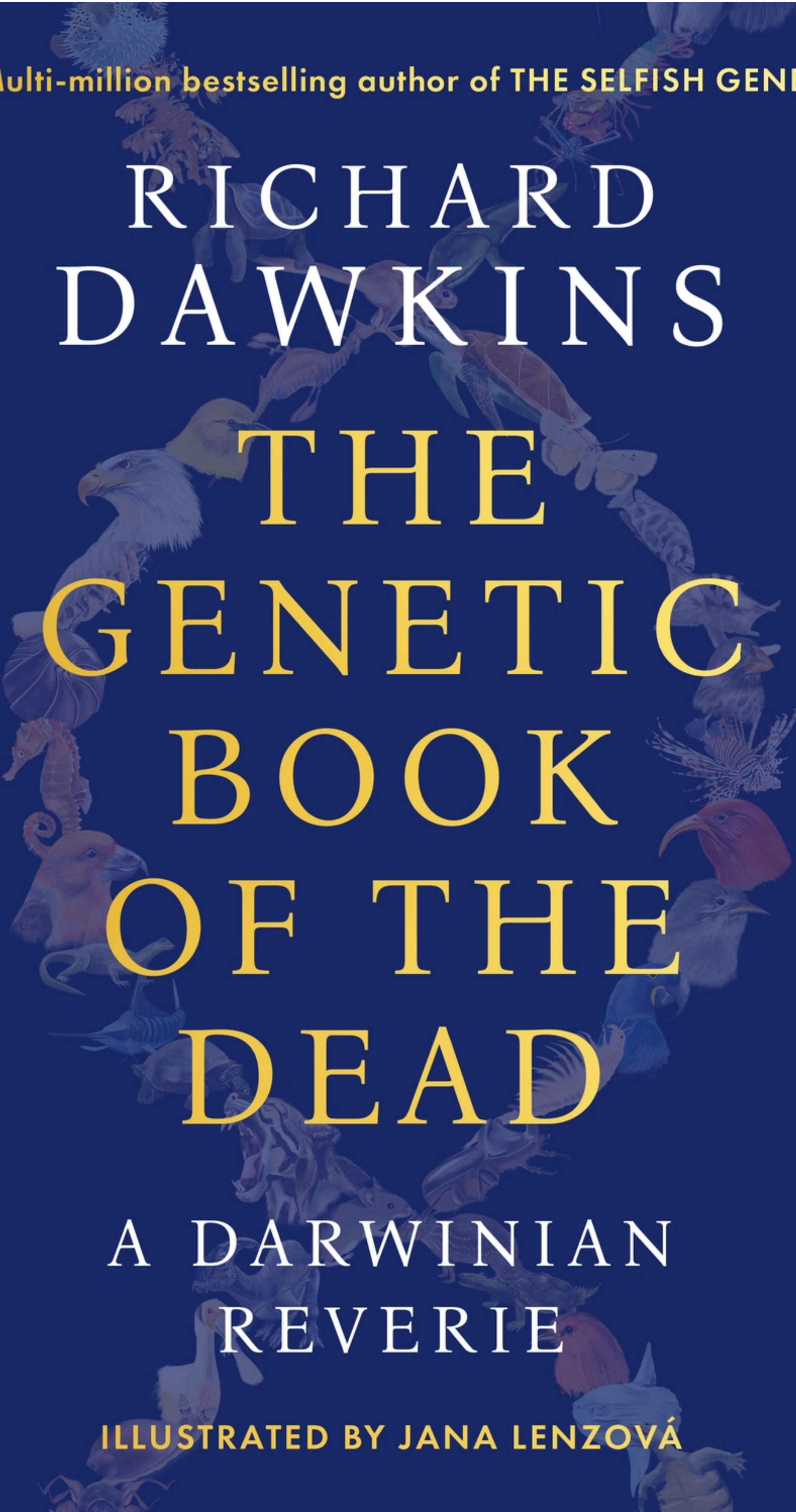
Multi-million bestselling author of THE SELFISH GENE

RICHARD DAWKINS

THE GENETIC BOOK OF THE DEAD

A DARWINIAN REVERIE



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Reading the Animal

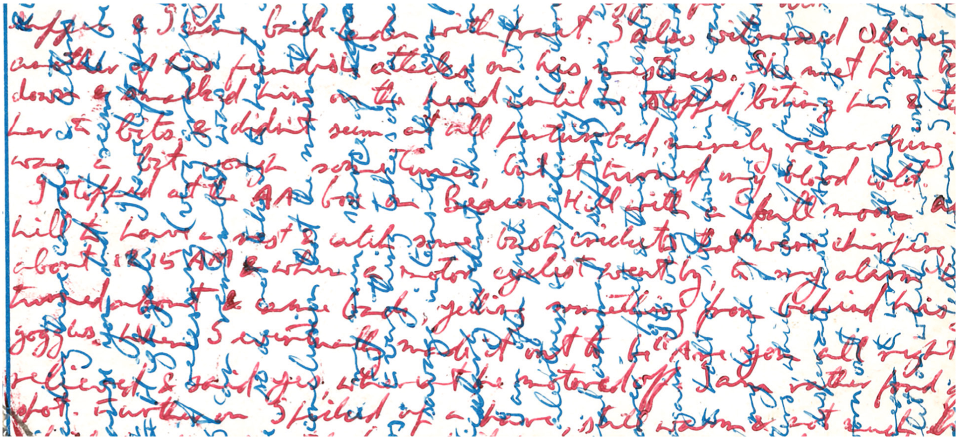
You are a book, an unfinished work of literature, an archive of descriptive history. Your body and your genome can be read as a comprehensive dossier on a succession of colourful worlds long vanished, worlds that surrounded your ancestors long gone: a genetic book of the dead. This truth applies to every animal, plant, fungus, bacterium, and archaean but, in order to avoid tiresome repetition, I shall sometimes treat all living creatures as honorary animals. In the same spirit, I treasure a remark by John Maynard Smith when we were together being shown around the Panama jungle by one of the Smithsonian scientists working there: 'What a pleasure to listen to a man who really loves his animals.' The 'animals' in question were palm trees.

