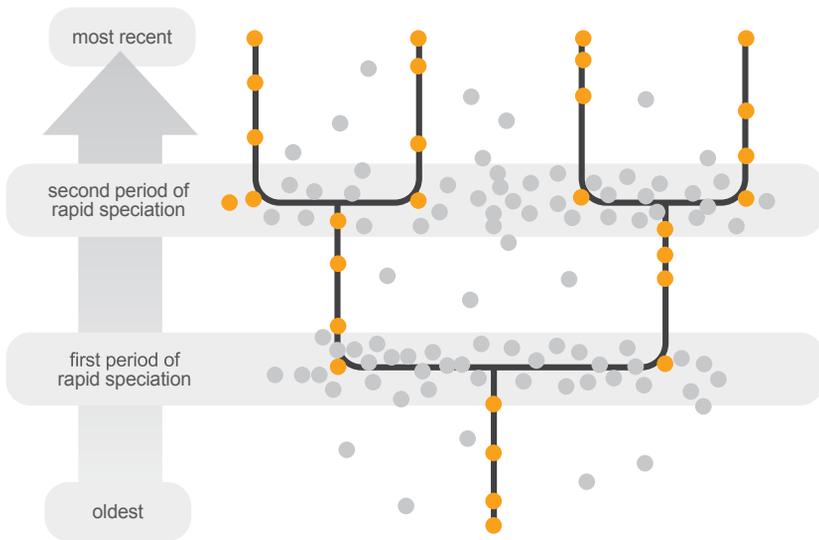
In the last paragraph, the word 'pre-adaptation' is used advisedly. It is, however, a word that has spent most of its life being misused. It implies prescience in evolution, suggesting that somehow characteristics of an organism are already adapted to functions that they will perform in some future evolutionary scenario. This is obvious nonsense. Not every part of an organism is perfectly adapted to its environment. Arthritic back pain is the price humans pay for walking upright; we are certainly not perfectly adapted to living an upright life, in any sense of the word. The vertebrate spine works best in fish. Its effect is to prevent them concertina-ing due to water resistance as they swim forwards. It certainly was not originally designed for vertical use.

Evolution, however, makes do with whatever it has handy. The evolutionary process is always making approximations, and those approximations depend very much on what has gone before and that in turn shapes the evolutionary future. We carry around with us many evolutionary relics of our ancestry. Sometimes, one of these relics is coopted by the evolutionary process and is modified into a useful adaptation. When that happens, we may say that the organism is 'pre-adapted' to its new condition as long as we remember 'pre-adaptation' does not imply that evolution had already earmarked it for future use!

Thus, pectoral fins originally allowed fish to plane up or down in the water and were there, ready to be used, for propping up the front end of a fish when it moved to colonise land. Later, pectoral fins became the forelegs of primitive amphibians and reptiles, the flippers of marine plesiosaurs, seals and dolphins, the wings of pterodactyls, bats and birds and the arms of humans. Fingers can be traced back to fin rays. These are all called homologous structures, having the same developmental origin. A crab leg, however, is an *analogous* structure to a mammalian leg; of similar function but derived from something else entirely. It is also important to remember that the visible parts of an homologous structure also have required simultaneous changes in internal structures, such as musculature and the internal architecture of the brain.

One of the great life changers is catastrophe. Catastrophism has been in and out of fashion since Noah's flood was used to explain the fossil record. This biblical idea was simply that every so often Jehovah got fed up with his creation, wiped the slate clean and started again. The alternative is gradualism. Today, as is now so often the case, instead of mutually exclusive gradualism or catastrophism, we can place them together in an interactive system without bothering Jehovah.

In 1972, Eldredge and Gould wrote an important paper called ‘Punctuated Equilibria’. They argued that the *absence* of palaeontological evidence for intermediate forms in evolution was, in fact, itself evidence. They maintained that we had to believe the palaeontological record of evolution, because it was the only record we had. If it showed, in so many cases, long periods of gradual change interspersed with short, frenetic periods of diversification, then that was probably what happened.



