



RIVER OUT OF EDEN

.....

A Darwinian View of Life

RICHARD DAWKINS

ILLUSTRATIONS BY LALLA WARD



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To the memory of
HENRY COLYEAR DAWKINS (1921–1992),
Fellow of St. John's College, Oxford:
a master of the art of making things clear.

.....

And a river went out of Eden to water the garden.

—*Genesis 2:10*

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PREFACE



Nature, it seems, is the popular name
For milliards and milliards and milliards
Of particles playing their infinite game
Of billiards and billiards and billiards.

—Piet Hein

Piet Hein captures the classically pristine world of physics. But when the ricochets of atomic billiards chance to put together an object that has a certain, seemingly innocent property, something momentous happens in the universe. That property is an ability to self-replicate; that is, the object is able to use the surrounding materials to make exact copies of itself, including replicas of such minor flaws in copying as may occasionally arise. What will follow from this singular occurrence, anywhere in the universe, is Darwinian selection and hence the baroque extravaganza that, on this planet, we call life. Never were so many facts explained by so few assumptions. Not only does the Darwinian theory command superabundant power to explain. Its economy in doing so has a sinewy elegance, a poetic beauty that outclasses even the most haunting of the world's origin myths. One of my purposes in writing this book has been to accord due recognition

to the inspirational quality of our modern understanding of Darwinian life. There is more poetry in Mitochondrial Eve than in her mythological namesake.

The feature of life that, in David Hume's words, most "ravishes into admiration all men who have ever contemplated it" is the complex detail with which its mechanisms—the mechanisms that Charles Darwin called "organs of extreme perfection and complication"—fulfill an apparent purpose. The other feature of earthly life that impresses us is its luxuriant diversity: as measured by estimates of species numbers, there are some tens of millions of different ways of making a living. Another of my purposes is to convince my readers that "ways of making a living" is synonymous with "ways of passing DNA-coded texts on to the future." My "river" is a river of DNA, flowing and branching through geological time, and the metaphor of steep banks confining each species' genetic games turns out to be a surprisingly powerful and helpful explanatory device.

In one way or another, all my books have been devoted to expounding and exploring the almost limitless power of the Darwinian principle—power unleashed whenever and wherever there is enough time for the consequences of primordial self-replication to unfold. *River Out of Eden* continues this mission and brings to an extraterrestrial climax the story of the repercussions that can ensue when the phenomenon of replicators is injected into the hitherto humble game of atomic billiards.

During the writing of this book I have enjoyed support, encouragement, advice and constructive criticism in varying combinations from Michael Birkett, John Brockman, Steve Davies, Daniel Dennett, John Krebs, Sara Lippincott, Jerry

Lyons, and especially my wife, Lalla Ward, who also did the drawings. Some paragraphs here and there are reworked from articles that have appeared elsewhere. The passages of chapter 1 on digital and analog codes are based on my article in *The Spectator* of June 11, 1994. Chapter 3's account of Dan Nilsson and Susanne Pelger's work on the evolution of the eye is partly taken from my "News and Views" article published in *Nature* on April 21, 1994. I acknowledge the editors of both these journals, who commissioned the articles concerned. Finally, I am grateful to John Brockman and Anthony Cheetham for the original invitation to join The Science Masters Series.

Oxford, 1994



All peoples have epic legends about their tribal ancestors, and these legends often formalize themselves into religious cults. People revere and even worship their ancestors—as well they might, for it is real ancestors, not supernatural gods, that hold the key to understanding life. Of all organisms born, the majority die before they come of age. Of the minority that survive and breed, an even smaller minority will have a descendant alive a thousand generations hence. This tiny minority of a minority, this progenitorial élite, is all that future generations will be able to call ancestral. Ancestors are rare, descendants are common.

All organisms that have ever lived—every animal and plant, all bacteria and all fungi, every creeping thing, and all readers of this book—can look back at their ancestors and make the following proud claim: Not a single one of our ancestors died in infancy. They all reached adulthood, and every single one was capable of finding at least one heterosexual partner and of successfully copulating.* Not a single one

*Strictly speaking, there are exceptions. Some animals, like aphids, reproduce without sex. Techniques such as artificial fertilization make it possible for modern humans to have a child without copulating, and even—since eggs for *in vitro* fertilization could be taken from a female fetus—without reaching adulthood. But for most purposes the force of my point is undiminished.

of our ancestors was felled by an enemy, or by a virus, or by a misjudged footstep on a cliff edge, before bringing at least one child into the world. Thousands of our ancestors' contemporaries failed in all these respects, but not a single solitary one of our ancestors failed in any of them. These statements are blindingly obvious, yet from them much follows: much that is curious and unexpected, much that explains and much that astonishes. All these matters will be the subject of this book.