From the animal's point of view, the genetic book of the dead can also be seen as a predictor of the future, following the reasonable assumption that the future will not be too different from the past. A third way to say it is that the animal, including its genome, embodies a *model* of past environments, a model that it uses to, in effect, predict the future and so succeed in the game of Darwinism, which is the game of survival and reproduction, or, more precisely, gene survival. The animal's genome makes a bet that the future will not be too different from the pasts that its ancestors successfully negotiated.

I said that an animal can be read as a book about past worlds, the worlds of its ancestors. Why didn't I use the present tense: read the animal as a description of the environment in which it itself lives? It can indeed be read in that way. But (with reservations to be discussed) every aspect of an animal's survival machinery was bequeathed via its genes by ancestral natural selection. So, when we read the animal, we are actually reading *past* environments. That is why my title includes 'the dead'. We are talking about reconstructing ancient worlds in which successive ancestors, now long dead, survived to pass on the genes that shape the way we modern animals are. At present it is a difficult undertaking, but a scientist of the future, presented with a hitherto unknown animal, will be able to read its body, and its genes, as a detailed description of the environments in which its ancestors lived.

I shall have frequent recourse to my imagined Scientist Of the Future, confronted with the body of a hitherto unknown animal and tasked with reading it. For brevity, since I'll need to mention her often, I shall use her initials, SOF. This distantly resonates with the Greek *sophos*, meaning 'wise' or 'clever', as in 'philosophy', 'sophisticated', etc. In order to avoid ungainly pronoun constructions, and as a courtesy, I arbitrarily assume SOF to be female. If I happened to be a female author, I'd reciprocate.

This genetic book of the dead, this 'readout' from the animal and its genes, this richly coded description of ancestral environments, must necessarily be a *palimpsest*. Ancient documents will be partially over-written by superimposed scripts laid down in later times. A palimpsest is defined by the *Oxford English Dictionary* as 'a manuscript in which later writing has been superimposed on earlier (effaced) writing'. A dear colleague, the late Bill Hamilton, had the engaging habit of writing postcards as palimpsests, using different-coloured inks to reduce confusion. His sister Dr Mary Bliss kindly lent me this example.



Besides his card being a nicely colourful palimpsest, it is fitting to use it because Professor Hamilton is widely regarded as the most distinguished Darwinian of his generation. Robert Trivers, mourning his death, said, 'He had the most subtle, multi-layered mind I have ever encountered. What he said often had double and even triple meanings so that, while the rest of us speak and think in single notes, he thought in chords.' Or should that be palimpsests? Anyway, I like to think he would have enjoyed the idea of evolutionary palimpsests. And, indeed, of the genetic book of the dead itself.

Both Bill's postcards and my evolution palimpsests depart from the strict dictionary definition: earlier writings are not irretrievably effaced. In the genetic book of the dead, they are partially overwritten, still there to be read, albeit we must peer 'through a glass darkly', or through a thicket of later writings. The environments described by the genetic book of the dead run the gamut from ancient Precambrian seas, via all intermediates through the mega-years to very recent. Presumably some kind of weighting balances modern scripts versus ancient ones. I don't think it follows a simple formula like the Koranic rule for handling internal contradictions – new always trumps old. I'll return to this in Chapter 3.

If you want to succeed in the world you have to predict, or behave as if predicting, what will happen next. All sensible prediction must be based on the past, and much sensible prediction is statistical rather than absolute. Sometimes the prediction is cognitive – 'I foresee that if I fall over that cliff (seize that snake by its rattling tail, eat those tempting *belladonna* berries), it is likely that I will suffer or die in consequence.' We humans are accustomed to predictions of that cognitive kind, but they are not the predictions I have in mind. I shall be more concerned with unconscious, statistical 'as-if' predictions of what might affect an animal's future chances of surviving and passing on copies of its genes.

This horned lizard of the Mojave, whose skin is tinted and patterned to resemble sand and small stones, embodies a prediction, by its genes, that it would find itself born (well, hatched) into a desert. Equivalently, a zoologist presented with the lizard could *read* its skin as a vivid *description* of the sand and stones of the desert environment in which its ancestors lived. And now here's my central message. Much more than skin deep, the whole body through and through, its very warp and woof, every organ, every cell and biochemical process, every smidgen of any animal, including its genome, can be read as describing ancestral worlds. In the lizard's case it will no doubt spin the same desert yarn as the skin. 'Desert' will be written into every reach of the animal, plus a whole lot more information about its ancestral past, information far exceeding what is available to present-day science.