**Figure 10. The punctuated equilibrium of a hypothetical fossil bed.**

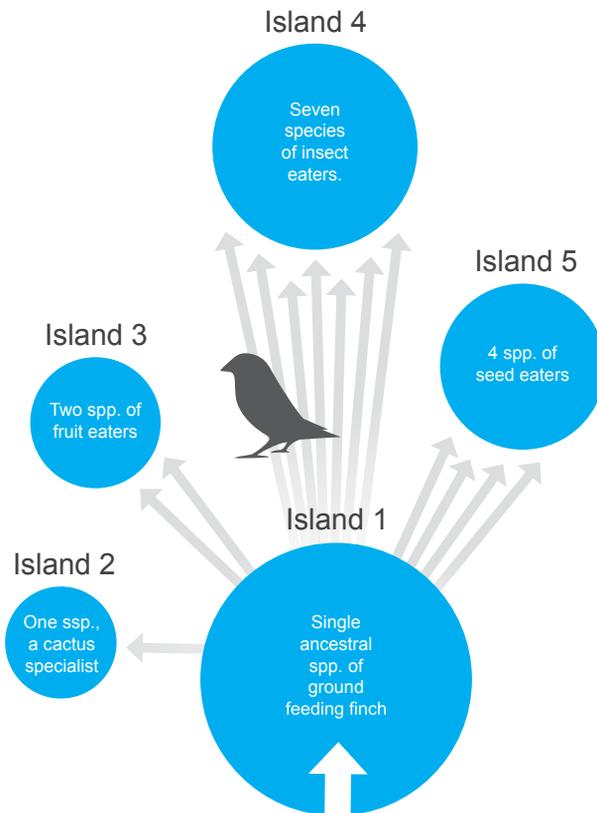
Figure 10 is the diagram of a hypothetical fossil bed, going from the oldest at the bottom to the most recent at the top. It shows punctuated equilibrium, layers where there are few fossils, indicated by circles, alternating with layers where there are many. Orange circles indicate the relatively few that have been ‘found’, the others are unknown and may never be known. A very neat tree showing possible relationships has been drawn through the orange circles, but it is not necessarily the right tree. Many others could be drawn.

‘Punctuated Equilibria’ disturbed two more heretical dogs in their uneasy slumber – first, the idea that evolution proceeded by a connected series of leaps and bounds. This was called *saltation* or jumping evolution. Second, it tended to resurrect the biblical teachings of *catastrophism*. In fact, the agitated response to this idea proved to be a storm in a teacup, and once again the sensible compromise prevailed. The evolutionary record is real, and various fossil lineages did indeed extend over long periods of slow

change (stasis) interspersed with short frenetic periods of evolution into uncolonised evolutionary niches. At that point, different varieties of the same organism rapidly established themselves in a range of different environments that had now become available to them.

‘Adaptive radiation’ is the name given to this process by which the pioneers of every successful species become adapted to new circumstances. Many are called; few are chosen. The majority die but the survivors comprise the group on which natural selection acts to generate novelty.

Figure 11 is a fanciful representation of the Galapagos Islands, and bears no resemblance to their actual geography! They are the home of a group of small birds known as Darwin’s finches because, as he was curating his bird collection, he was struck by the diversity of their beaks, providing him with yet another insight into the evolutionary process.



**Figure 11. The spread of Darwin’s finches.**

On Island 1, the ancestral species is a ground-feeding finch. As its population grew, finches began to fly to other islands, or were caught up in storms and deposited there, or they rafted there on floating detritus. This must have been quite a common occurrence but not every finch survived the trip. For them to set up a colony, at least one of each sex was required. The finches managed to get to Island 4 a number of times and diversified into seven species. Only one successful colonising event occurred on Island 2, with its single cactus specialist.