Since all organisms inherit all their genes from their ancestors, rather than from their ancestors' unsuccessful contemporaries, all organisms tend to possess successful genes. They have what it takes to become ancestors—and that means to survive and reproduce. This is why organisms tend to inherit genes with a propensity to build a well-designed machine—a body that actively works as if it is striving to become an ancestor. That is why birds are so good at flying, fish so good at swimming, monkeys so good at climbing, viruses so good at spreading. That is why we love life and love sex and love children. It is because we all, without a single exception, inherit all our genes from an unbroken line of successful ancestors. The world becomes full of organisms that have what it takes to become ancestors. That, in a sentence, is Darwinism. Of course, Darwin said much more than that, and nowadays there is much more we can say, which is why this book doesn't stop here.

There is a natural, and deeply pernicious, way to misunderstand the previous paragraph. It is tempting to think that when ancestors did successful things, the genes they passed on to their children were, as a result, upgraded relative to the genes they had received from their parents.

Something about their success rubbed off on their genes, and that is why their descendants are so good at flying, swimming, courting. Wrong, utterly wrong! Genes do not improve in the using, they are just passed on, unchanged except for very rare random errors. It is not success that makes good genes. It is good genes that make success, and nothing an individual does during its lifetime has any effect whatever upon its genes. Those individuals born with good genes are the most likely to grow up to become successful ancestors; therefore good genes are more likely than bad to get passed on to the future. Each generation is a filter, a sieve: good genes tend to fall through the sieve into the next generation; bad genes tend to end up in bodies that die young or without reproducing. Bad genes may pass through the sieve for a generation or two, perhaps because they have the luck to share a body with good genes. But you need more than luck to navigate successfully through a thousand sieves in succession, one sieve under the other. After a thousand successive generations, the genes that have made it through are likely to be the good ones.

I said that the genes that survive down the generations will be the ones that have succeeded in making ancestors. This is true, but there is one apparent exception I must deal with before the thought of it causes confusion. Some individuals are irrevocably sterile, yet they are seemingly designed to assist the passage of their genes into future generations. Worker ants, bees, wasps and termites are sterile. They labor not to become ancestors but so that their fertile relatives, usually sisters and brothers, will become ancestors. There are two points to understand here. First, in any kind of animal, sisters and brothers have a high probability of sharing copies of the

same genes. Second, it is the environment, not the genes, that determines whether an individual termite, say, becomes a reproducer or a sterile worker. All termites contain genes capable of turning them into sterile workers under some environmental conditions, reproducers under other conditions. The reproducers pass on copies of the very same genes that make the sterile workers help them to do so. The sterile workers toil under the influence of genes, copies of which are sitting in the bodies of reproducers. The worker copies of those genes are striving to assist their own reproductive copies through the transgenerational sieve. Termite workers can be male or female; but in ants, bees and wasps the workers are all female; otherwise the principle is the same. In a watered-down form, it also applies to several species of birds, mammals and other animals that exhibit a certain amount of caring for young by elder brothers or sisters. To summarize, genes can buy their way through the sieve, not only by assisting their own body to become an ancestor but by assisting the body of a relation to become an ancestor.

The river of my title is a river of DNA, and it flows through time, not space. It is a river of information, not a river of bones and tissues: a river of abstract instructions for building bodies, not a river of solid bodies themselves. The information passes through bodies and affects them, but it is not affected by them on its way through. The river is not only uninfluenced by the experiences and achievements of the successive bodies through which it flows. It is also uninfluenced by a potential source of contamination that, on the face of it, is much more powerful: sex.

In every one of your cells, half your mother's genes rub

shoulders with half your father's genes. Your maternal genes and your paternal genes conspire with one another most intimately to make you the subtle and indivisible amalgam you are. But the genes themselves do not blend. Only their effects do. The genes themselves have a flintlike integrity. When the time comes to move on to the next generation, a gene either goes into the body of a given child or it does not. Paternal genes and maternal genes do not blend; they recombine independently. A given gene in you came either from your mother or your father. It also came from one, and only one, of your four grandparents; from one, and only one, of your eight great-grandparents; and so on back.

I have spoken of a river of genes, but we could equally well speak of a band of good companions marching through geological time. All the genes of one breeding population are, in the long run, companions of each other. In the short run, they sit in individual bodies and are temporarily more intimate companions of the other genes sharing that body. Genes survive down the ages only if they are good at building bodies that are good at living and reproducing in the particular way of life chosen by the species. But there is more to it than this. To be good at surviving, a gene must be good at working together with the other genes in the same species—the same river. To survive in the long run, a gene must be a good companion. It must do well in the company of, or against the background of, the other genes in the same river. Genes of another species are in a different river. They do not have to get on well together—not in the same sense, anyway—for they do not have to share the same bodies.

The feature that defines a species is that all members of

any one species have the same river of genes flowing through them, and all the genes in a species have to be prepared to be good companions of one another. A new species comes into existence when an existing species divides into two. The river of genes forks in time. From a gene's point of view, *speciation*, the origin of new species, is "the long goodbye." After a brief period of partial separation, the two rivers go their separate ways forever, or until one or the other dries extinct into the sand. Secure within the banks of either river, the water is mixed and remixed by sexual recombination. But water never leaps its banks to contaminate the other river. After a species has divided, the two sets of genes are no longer companions. They no longer meet in the same bodies and they are no longer required to get on well together. There is no longer any intercourse between them—and intercourse here means, literally, sexual intercourse between their temporary vehicles, their bodies.