The lizard burst out of the egg endowed with a genetic prediction that it would find itself in a sun-parched world of sand and pebbles. If it were to violate its genetic prediction, say by straying from the desert onto a golf green, a passing raptor would soon pick it off. Or if the world itself changed, such that its genetic predictions turned out to be wrong, it would also likely be doomed. All useful prediction relies on the future being approximately the same as the past, at least in a statistical sense. A world of continual mad caprice, an environmental bedlam that changed randomly and undependably, would render prediction impossible and put survival in jeopardy. Fortunately, the world is conservative, and genes can safely bet on any given place carrying on pretty much as before. On those occasions when it doesn't – say after a catastrophic flood or volcanic eruption or, as in the case of the dinosaurs' tragic end when an asteroid-strike ravaged the world – all predictions are wrong, all bets are off, and whole groups of animals go extinct. More usually, we aren't dealing with such major catastrophes: not huge swathes of the animal kingdom being wiped out at a stroke, but only those variant individuals whose predictions are slightly wrong, or slightly more wrong than those of competitors within their own species. That is natural selection.

The top scripts of the palimpsest are so recent that they are of a special kind, written during the animal's own lifetime. The genes' description of ancestral worlds is overlain by modifications and detailed refinements scripted since the animal was born – modifications written or rewritten by the animal's *learning* from experience; or by the remarkable memory of past diseases laid down by the immune system; or by physiological acclimatisation, to altitude, say; or even by simulations in imagination of possible future outcomes. These recent palimpsest scripts are not handed down by the genes (though the equipment needed to write them is), but they still amount to information from the past, called into service to predict the future. It's just that it's the very recent past, the past enclosed within the animal's own lifetime. Chapter 7 is about those parts of the palimpsest that were scribbled in since the animal was born.

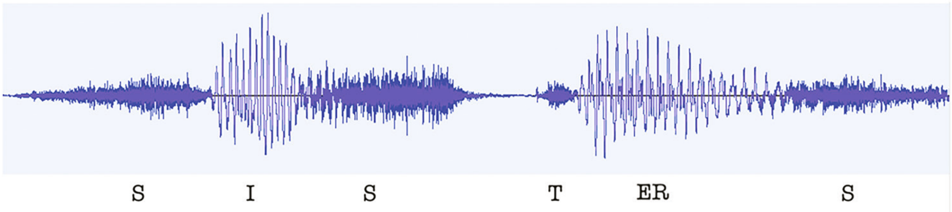
There is also an even more recent sense in which an animal's brain sets up a dynamic model of the immediately fluctuating environment, predicting moment to moment changes in real time. Writing this on the Cornish coast, I take envious pleasure in the gulls as they surf the wind battering the cliffs of the Lizard peninsula. The wings, tail, and even head angle of each bird sensitively adjust themselves to the changing gusts and updraughts. Imagine that SOF, our zoologist of the future, implants radio-linked electrodes in a flying gull's brain. She could obtain a readout of the gull's muscle-adjustments, which would translate into a running commentary, in real time, on the whirling eddies of the wind: a predictive model in the brain that sensitively fine-tunes the bird's flight surfaces so as to carry it into the next split second.

I said that an animal is not only a description of the past, not just a prediction of the future, but also a *model*. What is a model? A contour map is a model of a country, a model from which you can reconstruct the landscape and navigate its byways. So too is a list of zeros and ones in a computer, being a digitised rendering of the map, perhaps including information tied to it: local population size, crops grown, dominant religions, and so on. As an engineer might understand the word, any two systems are 'models' of each other if their behaviour shares the same underlying mathematics. You can wire up an electronic model of a pendulum. The periodicity of both pendulum and electronic oscillator are governed by the same equation. It's just that the symbols in the equation don't stand for the same things. A mathematician could treat either of them, together with the relevant equation written on paper, as a 'model' of any of the others. Weather forecasters construct a dynamic computer model of the world's weather, continually updated by information from strategically placed thermometers, barometers, anemometers, and nowadays above all, satellites. The model is run on into the future to construct a forecast for any chosen region of the world.

Sense organs do not faithfully project a movie of the outer world into a little cinema in the brain. The brain constructs a virtual reality (VR) model of the real world outside, a model that is continuously updated via the sense organs. Just as weather forecasters run their computer model of the world's weather into the future, so every animal does the same thing from second to second with its own world model, in order to guide its next action. Each species sets up its own world model, which takes a form useful for the species' way of life, useful for making vital predictions of how to survive. The model must be very different from species to species. The model in the head of a swallow or a bat must approximate a three-dimensional, aerial world of fast-moving targets. It may not matter that the model is updated by nerve impulses from the eyes in the one case, from the ears in the other. Nerve impulses are nerve impulses are nerve impulses, whatever their origin. A squirrel's brain must run a VR model similar to that of a squirrel monkey. Both have to navigate a three-dimensional maze of tree trunks and branches. A cow's model is simpler and closer to two dimensions. A frog doesn't model a scene as we would understand the word. The frog's eye largely confines itself to reporting small moving objects to the brain. Such a report typically initiates a stereotyped sequence of events: turning towards the object, hopping to get nearer, and finally shooting the tongue towards the target. The eye's wiring-up embodies a prediction that, were the frog to shoot out its tongue in the indicated direction, it would be likely to hit food.