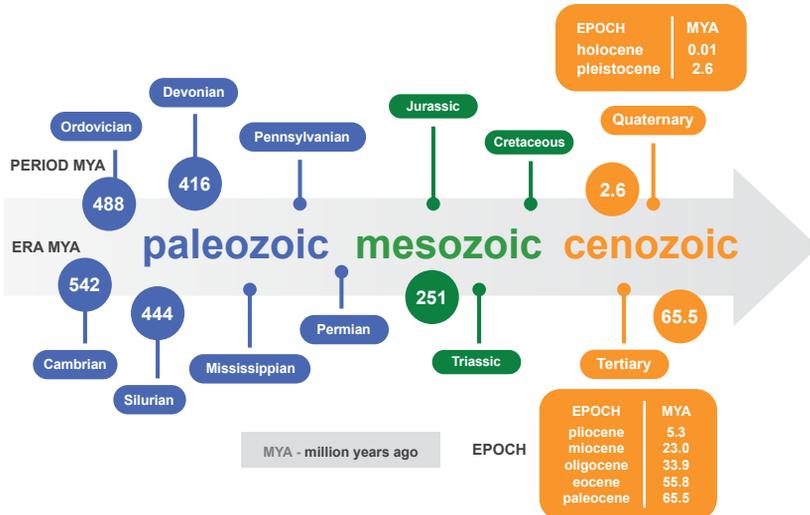
The upshot was that after an unknown number of generations, each island had its own unique populations of finches, distinguishable by the shape and size of their bills.

The new environmental conditions that permit adaptive radiation are brought about by various causes, one of which is indeed catastrophe. There is no escaping the effects of random events such as asteroid strikes over long periods of time. Extinction is a great stimulator of novelty by creating evolutionary space. The first great extinction occurred with the release of toxic oxygen into the atmosphere by ancient photosynthesisers, an event that put anaerobic microbes under intense selection pressure and killed off many of their species.

From counting known fossils, it appears that there have been at least five other *great* extinctions. Fossil counting is, of course, an imperfect measure, because not everything gets fossilised, especially organisms with no hard parts, and only a fraction of the possible total of fossils has been collected. It is, however, the best that can be done.

Figure 12 is a plan of the geological ages from the Cambrian, 500 million years ago, to the present. Figure 13 gives a rough suggestion of dominant life forms at various times. At the end of the Cambrian, 450 million years ago, the fossil record suggests that two events killed off 65 per cent of all species. After another 80 million years of recovery, 70 per cent of all species were lost in the Devonian. The largest event of all, at the juncture of the Permian and the Triassic, 250 million years ago, did away with 90 per cent of all species and even the colonisation of land by Amphibia was in jeopardy. The Triassic/Jurassic extinction followed 50 million years later, and 75 per cent of all species vanished. There were already evolutionary experiments going on, such as mammal-like reptiles and feathered dinosaurs, and the first true mammals and the birds took full advantage. The groundwork was laid down here for complex immune

systems to fight bacteria and enable temperature regulation at around 38–40°C. This is the temperature at which birds and mammals function best, but sadly it is also the one at which bacteria grow best.



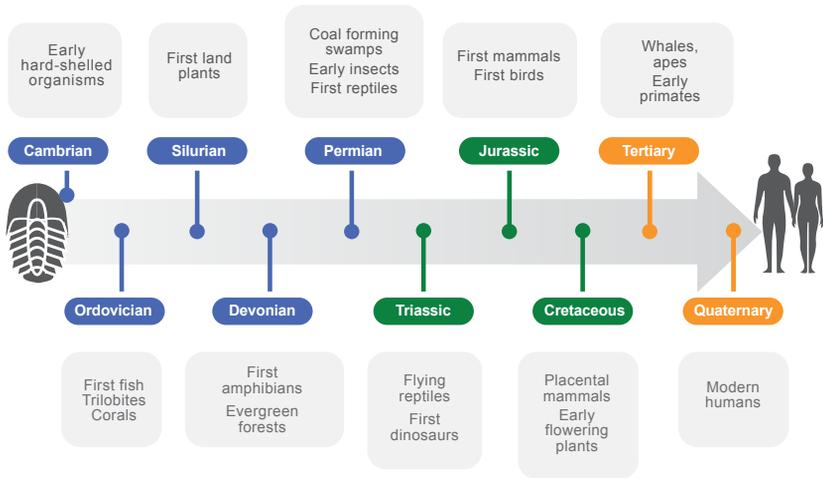
**Figure 12. Geological ages from the Cambrian period, 500 million years ago (MYA), to the present.**

The most notable extinction was caused 66 million years ago by the great asteroid strike on Earth, made famous by Luis and Walter Alvarez and colleagues (1980). It caused the extinction of 75 per cent of all known species. This discovery alerted everyone to how precarious was life on Earth. It is a chilling thought that another big asteroid is due in a few million years or so, unless we can achieve the technology necessary to divert its course.