Why should two species divide? What initiates the long goodbye of their genes? What provokes a river to split and the two branches to drift apart, never to meet again? The details are controversial, but nobody doubts that the most important ingredient is accidental geographical separation. The river of genes flows in time, but the physical repartnering of genes takes place in solid bodies, and bodies occupy a location in space. A gray squirrel in North America would be capable of breeding with a gray squirrel in England, if they ever met. But they are unlikely to meet. The river of gray-squirrel genes in North America is effectively separated, by three thousand miles of ocean, from the river of gray-squirrel genes in England. The two bands of genes are no longer companions in fact, although they are still presumably capable of acting as

good companions should the opportunity arise. They have said farewell, though it is not an irrevocable goodbye—yet. But given another few thousand years of separation, it is probable that the two rivers will have drifted so far apart that if individual squirrels meet, they will no longer be able to exchange genes. "Drift apart" here means apart not in space but in compatibility.

Something like this almost certainly lies behind the older separation between gray squirrels and red squirrels. They cannot interbreed. They overlap geographically in parts of Europe and, although they meet and probably confront one another over disputed nuts from time to time, they cannot mate to produce fertile offspring. Their genetic rivers have drifted too far apart, which is to say that their genes are no longer well suited to cooperate with one another in bodies. Many generations ago, ancestors of gray squirrels and ancestors of red squirrels were one and the same individuals. But they became geographically separated—perhaps by a mountain range, perhaps by water, eventually by the Atlantic Ocean. And their genetic ensembles grew apart. Geographical separation bred a lack of compatibility. Good companions became poor companions (or they would turn out to be poor companions if put to the test in a mating encounter). Poor companions became poorer still, until now they are not companions at all. Their goodbye is final. The two rivers are separate and destined to become more and more separate. The same story underlies the much earlier separation between, say, our ancestors and the ancestors of elephants. Or between ostrich ancestors (which were also our ancestors) and the ancestors of scorpions.

There are now perhaps thirty million branches to the river

of DNA, for that is an estimate of the number of species on earth. It has also been estimated that the surviving species constitute about 1 percent of the species that have ever lived. It would follow that there have been some three billion branches to the river of DNA altogether. Today's thirty million branch rivers are irrevocably separate. Many of them are destined to wither into nothing, for most species go extinct. If you follow the thirty million rivers (for brevity, I'll refer to the branch rivers as rivers) back into the past, you will find that, one by one, they join up with other rivers. The river of human genes joins with the river of chimpanzee genes at about the same time as the river of gorilla genes does, some seven million years ago. A few million years farther back, our shared African ape river is joined by the stream of orangutan genes. Farther back still, we are joined by a river of gibbon genes—a river that splits downstream into a number of separate species of gibbon and siamang. As we push on backward in time, our genetic river unites with rivers destined, if followed forward again, to branch into the Old World monkeys, the New World monkeys, and the lemurs of Madagascar. Even farther back, our river unites with those leading to other major groups of mammals: rodents, cats, bats, elephants. After that, we meet the streams leading to various kinds of reptiles, birds, amphibians, fish, invertebrates.

Now here is an important respect in which we have to be cautious about the river metaphor. When we think of the divide leading to all the mammals—as opposed to, say, the stream leading to the gray squirrel—it is tempting to imagine something on a grand, Mississippi/Missouri scale. The mammal branch is, after all, destined to branch and branch

and branch again, until it produces all the mammals—from pigmy shrew to elephant, from moles underground to monkeys atop the canopy. The mammal branch of the river is destined to feed so many thousands of important trunk waterways, how could it be other than a massive, rolling torrent? But this image is deeply wrong. When the ancestors of all the modern mammals broke away from those that are not mammals, the event was no more momentous than any other speciation. It would have gone unremarked by any naturalist who happened to be around at the time. The new branch of the river of genes would have been a trickle, inhabiting a species of little nocturnal creature no more different from its nonmammalian cousins than a red squirrel is from a gray. It is only with hindsight that we see the ancestral mammal as a mammal at all. In those days, it would have been just another species of mammal-like reptile, not markedly different from perhaps a dozen other small, snouty, insectivorous morsels of dinosaur food.

The same lack of drama would have attended the earlier splits between the ancestors of all the great groups of animals: the vertebrates, the mollusks, the crustaceans, the insects, the segmented worms, the flatworms, the jellyfish and so on. When the river that was to lead to the mollusks (and others) parted from the river that was to lead to the vertebrates (and others), the two populations of (probably wormlike) creatures would have been so alike that they could have mated with one another. The only reason they didn't is that they had become accidentally separated by some geographical barrier, perhaps dry land separating previously united waters. Nobody could have guessed that one population was destined to spawn the mollusks and the

other the vertebrates. The two rivers of DNA were stream-lets barely parted, and the two groups of animals were all but indistinguishable.