My Cornish grandfather was employed by the Marconi company in its pioneering days to teach the principles of radio to young engineers entering the company. Among his teaching aids was a clothesline that he waggled as a model of sound waves – or radio waves, for the same model applied to both, and that's the point. Any complicated pattern of waves – sound waves, radio waves, or even sea waves at a pinch – can be broken down into component sine waves – 'Fourier analysis', named after the French mathematician Joseph Fourier (1768–1830). These in turn can be summed again to reconstitute the original complex wave (Fourier synthesis). To demonstrate this, Grandfather attached his clothesline to rotating wheels. When only one wheel turned, the rope executed serpentine undulations approximating a sine wave. When a coupled wheel rotated at the same time, the rope's snaking waves became more complex. The sum of the sine waves was an elementary but vivid demonstration of the Fourier principle. Grandfather's snaking rope was a model of a radio wave travelling from transmitter to receiver. Or of a sound wave entering the ear: a compound wave upon which the brain presumably performs something equivalent to Fourier analysis when it unravels, for example, a pattern even as complex as whispered speech plus intrusive coughing against the background of an orchestral concert. Amazingly, the human ear, well, actually, the human brain, can pick out here an oboe, there a French horn, from the compound waveform of the whole orchestra.

Today's equivalent of my grandfather would use a computer screen instead of a clothesline, displaying first a simple sine wave, then another sine wave of different frequency, then adding the two together to generate a more complex wiggly line, and so on. The following is a picture of the sound waveform – high-frequency air pressure changes – when I uttered a single English word. If you knew how to analyse it, the numerical data embodied in (a much-expanded image of) the picture would yield a readout of what I said. In fact, it would require a great deal of mathematical wizardry and computer power for you to decipher it. But let the same wiggly line be the groove in which an old-fashioned gramophone needle sits. The resulting waves of changing air pressure would bombard your eardrums and be transduced to pulse patterns in nerve cells connected to your brain. Your brain would then without difficulty, in real time, perform the necessary mathematical wizardry to recognise the spoken word 'sisters'.



Our sound-processing brain software effortlessly recognises the spoken word, but our sight-processing software has extreme difficulty deciphering it when confronted with a wavy line on paper, on a computer screen, or with the numbers that composed that wavy line. Nevertheless, all the information is contained in the numbers, no matter how they are represented. To decipher it, we'd need to do the mathematics explicitly with the aid of a high-speed computer, and it would be a difficult calculation. Yet our brains find it a doddle if presented with the same data in the form of sound waves. This is a parable to drive home the point – pivotal to my purpose, which is why I said it twice – that some parts of an animal are hugely harder to 'read' than others. The patterning on our Mojave lizard's back was easy: equivalent to *hearing* 'sisters'. Obviously, this animal's ancestors survived in a stony desert. But let us not shrink from the difficult readings – the cellular chemistry of the liver, say. That might be difficult in the same way as *seeing* the waveform of 'sisters' on an oscilloscope screen is difficult. But nothing negates the main point, which is that the information, however hard to decipher, is lurking within. The genetic book of the dead may turn out to be as inscrutable as Linear A or the Indus Valley script. But the information, I believe, is all there.

The pattern to the right is a QR code. It contains a concealed message that your human eye cannot read. But your smartphone can instantly decipher it and reveal a line from my favourite poet. The genetic book of the dead is a palimpsest of messages about ancestral worlds, concealed in an animal's body and genome. Like QR codes, they mostly cannot be read by the naked eye, but zoologists of the future, armed with advanced computers and other tools of their day, will read them.

To repeat the central point, when we examine an animal there are some cases – the Mojave horned lizard is one – where we can instantly read the embodied description of its ancestral environment, just as our auditory system can instantly decipher the spoken word 'sisters'. Chapter 2 examines animals who have their ancestral environments almost literally painted on their backs. But mostly we must resort to more indirect and difficult methods in order to extract our readout. Later chapters feel their way towards possible ways of doing this. But in most cases the techniques are not yet properly developed, especially those that involve reading genomes. Part of my purpose is to inspire mathematicians, computer scientists, molecular geneticists, and others better qualified than I am, to develop such methods.

At the outset I need to dispel five possible misunderstandings of the main title, *Genetic Book of the Dead*. First is the disappointing revelation that I am deferring the task of deciphering much of the book of the dead to the sciences of the future. Nothing much I can do about that. Second, there is little connection, other than a poetic resonance, with the Egyptian Books of the Dead. These were instruction manuals buried with the dead, to help them navigate their way to immortality. An animal's genome is an instruction manual telling the animal how to navigate through the world, in such a way as to pass the manual (not the body) on into the indefinite future, if not actual immortality.

Third, my title might be misunderstood to be about the fascinating subject of Ancient DNA. The DNA of the long dead – well, not *very* long, unfortunately – is in some cases available to us, often in disjointed fragments. The Swedish geneticist Svante Pääbo won a Nobel prize for jigsawing the genome of Neanderthal and Denisovan humans, otherwise known only from fossils; in the Denisovan case only three teeth and five bone fragments. Pääbo's work incidentally shows that Europeans, but not sub-Saharan Africans, are descended from rare cases of interbreeding with Neanderthals. Also, some modern humans, especially Melanesians, can be traced back to interbreeding events with Denisovans. The field of 'Ancient DNA' research is now flourishing. The woolly mammoth genome is almost completely known, and there are serious hopes of reviving the species. Other possible 'resurrections' might include the dodo, passenger pigeon, great auk, and thylacine (Tasmanian wolf). Unfortunately, sufficient DNA doesn't last more than a few thousand years at best. In any case, interesting though it is, Ancient DNA is outside the scope of this book.

