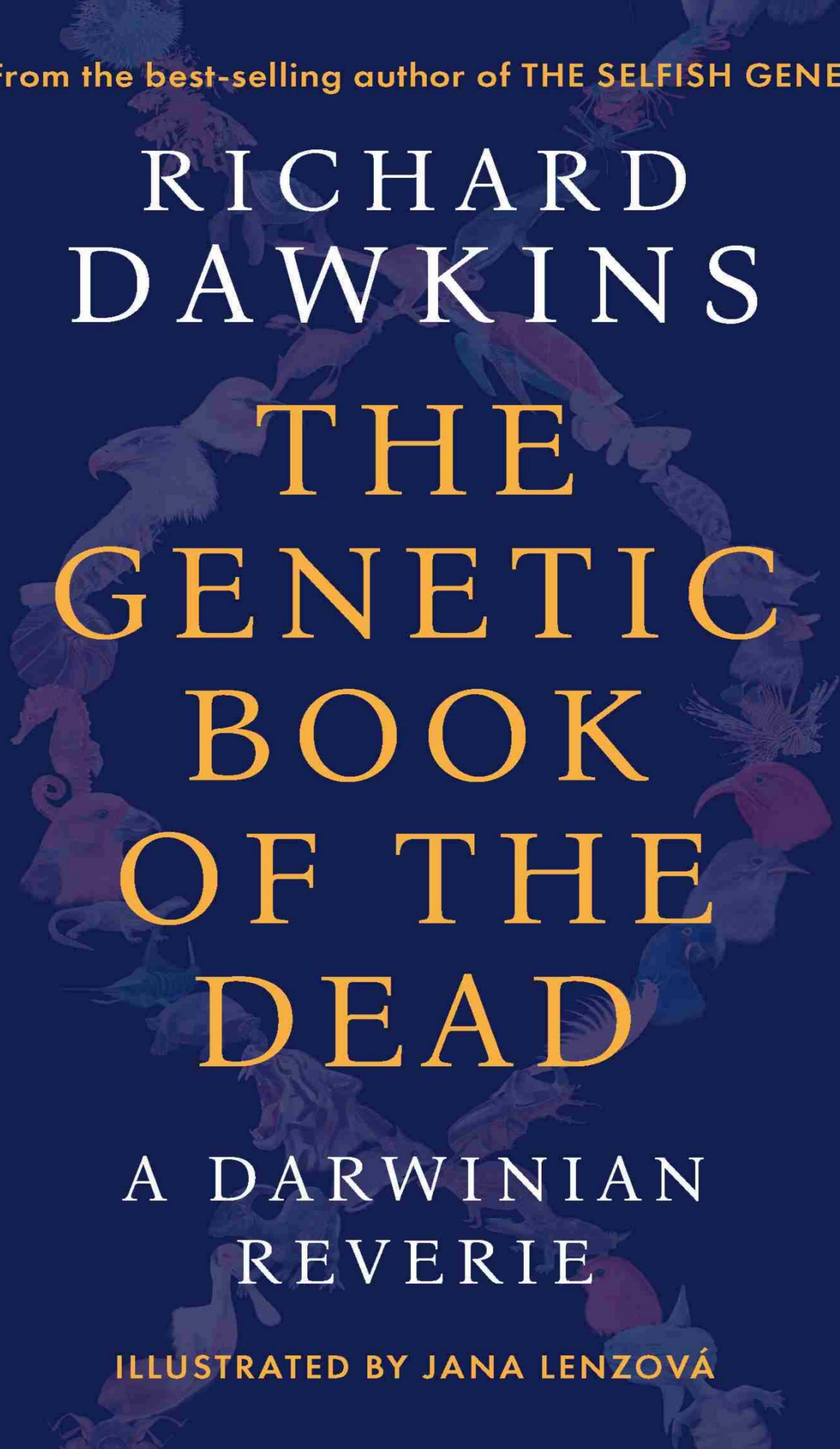
From the best-selling author of THE SELFISH GENE