Zoologists know all this, but they forget it sometimes when contemplating the really big animal groups, like mollusks and vertebrates. They are tempted to think of the divide between major groups as a momentous event. The reason zoologists may be so misled is that they have been brought up in the almost reverential belief that each of the great divisions of the animal kingdom is furnished with something deeply unique, often called by the German word *Bauplan*. Although this word just means "blueprint," it has become a recognized technical term, and I shall inflect it as an English word, even though (as I am slightly shocked to discover) it is not yet in the current edition of the Oxford English Dictionary. (Since I enjoy the word less than some of my colleagues do, I admit to a tiny *frisson* of *Schadenfreude* at its absence; those two foreign words *are* in the Dictionary, so there is no systematic prejudice against importation.) In its technical sense, *bauplan* is often translated as "fundamental body plan." The use of the word "fundamental" (or, equivalently, the self-conscious dropping into German to indicate profundity) is what causes the damage. It can lead zoologists to make serious errors.

One zoologist, for instance, has suggested that evolution in the Cambrian period (between about six hundred million and about five hundred million years ago) must have been a completely different kind of process from evolution in later times. His reasoning was that nowadays it is new species that are coming into existence, whereas in the Cambrian period major groups were appearing, such as the mollusks

and the crustaceans. The fallacy is glaring! Even creatures as radically different from one another as mollusks and crustaceans were originally just geographically separated populations of the same species. For a while, they could have interbred if they had met, but they did not. After millions of years of separate evolution, they acquired the characteristics which we, with the hindsight of modern zoologists, now recognize as those of mollusks and crustaceans respectively. These characteristics are dignified with the grandiose title of "fundamental body plan" or "bauplan." But the major bauplans of the animal kingdom diverged from common origins by gradual degrees.

Admittedly, there is a minor, if much publicized, disagreement over quite *how* gradual or "jumpy" evolution is. But nobody, and I mean nobody, thinks that evolution has ever been jumpy enough to invent a whole new bauplan in one step. The author I quoted was writing in 1958. Few zoologists would explicitly take his position today, but they sometimes do so implicitly, speaking as though the major groups of animals arose spontaneously and perfectly formed, like Athena from the head of Zeus, rather than by divergence of an ancestral population while in accidental geographical isolation.*

The study of molecular biology has, in any case, shown the great animal groups to be much closer to one another than we used to think. You can treat the genetic code as a dictionary in which sixty-four words in one language (the sixty-four

*Readers might like to keep these points in mind when consulting *Wonderful Life*, Stephen J. Gould's beautifully written account of the Burgess Shale Cambrian fauna.

possible triplets of a four-letter alphabet) are mapped onto twenty-one words in another language (twenty amino acids plus a punctuation mark). The odds of arriving at the same 64:21 mapping twice by chance are less than one in a million million million million million. Yet the genetic code is in fact literally identical in all animals, plants and bacteria that have ever been looked at. All earthly living things are certainly descended from a single ancestor. Nobody would dispute that, but some startlingly close resemblances between, for instance, insects and vertebrates are now showing up when people examine not just the code itself but detailed sequences of genetic information. There is a quite complicated genetic mechanism responsible for the segmented body plan of insects. An uncannily similar piece of genetic machinery has also been found in mammals. From a molecular point of view, all animals are pretty close relatives of one another and even of plants. You have to go to bacteria to find our distant cousins, and even then the genetic code itself is identical to ours. The reason it is possible to do such precise calculations on the genetic code but not on the anatomy of bauplans is that the genetic code is strictly digital, and digits are things you can count precisely. The river of genes is a digital river, and I must now explain what this engineering term means.

Engineers make an important distinction between digital and analog codes. Phonographs and tape recorders—and until recently most telephones—use analog codes. Compact disks, computers, and most modern telephone systems use digital codes. In an analog telephone system, continuously fluctuating waves of pressure in the air (sounds) are transduced into correspondingly fluctuating waves of voltage in a wire. A

phonograph record works in a similar way: the wavy grooves cause a stylus to vibrate, and the movements of the stylus are transduced into corresponding fluctuations in voltage. At the other end of the line these voltage waves are reconverted, by a vibrating membrane in the telephone's earpiece or the phonograph's loudspeaker, back into the corresponding air-pressure waves, so that we can hear them. The code is a simple and direct one: electrical fluctuations in wire are proportional to pressure fluctuations in air. All possible voltages, within certain limits, may pass down the wire, and the differences between them matter.

In a digital telephone, only two possible voltages—or some other discrete number of possible voltages, such as 8 or 256—pass down the wire. The information lies not in the voltages themselves but in the patterning of the discrete levels. This is called Pulse Code Modulation. The actual voltage at any one time will seldom be exactly equal to any of the eight, say, nominal values, but the receiving apparatus will round it off to the nearest of the designated voltages, so that what emerges at the other end of the line is well-nigh perfect even if the transmission along the line is poor. All you have to do is set the discrete levels far enough apart so that random fluctuations can never be misinterpreted by the receiving instrument as the wrong level. This is the great virtue of digital codes, and it is why audio and video systems—and information technology generally—are increasingly going digital. Computers, of course, use digital codes for everything they do. For reasons of convenience, it is a binary code—that is, it has only two levels of voltage instead of 8 or 256.