Add to all this mayhem the so-called lesser extinctions – about 20 of them, not including the one currently being precipitated by humanity – and the odds against any one genetic line making it through from the origin of cells to the present day are enormous.

But hey! Look around. We all did it, from the meanest bacillus to the blue whale! Gaia is nothing if not resilient. She is, after all, a ‘tough bitch’ as Margulis colourfully described her, in a book of essays edited by Brockman (1996).

## COOPERATIVE EVOLUTION



**Figure 13. Dominant life forms across the geological ages.**

Another great source of change for living organisms lies in the possibility that the rates of development at various times in their life cycles can vary. Every organism must be adapted to its environment at every stage of its life history. A common example is the cabbage white caterpillar that lives in an entirely different world from the butterfly into which it metamorphoses. In Lepidoptera, the caterpillar is the form that does the heavy feeding and the butterfly form does the breeding. Both caterpillar and butterfly must 'be fit for purpose', adapted to the life they lead. In fact, in these insects, the caterpillar spends most of its life feeding in that form, turning into the relatively short-lived winged form only to seek a mate and breed.

Even in organisms that do not experience the remarkable shape change of the butterfly, development does not always occur at the same rate throughout its growth phase. Sometimes it slows, at other time it accelerates, the changes in each phase having consequences for the form of the adult. If the organism passes through markedly different juvenile forms on the way to adulthood – the larval form, say, in animals or the production of juvenile foliage in plants such as the eucalypts – these different developmental forms must be as well adapted to their environments as the adult forms. At the beginning of the last century, Edith Johnson (1926) showed that the two sorts of leaves in *Eucalyptus globulus* worked in different ways. The juvenile leaf faces the sun but is much more likely to be shaded by other shrubs than the adult one. It has a thicker layer of wax to inhibit water loss by transpiration and also is

less easy to wet, reducing the chances of fungal attack. The adult leaf, on the other hand, tends to be edge-on to the sun, has no wax but it does have a thicker cuticle and a greater rate of water transfer. There are other differences but, unsurprisingly, it seems that the juvenile leaf is adapted to life in the understorey of the forest, while the adult foliage is adapted for life in the canopy.

A forest tree thus grows through two environments, first as a bush and then a tree, and exploits each while staying in the same place. Marine animals, like sea squirts and barnacles, that stay in the same place as adults, do not usually have that luxury. The strategy they adopt is to insert a larval stage into their development. There are many examples of larvae – for example those of crabs, mosquitoes and frogs – with lives different from their adults. These larvae must be capable of surviving their free-living phases – that is, be adapted to their environment. For animals where the adults are cemented into position, like the corals and barnacles, the imperative for the larva is to survive long enough to find a safe living space, where they can settle and develop into reproductive adults.

It is possible to think of the human foetus in this way. Humans do not have larvae but given the immature and unprotected state of small children, they might as well have. Organic evolution, however, has been complemented by social evolution. Adults provide their children with food, clothes, shelter and a collaborating society that allows humans to adjust to changes in the environment without going the direct genetic route. The sequence of agricultural revolutions that created stable environments is part of this and comprises a major evolutionary advance for the human species.

Varying the relative lengths of a life history so that an organism becomes adapted to two or more environments in its lifetime is thus a common evolutionary trick. Larval mayflies spend months living under stones in stream beds, feeding, and only a day or two as winged insects whose function is reproduction. One species of cicada (*Magicada*) spends 17 years underground with its mouthparts stuck into tree roots, feeding. The adults emerge to reproduce and live about four months. Another animal, the liver fluke (*Fasciola hepatica*), has three quite distinct forms to cope with three different environments during its life. A close relative has four!