Fourth, I shall not be dealing with comparisons of DNA sequences in different populations of modern humans and the light that they throw on history, including the waves of human migration that have swept over Earth's land surface. Tantalisingly, these genetic studies overlap with comparisons between languages. For example, the distribution of both genes and words across the Micronesian islands of the Western Pacific islands shows a mathematically lawful relationship between inter-island distance and word-resemblance. We can picture outrigger canoes scudding across the open Pacific, laden with both genes and words! But that would be a chapter in another book. Might it be called *The Selfish Meme*?

The present book's title should not be taken to mean that existing science is ready to translate DNA sequences into descriptions of ancient environments. Nobody can do that, and it's not clear that SOF will ever do so. This book is about reading the animal itself, its body and behaviour – the 'phenotype'. It remains true that the descriptive messages from the past are transmitted by DNA. But for the moment we read them indirectly via phenotypes. The easiest, if not the only, way to translate a human genome into a working body is to feed it into a very special interpreting device called a woman.

The Species as Sculpture; the Species as Averaging Computer

Sir D'Arcy Thompson (1860–1948), that immensely learned zoologist, classicist, and mathematician, made a remark that seems trite, even tautological, but it actually provokes thought. 'Everything is the way it is because it got that way.' The solar system is the way it is because the laws of physics turned a cloud of gas and dust into a spinning disc, which then condensed to form the sun, plus orbiting bodies rotating in the same plane as each other and in the same direction, marking the plane of the original disc. The moon is the way it is because a titanic bombardment of Earth 4.5 billion years ago hived off into orbit a great quantity of matter, which then was pulled and kneaded by gravity into a sphere. The moon's initial rotation later slowed, in a phenomenon called 'tidal locking', such that we only ever see one face of it. More minor bombardments disfigured the moon's surface with craters. Earth would be pockmarked in the same way but for erosive and tectonic obliteration. A sculpture is the way it is because a block of Carrara marble received the loving attention of Michelangelo.

Why are our bodies the way they are? Partly, like the moon, we bear the scars of foreign insults – bullet wounds, souvenirs of the duellist's sabre or the surgeon's knife, even actual craters from smallpox or chickenpox. But these are superficial details. A body mostly got that way through the processes of embryology and growth. These were, in turn, directed by the DNA in its cells. And how did the DNA get to be the way it is? Here we come to the point. The genome of every individual is a sample of the gene pool of the species. The gene pool got to be the way it is over many generations, partly through random drift, but more pertinently through a process of non-random sculpture. The sculptor is natural selection, carving and whittling the gene pool until it – and the bodies that are its outward and visible manifestation – is the way it is.

Why do I say it's the species gene pool that is sculpted rather than the individual's genome? Because, unlike Michelangelo's marble, the genome of an individual doesn't change. The individual genome is not the entity that the sculptor carves. Once fertilisation has taken place, the genome remains fixed, from zygote right through embryonic development, to childhood, adulthood, old age. It is the gene pool of the species, not the genome of the individual, that changes under the Darwinian chisel. The change deserves to be called sculpting to the extent that the typical animal form that results is an improvement. Improvement doesn't have to mean more beautiful like a Rodin or a Praxiteles (though it often is). It means only getting better at surviving and reproducing. Some individuals survive to reproduce. Others die young. Some individuals have lots of mates. Others have none. Some have no children. Others a swarming, healthy brood. Sexual recombination sees to it that the gene pool is stirred and shaken. Mutation sees to it that new genetic variants are fed into the mingling pool. Natural selection and sexual selection see to it that, as generation succeeds generation, the shape of the average genome of the species changes in constructive directions.

Unless we are population geneticists, we don't see the shifting of the sculpted gene pool directly. Instead, we observe changes in the average bodily form and behaviour of members of the species. Every individual is built by the cooperative enterprise of a sample of genes taken from the current pool. The gene pool of a species is the ever-changing marble upon which the chisels, the fine, sharp, exquisitely delicate, deeply probing chisels of natural selection, go to work.

A geologist looks at a mountain or valley and 'reads' it, reconstructs its history from the remote past through to recent times. The natural sculpting of the mountain or valley might begin with a volcano, or tectonic subduction and upthrust. The chisels of wind and rain, rivers and glaciers then take over. When a biologist looks at fossil history, she sees not genes but things that eyes are equipped to see: progressive changes in average phenotype. But the entity being carved by natural selection is the species gene pool.

The existence of sexual reproduction confers on The Species a very special status not shared by other units in the taxonomic hierarchy – genus, family, order, class, etc. Why? Because sexual recombining of genes – shuffling the pack (American deck) – takes place only within the species. That is the very definition of 'species'. And it leads me to the second metaphor in the title of this section: the species as averaging computer.

The genetic book of the dead is a written description of the world of no particular ancestral individual more than another. It is a description of the environments that sculpted the whole gene pool. Any individual whom we examine today is a sample from the shuffled pack, the shaken and stirred gene pool. And the gene pool in every generation was the result of a statistical process averaged over all those individual successes and failures within the species. The species is an averaging computer. The gene pool is the database upon which it works.