Even in a digital telephone, the sounds entering the

mouthpiece and leaving the earpiece are still analog fluctuations in air pressure. It is the information traveling from exchange to exchange that is digital. Some kind of code has to be set up to translate analog values, microsecond by microsecond, into sequences of discrete pulses—digitally coded numbers. When you plead with your lover over the telephone, every nuance, every catch in the voice, every passionate sigh and yearning timbre is carried along the wire solely in the form of numbers. You can be moved to tears by numbers—provided they are encoded and decoded fast enough. Modern electronic switching gear is so fast that the line's time can be divided into slices, rather as a chess master may divide his time among twenty games in rotation. By this means, thousands of conversations can be slotted into the same telephone line, apparently simultaneously yet electronically segregated without interference. A trunk data line—many of them nowadays are not wires at all but radio beams, either transmitted directly from hilltop to hilltop or bounced off satellites—is a massive river of digits. But because of this ingenious electronic segregation, it is thousands of digital rivers, which share the same banks only in a superficial sense—like red squirrels and gray, who share the same trees but never intermingle their genes.

Back in the world of engineers, the deficiencies of analog signals don't matter too much, as long as they aren't copied repeatedly. A tape recording may have so little hiss on it that you hardly notice it—unless you amplify the sound, in which case you amplify the hiss and introduce some new noise too. But if you make a tape of the tape, then a tape of the tape of the tape, and so on and on, after a

hundred “generations” a horrible hiss will be all that remains. Something like this was a problem in the days when telephones were all analog. Any telephone signal fades over a long wire and has to be boosted—reamplified—every hundred miles or so. In analog days this was a bugbear, because each amplification stage increased the proportion of background hiss. Digital signals, too, need boosting. But, for the reason we've seen, the boosting does not introduce any error: things can be set up so that the information gets through perfectly, no matter how many boosting stations intervene. Hiss does not increase even over hundreds and hundreds of miles.

When I was a small child, my mother explained to me that our nerve cells are the telephone wires of the body. But are they analog or digital? The answer is that they are an interesting mixture of both. A nerve cell is not like an electric wire. It is a long thin tube along which waves of chemical change pass, like a trail of gunpowder fizzing along the ground—except that, unlike a trail of gunpowder, the nerve soon recovers and can fizz again after a short rest period. The absolute magnitude of the wave—the temperature of the gunpowder—may fluctuate as it races along the nerve, but this is irrelevant. The code ignores it. Either the chemical pulse is there or it is not, like two discrete voltage levels in a digital telephone. To this extent, the nervous system is digital. But nerve impulses are not dragged into bytes: they don't assemble into discrete code numbers. Instead, the strength of the message (the loudness of the sound, the brightness of the light, maybe even the agony of the emotion) is encoded as the rate of impulses. Engineers know this as Pulse Frequency Modulation, and it

was popular with them before Pulse Code Modulation was adopted.

A pulse rate is an analog quantity, but the pulses themselves are digital: they are either there or they are not, with no half measures. And the nervous system reaps the same benefit from this as any digital system does. Because of the way nerve cells work, there is the equivalent of an amplifying booster, not every hundred miles but every millimeter—eight hundred boosting stations between the spinal cord and your fingertip. If the absolute height of the nerve impulse—the gunpowder wave—mattered, the message would be distorted beyond recognition over the length of a human arm, let alone a giraffe's neck. Each stage in the amplification would introduce more random error, like what happens when a tape recording is made of a tape recording eight hundred times over. Or when you Xerox a Xerox of a Xerox. After eight hundred photocopying "generations," all that's left is a gray blur. Digital coding offers the only solution to the nerve cell's problem, and natural selection has duly adopted it. The same is true of genes.

Francis Crick and James Watson, the unravelers of the molecular structure of the gene, should, I believe be honored for as many centuries as Aristotle and Plato. Their Nobel Prizes were awarded "in physiology or medicine," and this is right but almost trivial. To talk of continuous revolution is almost a contradiction in terms, yet not only medicine but our whole understanding of life will go on being revolutionized again and again as a direct result of the change in thinking that those two young men initiated in 1953. Genes themselves, and genetic disease, are only the tip of the iceberg. What is truly revolutionary about

molecular biology in the post-Watson-Crick era is that it has become digital.

After Watson and Crick, we know that genes themselves, within their minute internal structure, are long strings of pure digital information. What is more, they are truly digital, in the full and strong sense of computers and compact disks, not in the weak sense of the nervous system. The genetic code is not a binary code as in computers, nor an eight-level code as in some telephone systems, but a quaternary code, with four symbols. The machine code of the genes is uncannily computerlike. Apart from differences in jargon, the pages of a molecular-biology journal might be interchanged with those of a computer-engineering journal. Among many other consequences, this digital revolution at the very core of life has dealt the final, killing blow to vitalism—the belief that living material is deeply distinct from nonliving material. Up until 1953 it was still possible to believe that there was something fundamentally and irreducibly mysterious in living protoplasm. No longer. Even those philosophers who had been predisposed to a mechanistic view of life would not have dared hope for such total fulfillment of their wildest dreams.