Every stage of an animal's – or plant's – life history is therefore tested by natural selection and that includes its *duration*. It may be either lengthened or shortened. One way is paedomorphosis, meaning literally

‘child form’, the retention of an early developmental stage into adulthood, when the animal becomes reproductive. It is an idea that was particularly well developed by marine biologist NJ Berrill (1955), who suggested that it was responsible for the origin of vertebrates. This was because the free-swimming larvae of sea squirts had a number of vertebrate-like characteristics. Berrill suggested that some larvae long ago failed to turn into adult sea squirts and became sexually mature, thus affording access to a whole new evolutionary space now occupied by vertebrates. The present view is that he was nearly right, but it is more likely the vertebrates are derived from a sister group.

Neoteny is said to occur when the physiological or bodily development of an organism, usually an animal, is slowed or delayed. Ultimately neoteny results in the retention of juvenile physical characteristics in the mature adult form of a species. The classic modern example is the axolotl, which looks like a giant larval salamander when it is sexually mature, while having retained its larval traits.

Another example of neoteny is our own species. Structural human neoteny is a respectably old concept dating back to the 1920s. There are a number of human features that are characteristic of foetal apes, and it is difficult not to conclude that humans are neotenic apes. The process of neoteny seems to have been led by the evolutionary advantages afforded by a big brain, while constrained within a simian morphology. We discuss this at greater length in Chapter 11.

In humans, the juvenile growth stages, childlike characteristics, are maintained into adulthood. They do not take a physically different form except in relative proportions as in, say, head circumference and length of arm. It is possible, however, that brain development is discontinuous. Piaget made a strong, although contended, case for the following stages of human development:

1. Age one to three years, in which the individual believes, and acts, as if they are the centre of the universe.
2. At about seven years, they are able to recognise that the world can change, and they can recognise the change.
3. For most, it is 12 years or more before the child can think or speak of abstractions, such as peace, humility, ageing and other concepts.

The development stages are cumulative, unlike the butterfly that dispenses with the earlier form!

Recently, the concept that each organism is not an individual but a collaboration of many different sets of genes, has been incorporated into a hologenome theory of evolution. It is hotly debated (Bordenstein and Theis 2015; Moran and Sloan 2015). It proposes that natural selection does not occur at the level of an individual organism but at the level of what has been called a ‘performance unit’. A performance unit comprises a primary biont – such as a cow or a human – and its population of symbiotic microbes. That is to say, in my case, the primary biont is what I think of as ‘me’ and the secondary ones are all the hangers-on on my skin and in my intestine. In short, what I think of as ‘myself’ is a community, a holobiont.

This is an important change of perspective. The unit of evolution becomes a community, a set of cooperating and interdependent individuals – or genomes. This is indeed the triumph of the world of ancient cells, if you count the modern cells of a human being as ancient cell constructs. The population structure of microbes in the holobiont, however, is neither fixed nor necessarily totally predictable, and so the hologenome community depends on circumstance.

The acquisition of, and providing homes for, various microbes can give animals and plants access to new resources – the ability to consume a new kind of food or to survive in a different environment. This is well illustrated by the termites and the ruminant mammals, whose intestinal denizens allow them to digest cellulose. When this happened the first time, a whole new world based on cellulose as a food source was opened up. Plants also acquire symbionts and fail to thrive without them; for example, the fungal root nodules that fix nitrogen in legumes and many other beneficial plant–microbial interactions.

Future technology will always look like magic from the viewpoint of someone 50 years in the past. If you had told someone in the 1960s that you could tell who and what had been swimming in a river merely by examining a few litres of its water, they would have thought you either mad or a magician. Life is, however, deciduous, always shedding little bits of its DNA everywhere. Today, the magic can be done by collecting the minute fragments of DNA the water contains, replicating them over and over

again by a simple, repetitive chemical process and asking a computer to identify them by comparing them with its database of known organisms. This process is now a valuable ecological tool.

There are other 'rivers', such as the one consisting of food breakdown products and liquids that flows through your intestine. Easily, if embarrassingly, sampled, the DNA there provides evidence of the many hundreds, maybe many thousands, of different microbes that contribute to the health of the holobiont that you are pleased to call 'I'. And many of them have been unknown to science.

One final important point: holobionts, complete with fellow travellers, *do not change the rules* of evolutionary biology. Although these concepts redefine what constitutes an individual animal or plant, they do not require a fundamental rewriting of Darwin's theory of evolution by natural selection. Rather, they increase the significance of considering both parts and wholes as sets of fruitful relationships.

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