2

'Paintings' and 'Statues'

When, like that Mojave Desert lizard, an animal has its ancestral home painted on its back, our eyes give us an instant and effortless readout of the worlds of its forebears, and the hazards that they survived. Here's another highly camouflaged lizard. Can you see it on its background of tree bark? You can, because the photograph was taken in a strong light from close range. You are like a predator who has had the good fortune to stumble upon a victim under ideal seeing conditions. It is such close encounters that exerted the selection pressure to put the finishing touches to the camouflage's perfection. But how did the evolution of camouflage get its start? Wandering predators, idly scanning out of the corner of their eye, or hunting when the light was poor, supplied the selection pressures that began the process of evolution

towards tree bark mimicry, back when the incipient resemblance was only slight. The intermediate stages of camouflage perfection would have relied upon intermediate seeing conditions. There's a continuous gradient of available conditions, from 'seen at a distance, in a poor light, out of the corner of the eye, or when not paying attention' all the way up to 'close-up, good light, full-frontal'. The lizard of today has a detailed, highly accurate 'painting' of tree bark on its back, painted by genes that survived in the gene pool because they produced increasingly accurate pictures.

We have only to glance at this frog to 'read' the environment of its ancestors as being rich in grey lichen. Or, in another of Chapter 1's

formulations, the frog's genes 'bet' on lichen. I intend 'bet' and 'read' in a sense that is close to literal. It requires no sophisticated techniques or apparatus. The zoologist's eyes are sufficient. And the Darwinian reason for this is that the painting is designed to deceive predatory eyes that work in the same kind of way as the zoologist's own eyes. Ancestral frogs survived because they successfully deceived predatory eyes similar to the eyes of the zoologist – or of you, vertebrate reader.

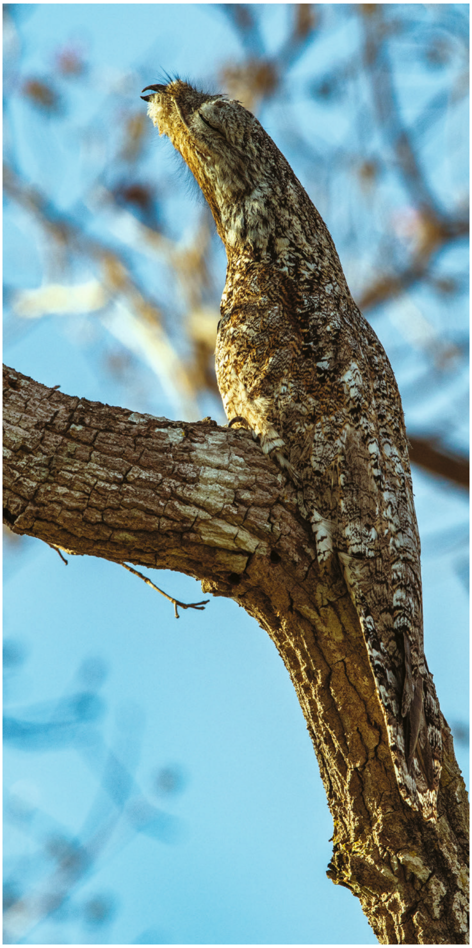
In some cases, it is not prey but predators whose outer surface is painted with the colours and patterning of their ancestral world, the better to creep up on prey unseen. A tiger's genes bet on the tiger being born into a world of light and shade striped by vertical stems. The zoologist examining the body of a snow leopard could bet that its ancestors lived in a mottled world of stones and rocks, perhaps a mountainous region. And its genes place a future bet on the same environment as cover for its offspring.

By the way, the big cat's mammalian prey might find its camouflage more baffling than we do. We apes and Old World monkeys have trichromatic vision, with three colour-sensitive cell types in our retinas, like modern digital cameras. Most mammals are dichromats: they are what we would call red-green colour-blind. This probably means they'd find a tiger or snow leopard even harder to distinguish from its background than we would. Natural selection has 'designed' the stripes of tigers, and the blotches of snow leopards, in such a way as to fool the dichromat eyes of their typical prey. They are pretty good at fooling our trichromat eyes too.

Also in passing, I note how surprising it is that otherwise beautifully camouflaged animals are let down by a dead giveaway – symmetry. The feathers of this owl beautifully imitate tree bark. But the symmetry gives the game away. The camouflage is broken.

I am reduced to suspecting that there must be some deep embryological constraint, making it hard to break away from left-right symmetry. Or does symmetry confer some inscrutable advantage in social encounters? To intimidate rivals, perhaps? Owls can rotate their necks through a far greater angle than we can. Perhaps that mitigates the problem of a symmetrical face. This particular photograph tempts the speculation that natural selection might have favoured the habit of closing one eye because it reduces symmetry. But I suppose that's too much to hope for.

Subtly different from 'paintings' are 'statues'. Here the animal's whole body resembles a discrete object that it is not. A tawny frogmouth or a potoo resembling a broken stump of a tree branch, a stick caterpillar sculpted as a twig, a grasshopper resembling a stone or a clod of dry soil, a caterpillar mimicking a bird dropping, are all examples of animal 'statues'.