The following science-fiction plot is feasible, given a technology that differs from today's only in being a little speeded up. Professor Jim Crickson has been kidnapped by an evil foreign power and forced to work in its biological-warfare labs. To save civilization it is vitally important that he should communicate some top-secret information to the outside world, but all normal channels of communication are denied him. Except one. The DNA code consists of sixty-four triplet "codons," enough for a complete upper- and lower-case Eng-

lish alphabet plus ten numerals, a space character and a full stop. Professor Crickson takes a virulent influenza virus off the laboratory shelf and engineers into its genome the complete text of his message to the outside world, in perfectly formed English sentences. He repeats his message over and over again in the engineered genome, adding an easily recognizable “flag” sequence—say, the first ten prime numbers. He then infects himself with the virus and sneezes in a room full of people. A wave of flu sweeps the world, and medical labs in distant lands set to work to sequence its genome in an attempt to design a vaccine. It soon becomes apparent that there is a strange repeated pattern in the genome. Alerted by the prime numbers—which cannot have arisen spontaneously—somebody tumbles to the idea of deploying code-breaking techniques. From there it would be short work to read the full English text of Professor Crickson’s message, sneezed around the world.

Our genetic system, which is the universal system of all life on the planet, is digital to the core. With word-for-word accuracy, you could encode the whole of the New Testament in those parts of the human genome that are at present filled with “junk” DNA—that is, DNA not used, at least in the ordinary way, by the body. Every cell in your body contains the equivalent of forty-six immense data tapes, reeling off digital characters via numerous reading heads working simultaneously. In every cell, these tapes—the chromosomes—contain the same information, but the reading heads in different kinds of cells seek out different parts of the database for their own specialist purposes. That is why muscle cells are different from liver cells. There is no spirit-driven life force, no throbbing, heaving, pullulating, proto-

plasmic, mystic jelly. Life is just bytes and bytes and bytes of digital information.

Genes are pure information—information that can be encoded, recoded and decoded, without any degradation or change of meaning. Pure information can be copied and, since it is digital information, the fidelity of the copying can be immense. DNA characters are copied with an accuracy that rivals anything modern engineers can do. They are copied down the generations, with just enough occasional errors to introduce variety. Among this variety, those coded combinations that become more numerous in the world will obviously and automatically be the ones that, when decoded and obeyed inside bodies, make those bodies take active steps to preserve and propagate those same DNA messages. We—and that means all living things—are survival machines programmed to propagate the digital database that did the programming. Darwinism is now seen to be the survival of the survivors at the level of pure, digital code.

With hindsight, it could not have been otherwise. An analog genetic system could be imagined. But we have already seen what happens to analog information when it is recopied over successive generations. It is Chinese Whispers. Boosted telephone systems, recopied tapes, photocopies of photocopies— analog signals are so vulnerable to cumulative degradation that copying cannot be sustained beyond a limited number of generations. Genes, on the other hand, can self-copy for ten million generations and scarcely degrade at all. Darwinism works only because—apart from discrete mutations, which natural selection either weeds out or preserves—the copying process is perfect. Only a digital genetic system is capable of sustaining Darwinism over eons of geological time.

Nineteen fifty-three, the year of the double helix, will come to be seen not only as the end of mystical and obscurantist views of life; Darwinians will see it as the year their subject went finally digital.

The river of pure digital information, majestically flowing through geological time and splitting into three billion branches, is a powerful image. But where does it leave the familiar features of life? Where does it leave bodies, hands and feet, eyes and brains and whiskers, leaves and trunks and roots? Where does it leave us and our parts? We—we animals, plants, protozoa, fungi and bacteria—are we just the banks through which rivulets of digital data flow? In one sense, yes. But there is, as I have implied, more to it than that. Genes don't only make copies of themselves, which flow on down the generations. They actually spend their time in bodies, and they influence the shape and behavior of the successive bodies in which they find themselves. Bodies are important too.

The body of, say, a polar bear is not just a pair of riverbanks for a digital streamlet. It is also a machine of bear-sized complexity. All the genes of the whole population of polar bears are a collective—good companions, jostling with one another through time. But they do not spend all the time in the company of all the other members of the collective: they change partners within the set that is the collective. The collective is defined as the set of genes that can potentially meet any other genes in the collective (but no member of any of the thirty million other collectives in the world). The actual meetings always take place inside a cell in a polar bear's body. And that body is not a passive receptacle for DNA.