RICHARD DAWKINS

THE GENETIC BOOK OF THE DEAD

A DARWINIAN REVERIE



ILLUSTRATED BY JANA LENZOVÁ

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ALSO BY RICHARD DAWKINS

The Selfish Gene

The Extended Phenotype

The Blind Watchmaker

River Out of Eden

Climbing Mount Improbable

Unweaving the Rainbow

A Devil's Chaplain

The Ancestor's Tale (with Yan Wong)

The God Delusion

The Greatest Show on Earth

The Magic of Reality (with Dave McKean)

An Appetite for Wonder

Brief Candle in the Dark

Science in the Soul

Outgrowing God

Books Do Furnish a Life

Flights of Fancy

RICHARD
DAWKINS

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Mike Cullen (1927–2001)
In grateful memory

You would have a problem with your research. You knew exactly where to go for help, and there he would be for you. I see the scene as yesterday. The wiry, boyish figure in the red sweater, slightly hunched like a spring wound up with intense intellectual energy, sometimes rocking back and forth with concentration. The deeply intelligent eyes, understanding what you meant even before the words came out. The back of the envelope to aid explanation, the occasionally sceptical, quizzical tilt of the eyebrows, under the untidy hair. Then he would have to rush off – he always rushed everywhere – and he would seize his biscuit tin by its wire handles, and disappear. But next morning the answer to your problem would arrive, in Mike's small, distinctive handwriting, two pages, often some algebra, diagrams, a key reference to the literature, perhaps an apt classical quotation or a verse of his own composition. Always encouragement.

We may know other scientists as intelligent as Mike Cullen – though not many. We may know other scientists who were as generous in support – though vanishingly few. But I declare, we have known nobody who had so much to give, combined with so much generosity in giving it.

From my eulogy at his memorial service in Wadham College Chapel, Nov 2001

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Reading the Animal

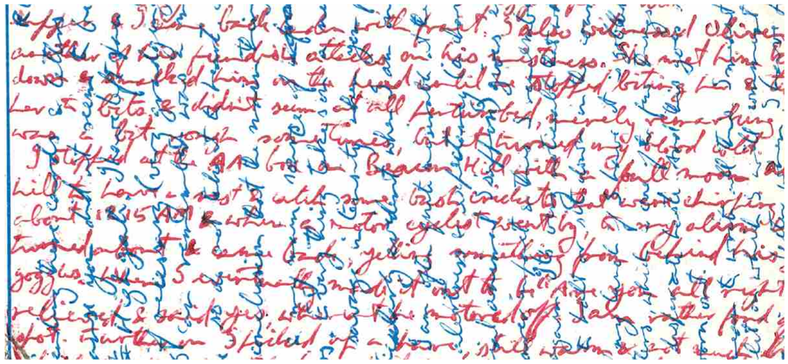
You are a book, an unfinished work of literature, an archive of descriptive history. Your body and your genome can be read as a comprehensive dossier on a succession of colourful worlds long vanished, worlds that surrounded your ancestors long gone: a genetic book of the dead. This truth applies to every 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.

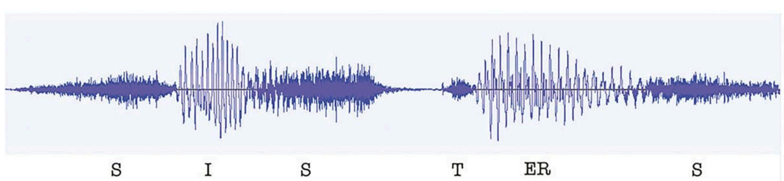
There is also an even more recent sense in which an animal's brain sets up a dynamic model of the immediately fluctuating environment, predicting moment to moment changes in real time. Writing this on the Cornish coast, I take envious pleasure in the gulls as they surf the wind battering the cliffs of 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 highspeed 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,