The working difference between a 'painting' and a 'statue' is that a painting, but not a statue, ceases to deceive the moment the animal is removed from its natural background. A 'painted' peppered moth removed from the light-coloured bark that it resembles and placed on any other background will instantly be seen and caught by a predator. In this photograph, the background is a soot-blackened tree in an industrial area, which is perfect for the dark, melanic mutant of the same species of moth that you may have noticed less immediately by its side. On the other hand,

the masquerading Geometrid stick caterpillar photographed by Anil Kumar Verma in India, if placed on any background, would have a good chance of still being mistaken for a stick and overlooked by a predator. That is the mark of a good animal statue.

Although a statue resembles objects in the natural background, it does not depend for its effectiveness on being seen against that background in the way that a 'painting' does. On the contrary, it might be in greater danger. A lone stick insect on a lawn might be overlooked, as a stick that had fallen there. A stick insect surrounded by real sticks might be spotted as the odd one out. When drifting alone, the

leafy sea dragon's resemblance to a wrack might protect it, at least more so than its seahorse cousin whose shape in no way mimics a seaweed. But would this statue be less safe when nestling in a waving bed of real seaweed? It's a moot question.

Freshwater mussels of the species *Lampsilis cardium* have larvae that grow by feeding on blood, which they suck from the gills of a fish. The mussel has to find a way to put its larvae into the fish. It does it by means of a 'statue', which fools the fish. The mussel has a brood pouch for very young larvae on the edge of its mantle. The brood pouch is an impressive replica of a pair of small fish, complete with false eyes and false, very fish-like, 'swimming' movements. Statues don't move, so the word 'statue' is strictly inappropriate, but never mind, you get the point. Larger fish approach and attempt to catch the dummy fish. What they actually catch – and it does them no good – is a squirt of mussel larvae.

This highly camouflaged snake from Iran has a dummy spider at the tip of its tail. It may look only half convincing in a still picture. But the snake moves its tail in such a way that it looks strikingly like a spider scuttling about. Very realistic indeed, especially when the snake itself is concealed in a burrow with only the tail tip visible. Birds swoop down on the spider. And that is the last thing they do. It is worth reflecting on how remarkable it is that such a trick has evolved by natural selection. What might the intermediate stages have looked like? How did the evolutionary sequence get started? I suppose that, before the tip of the tail looked anything like a spider, simply waggling it about was somewhat attractive to birds, who are drawn to any small moving object.

Both 'paintings' and 'statues' are easy-to-read descriptions of ancestral worlds, the environments in which ancestors survived. The stick caterpillar is a detailed description of ancient twigs. The potoo is a perfect model of long-forgotten stumps. Except that they are not really forgotten. The potoo itself is the memory. Twigs of past ages have carved their own likeness into the masquerading body of that caterpillar. The sands of time have painted their collective self-portrait on the surface of this spider, which you may have trouble spotting.

'Where are the snows of yesteryear?' Natural selection has frozen them in the winter plumage of the willow ptarmigan.

The leaf-tailed gecko recalls to our minds, though not his, the dead leaves among which his ancestors lived. He embodies the Darwinian 'memory' of generations of leaves that fell long before men arrived in Madagascar to see them, probably long before men existed anywhere.

The green katydid (long-horned grasshopper) has no idea that it embodies a genetic memory of green mosses and fronds over which its ancestors walked. But we can read at a glance that this is so. Same with this adorable little Vietnamese mossy frog.

Statues don't always copy inanimate objects like sticks or pebbles, dead leaves, or tree branch stubs. Some mimics pretend to be poisonous or distasteful models, and inconspicuous is precisely what they are not. At first glance you might think this was a wasp and hesitate

to pick it up. It's actually a harmless hoverfly. The eyes give it away. Flies have bigger compound eyes than wasps. This feature is probably written in a deep layer of palimpsest that, for some reason, is hard to over-write. The largest anatomical difference between flies and wasps – two wings rather than four (the feature that gives the fly Order its Latin name, Diptera) – is perhaps also difficult to over-write. But maybe, too, that potential clue is hard to notice. What predator is going to take the time to count wings?

Real wasps, the models for the hoverfly mimicry, are not trying to hide. They're the opposite of camouflaged. Their vividly striped abdomen shouts 'Beware! Don't mess with me!' The hoverfly is shouting the same thing, but it's a lie. It has no sting and would be good to eat if only the predator dared to attack it. It is a statue, not a painting, because its (fake) warning doesn't depend on the background. From our point of view in this book, we can read its stripes as telling us that the ecology of its ancestors contained dangerous yellow-and-black stripy things, and predators that feared them. The fly's stripes are a simulacrum of erstwhile wasp stripes, painted on its abdomen by natural selection. Yellow and black stripes on an insect reliably signify a warning – either true or false – of dire consequences to would-be attackers. The beetle to the right is another, especially vivid example.

If you came face to face with this, peering at you through the undergrowth, would you start back, thinking it was a snake?

It isn't peering and it isn't a snake. It's the chrysalis of a butterfly, *Dynastor darius*, and chrysalises don't peer. As a fine pretence of the front end of a snake, it's well calculated to frighten. Never mind that rational second thoughts could calculate that it's a bit on the small side to be a dangerous snake. There exists a distance – still close enough to be worrying – at which a snake would look that small. Besides, a panicking bird has no time for second thoughts. One startled squawk and it's away. Having more time for reflection, the Darwinian student of the genetic book of the dead will read the caterpillar's ancestral world as inhabited by dangerous snakes. Some caterpillars, whose rear ends pull the same snake trick, even move muscles in such a way that the fake eyes seem to close and open.