For a start, the sheer number of cells, in every one of which is a complete set of genes, staggers the imagination: about nine hundred million million for a large male bear. If you lined up all the cells of a single polar bear in a row, the array would comfortably make the round trip from here to the moon and back. These cells are of a couple of hundred distinct types, essentially the same couple of hundred for all mammals: muscle cells, nerve cells, bone cells, skin cells and so on. Cells of any one of these distinct types are massed together to form tissues: muscle tissue, bone tissue and so on. All the different types of cells contain the genetic instructions needed to make any of the types. Only the genes appropriate to the tissue concerned are switched on. This is why cells of the different tissues are of different shapes and sizes. More interestingly, the genes switched on in the cells of a particular type cause those cells to grow their tissues into particular shapes. Bones are not shapeless masses of hard, rigid tissue. Bones have particular shapes, with hollow shafts, balls and sockets, spines and spurs. Cells are programmed, by the genes switched on inside them, to behave as if they know where they are in relation to their neighboring cells, which is how they build their tissues up into the shape of ear lobes and heart valves, eye lenses and sphincter muscles.

The complexity of an organism such as a polar bear is many-layered. The body is a complex collection of precisely shaped organs, like livers and kidneys and bones. Each organ is a complex edifice fashioned from particular tissues whose building bricks are cells, often in layers or sheets but often in solid masses too. On a much smaller scale, each cell has a highly complex interior structure of folded membranes. These

membranes, and the water between them, are the scene of intricate chemical reactions of very numerous distinct types. A chemical factory belonging to ICI or Union Carbide may have several hundred distinct chemical reactions going on inside it. These chemical reactions will be kept separate from one another by the walls of the flasks, tubes and so on. A living cell might have a similar number of chemical reactions going on inside it simultaneously. To some extent the membranes in a cell are like the glassware in a laboratory, but the analogy is not a good one for two reasons. First, although many of the chemical reactions go on between the membranes, a good many go on *within* the substance of the membranes themselves. Second, there is a more important way in which the different reactions are kept separate. Each reaction is catalyzed by its own special enzyme.

An enzyme is a very large molecule whose three-dimensional shape speeds up one particular kind of chemical reaction by providing a surface that encourages that reaction. Since what matters about biological molecules is their three-dimensional shape, we could regard an enzyme as a large machine tool, carefully jigged to turn out a production line of molecules of a particular shape. Any one cell, therefore, may have hundreds of separate chemical reactions going on inside it simultaneously and separately, on the surfaces of different enzyme molecules. Which particular chemical reactions go on in a given cell is determined by which particular kinds of enzyme molecules are present in large numbers. Each enzyme molecule, including its all-important shape, is assembled under the deter-

ministic influence of a particular gene. To be specific, the precise sequence of several hundred code letters in the gene determines, by a set of rules that are totally known (the genetic code), the sequence of amino acids in the enzyme molecule. Every enzyme molecule is a linear chain of amino acids, and every linear chain of amino acids spontaneously coils up into a unique and particular three-dimensional structure, like a knot, in which parts of the chain form cross-links with other parts of the chain. The exact three-dimensional structure of the knot is determined by the one-dimensional sequence of amino acids, and therefore by the one-dimensional sequence of code letters in the gene. And thus the chemical reactions that take place in a cell are determined by which genes are switched on.

What, then, determines which genes are switched on in a particular cell? The answer is the chemicals that are already present in the cell. There is an element of chicken-and-egg paradox here, but it is not insuperable. The solution to the paradox is actually very simple in principle, although complicated in detail. It is the solution that computer engineers know as bootstrapping. When I first started using computers, in the 1960s, all programs had to be loaded via paper tape. (American computers of the period often used punched cards, but the principle was the same.) Before you could load in the large tape of a serious program, you had to load in a smaller program called the bootstrap loader. The bootstrap loader was a program to do one thing: to tell the computer how to load paper tapes. But—here is the chicken-and-egg paradox—how was the bootstrap-loader tape itself loaded? In modern computers, the equivalent of the bootstrap loader is hardwired

into the machine, but in those early days you had to begin by toggling switches in a ritually patterned sequence. This sequence told the computer how to begin to read the first part of the bootstrap-loader tape. The first part of the bootstrap-loader tape then told it a bit more about how to read the next part of the bootstrap-loader tape and so on. By the time the whole bootstrap loader had been sucked in, the computer knew how to read any paper tape, and it had become a useful computer.

When an embryo begins, a single cell, the fertilized egg, divides into two; each of the two divides into four; each of the four divides to make eight, and so on. It takes only a few dozen generations to work the cell numbers up into the trillions, such is the power of exponential division. But, if this were all there was to it, the trillions of cells would all be the same. How, instead, do they differentiate (to use the technical term) into liver cells, kidney cells, muscle cells and so on, each with different genes turned on and different enzymes active? By bootstrapping, and it works like this. Although the egg looks like a sphere, it actually has polarity in its internal chemistry. It has a top and a bottom and, in many cases, a front and a rear (and therefore also a left and a right side) as well. These polarities show themselves in the form of gradients of chemicals. Concentrations of some chemicals steadily increase as you move from front to rear, others as you move from top to bottom. These early gradients are pretty simple, but they are enough to form the first stage in a bootstrapping operation.