Would-be predators can't be expected to know that snakes don't do that.

Eyes are scary in themselves. That's why some moths have eyespots on their wings, which they suddenly expose when surprised by a predator. If you had good reason to fear tigers or other members of the cat family, might you not start back in alarm if suddenly confronted with this, the so-called owl moth of South East Asia?

There exists a distance – a dangerous distance – at which a tiger or a leopard would present a retinal image the same size as a close-up moth. OK, it doesn't look very like any particular member of the cat family to our eyes. But there's plenty of evidence that animals of various species respond to dummies that bear only a crude resemblance to the real thing – scarecrows are a familiar example, and there's lots of experimental evidence as well. Black-headed gulls respond to a model gull head on the end of a stick, as though it were a whole real gull. A shocked withdrawal might be all it takes to save this moth.

I am amused to learn that eyes painted on the rumps of cattle are effective in deterring predation by lions.

We could call it the Babar effect, after Jean de Brunhoff's lovable and wise King of the Elephants, who won the war against the rhinoceroses by painting scary eyes on elephant rumps.

What on Earth is this? A dragon? A nightmare devil horse? It is in fact the caterpillar of an Australian moth, the pink underwing. The spectacular eye and teeth pattern is not visible when the caterpillar is at rest. It is screened by folds of skin. When threatened, the animal pulls back the skin screen to unveil the display, and, well, all I can say is that if I were a would-be predator, I wouldn't hang about.

PHOTO (RIGHT): HUSEIN LATIF

The scariest false face I know? It's a toss-up between the octopus on the left and the vulture on the right. The real eyes of the octopus can just be seen above the inner ends of the 'eyebrows' of the large, prominent false eyes. You can find the real eyes of the Himalayan griffon vulture if you first locate the beak and hence the real head. The false eyes of the octopus presumably deter predators. The vulture seems to use its false face to intimidate other vultures, thereby clearing a path through a crowd around a carcase.

Some butterflies have a false head at the back of the wings. How might this benefit the insect? Five hypotheses have been proposed, of which the consensus favourite is the deflection hypothesis: birds are thought to peck at the less vulnerable false head, sparing the real one. I slightly prefer a sixth idea, that the predator expects the butterfly to take off in the wrong direction. Why do I prefer it? Perhaps because I am committed to the idea that animals survive by predicting the future.

Paintings and statues aimed at fooling predators constitute the nearest approach achieved by any book of the dead to a literal readout, a literal description of ancestral worlds. And the aspect of this that I want to stress is its astounding accuracy and attention to detail. This leaf insect even has fake blemishes. The stick caterpillar (page 19) has fake buds.

I see no reason why the same scrupulous attention to detail should not pervade less literal, less obvious parts of the readout. I believe the same detailed perfection is lurking, waiting to be discovered, in internal organs, in brain-wiring of behaviour, in cellular biochemistry, and other more indirect or deeply buried readings that can be dug out if only we could develop the tools to do so. Why should natural selection escalate its vigilance specifically for the *external appearance* of animals? Internal details, *all* details, are no less vital to survival. They are equally subject to becoming written descriptions of past worlds, albeit written in a less transparent script, harder to decipher than this chapter's superficial paintings and statues. The reason paintings and statues are easier for us to read than internal pages of the genetic book of the dead is not far to seek. They are aimed at eyes, especially predatory eyes. And, as already pointed out, predatory eyes, vertebrate ones at least, work in the same way as our eyes. No wonder it is camouflage and other versions of painting and sculpture that most impress us among all the pages of the book of the dead.

I believe the internally buried descriptions of ancestral worlds will turn out to have the same detailed perfection as the externally seen paintings and statues. Why should they not? The descriptions will just be written less literally, more cryptically, and will require more sophisticated decoding. As with the ear's decoding of Chapter 1's spoken word 'sisters', the paintings and statues of this chapter are effortlessly read pages from books of the dead. But just as the 'sisters' waveform, when presented in the recalcitrant form of binary digits, will eventually yield to analysis, so too will the non-obvious, non-skin-deep details of animals and their genes. The book of the dead will be read, even down to minute details buried deep inside every cell.

This is my central message, and it will bear repeating here. The fine-fingered sculpting of natural selection works not just on the external appearance of an animal such as a stick caterpillar, a tree-climbing lizard, a leaf insect or a tawny frogmouth, where we can appreciate it with the naked eye. The Darwinian sculptor's sharp chisels penetrate every internal cranny and nook of an animal, right down to the sub-microscopic interior of cells and the high-speed chemical wheels that turn therein. Do not be deceived by the extra difficulty of discerning details more deeply buried. There is every reason to suppose that painted lizards or moths, and moulded potoos or caterpillars, are the outward and visible tips of huge, concealed icebergs. Darwin was at his most eloquent in expressing the point.

> It may be said that natural selection is daily and hourly scrutinising, throughout the world, every variation, even the slightest; rejecting that which is bad, preserving and adding up all that is good; silently and insensibly working, whenever and wherever opportunity offers, at the improvement of each organic being in relation to its organic and inorganic conditions of life. We see nothing of these slow changes in progress, until the hand of time has marked the long lapse of ages, and then so imperfect is our view into long past geological ages, that we only see that the forms of life are now different from what they formerly were.