When the egg has divided into, say, thirty-two cells—that is, after five divisions—some of those thirty-two cells will

have more than their fair share of topside chemicals, others more than their fair share of bottomside chemicals. The cells may also be unbalanced with respect to the chemicals of the fore-and-aft gradient. These differences are enough to cause different combinations of genes to be turned on in different cells. Therefore different combinations of enzymes will be present in the cells of different parts of the early embryo. This will see to it that different combinations of further genes are turned on in different cells. Lineages of cells diverge, therefore, instead of remaining identical to their clone-ancestors within the embryo.

These divergences are very different from the divergences of species we talked about earlier. These cell divergences are programmed and predictable in detail, whereas those species divergences were the fortuitous results of geographical accidents and were unpredictable. Moreover, when species diverge, the genes themselves diverge, in what I fancifully called the long goodbye. When cell lineages within an embryo diverge, both divisions receive the same genes—all of them. But different cells receive different combinations of chemicals, which switch on different combinations of genes, and some genes work to switch other genes on or off. And so the bootstrapping continues, until we have the full repertoire of different kinds of cells.

The developing embryo doesn't just differentiate into a couple of hundred different types of cells. It also undergoes elegant dynamic changes in external and internal shape. Perhaps the most dramatic of these is one of the earliest: the process known as gastrulation. The distinguished embryologist Lewis Wolpert has gone so far as to say, "It is not birth,

marriage, or death, but gastrulation which is truly the most important time in your life." What happens at gastrulation is that a hollow ball of cells buckles to form a cup with an inner lining. Essentially all embryologies throughout the animal kingdom undergo this same process of gastrulation. It is the uniform foundation on which the diversity of embryologies rests. Here I mention gastrulation as just one example—a particularly dramatic one—of the kind of restless, origami-like movement of whole sheets of cells that is often seen in embryonic development.

At the end of a virtuoso origami performance; after numerous foldings-in, pushings-out, bulgings and stretchings of layers of cells; after much dynamically orchestrated differential growth of parts of the embryo at the expense of other parts; after differentiation into hundreds of chemically and physically specialized kinds of cells; when the total number of cells has reached into the trillions, the final product is a baby. No, even the baby is not final, because the whole growth of the individual—again, with some parts growing faster than others—past adulthood into old age should be seen as an extension of the same process of embryology: total embryology.

Individuals vary because of differences in quantitative details in their total embryology. A layer of cells grows a little farther before folding in on itself, and the result is—What?—an aquiline rather than a retroussé nose; flat feet, which may save your life because they debar you from the Army; a particular conformation of the shoulder blade that predisposes you to be good at throwing spears (or hand grenades, or cricket balls, depending on your circum-

stances). Sometimes individual changes in the origami of cell layers can have tragic consequences, as when a baby is born with stumps for arms and no hands. Individual differences that do not manifest themselves in cell-layer origami but purely chemically may be no less important in their consequences: an inability to digest milk, a predisposition to homosexuality, or to peanut allergy, or to think that mangos taste offensively of turpentine.

Embryonic development is a very complicated physical and chemical performance. Change of detail at any point in its course can have remarkable consequences farther down the line. This is not so surprising, when you recall how heavily bootstrapped the process is. Many of the differences in the way individuals develop are due to differences in environment—oxygen starvation or exposure to thalidomide, for instance. Many other differences are due to differences in genes—not just genes considered in isolation but genes in interaction with other genes, and in interaction with environmental differences. Such a complicated, kaleidoscopic, intricately and reciprocally bootstrapped process as embryonic development is both robust and sensitive. It is robust in that it fights off many potential changes, to produce a living baby against odds that sometimes seem almost overwhelming; at the same time it is sensitive to changes in that no two individuals, not even identical twins, are literally identical in all their features.

And now for the point that this has all been leading up to. To the extent that differences between individuals are due to genes (which may be a large extent or a small one), natural selection can favor some quirks of embryological

origami or embryological chemistry and disfavor others. To the extent that your throwing arm is influenced by genes, natural selection can favor it or disfavor it. If being able to throw well has an effect, however slight, on an individual's likelihood of surviving long enough to have children, to the extent that throwing ability is influenced by genes, those genes will have a correspondingly greater chance of winning through to the next generation. Any one individual may die for reasons having nothing to do with his ability to throw. But a gene that tends to make individuals better at throwing when it is present than when it is absent will inhabit lots of bodies, both good and bad, over many generations. From the point of view of the particular gene, the other causes of death will average out. From the gene's perspective, there is only the long-term outlook of the river of DNA flowing down through the generations, only temporarily housed in particular bodies, only temporarily sharing a body with companion genes that may be successful or unsuccessful.

In the long term, the river becomes full of genes that are good at surviving for their several reasons: slightly improving the ability to throw a spear, slightly improving the ability to taste poison, or whatever it may be. Genes that, on average, are less good at surviving—because they tend to cause astigmatic vision in their successive bodies, who are therefore less successful spear throwers; or because they make their successive bodies less attractive and therefore less likely to mate—such genes will tend to disappear from the river of genes. In all this, remember the point we made earlier: the genes that survive in the river will be the ones

that are good at surviving in the average environment of the species, and perhaps the most important aspect of this average environment is the other genes of the species; the other genes with which a gene is likely to have to share a body; the other genes that swim through geological time in the same river.