RICHARD DAWKINS

THE OXFORD BOOK OF
MODERN SCIENCE WRITING

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INTRODUCTION

■ My introductory remarks are distributed through the book itself, so I shall here limit myself mostly to acknowledgements. The idea for an anthology of modern science writing was put to me by Latha Menon of Oxford University Press, and it was a pleasure to work with her on it. She and I had previously collaborated on a collection of my own occasional writings, and we slipped effortlessly back into the same synoptic vein as before. We disagreed only over whether or not to include anything from my own books. I won, and we didn't.

This is a collection of good writing by professional scientists, not excursions into science by professional writers. Another difference from John Carey's admirable *Faber Book of Science* is that we go back only one century. Within that century, no attempt was made to arrange the pieces chronologically. Instead, the selections fall roughly into four themes, although some of the entries could have fitted into more than one of these divisions. My biggest regret concerns the number of excellent scientists that I have had to leave out, for reasons of space. I would apologize to them, did I not suspect that my own pain at their omission is greater than theirs. The collection is limited to the English language and, with very few exceptions, I have omitted translations from books originally composed in other languages.

My wife, Lalla Ward, has again lent her finely tuned ear for the English language, together with her unfailing encouragement. I remain deeply grateful to her.

I have long wanted to dedicate a book to Charles Simonyi, but I was anxious to be clear that it was a dedication to him as an individual and friend, rather than as the munificent benefactor of the Oxford professorship in Public Understanding of Science that I hold. Now, in the year of my retirement, it finally seems appropriate to offer this volume to him as a personal friend, while at the same time conveying Oxford's gratitude to a major benefactor through a book published by the University Press. Charles Simonyi is a sort of combination of International Renaissance Man, Playboy of the Scientific World, Test Pilot of the Intellect, and Space-age Orbiter of the Mind as well as of the Planet. Although most of the words in an anthology belong to others, I hope that my love of science and of writing, which Charles shares and which he generously chose to encourage in me, will shine through both my selections and my commentary, and give him pleasure. ■

Richard Dawkins
Oxford, September 2007

PART I

WHAT SCIENTISTS STUDY

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James Jeans

from THE MYSTERIOUS UNIVERSE

■ Our ability to understand the universe and our position in it is one of the glories of the human species. Our ability to link mind to mind by language, and especially to transmit our thoughts across the centuries is another. Science and literature, then, are the two achievements of *Homo sapiens* that most convincingly justify the specific name. In attempting, however inadequately, to bring the two together, this book can be seen as a celebration of humanity. It is only superficially paradoxical to begin our celebration by cutting humanity down to size, and no science puts us in our place better than astronomy. I begin with a fragment from James Jeans's 1930 book, *The Mysterious Universe*, which is a fine example of the humbling prose poetry that the stars so intoxicatingly inspire. ■

Standing on our microscopic fragment of a grain of sand, we attempt to discover the nature and purpose of the universe which surrounds our home in space and time. Our first impression is something akin to terror. We find the universe terrifying because of its vast meaningless distances, terrifying because of its inconceivably long vistas of time which dwarf human history to the twinkling of an eye, terrifying because of our extreme loneliness, and because of the material insignificance of our home in space—a millionth part of a grain of sand out of all the sea-sand in the world. But above all else, we find the universe terrifying because it appears to be indifferent to life like our own; emotion, ambition and achievement, art and religion all seem equally foreign to its plan. Perhaps indeed we ought to say it appears to be actively hostile to life like our own. For the most part, empty space is so cold that all life in it would be frozen; most of the matter in space is so hot as to make life on it impossible; space is traversed, and astronomical bodies continually bombarded, by radiation of a variety of kinds, much of which is probably inimical to, or even destructive of, life.

Into such a universe we have stumbled, if not exactly by mistake, at least as the result of what may properly be described as an accident. The use of such a word need not imply any surprise that our earth exists, for accidents will happen, and if the universe goes on for long enough, every conceivable accident is likely to happen in time. It was, I think, Huxley who said that six monkeys, set to strum unintelligently on typewriters for millions of millions of years, would be bound in time to write all the books in the British Museum. If we examined the last page which a particular monkey had typed, and found that it had chanced, in its blind strumming, to type a Shakespeare sonnet, we should rightly regard the occurrence as a remarkable accident, but if we looked through all the millions of pages the monkeys had turned off in untold millions of years, we might be sure of finding a Shakespeare sonnet somewhere amongst them, the product of the blind play of chance.

Martin Rees

from JUST SIX NUMBERS

■ As Astronomer Royal and President of the Royal Society, Martin Rees, too, is no stranger to the romance of the stars and of science. His approach to putting us in our place invokes the mythical symbol of the *ouraborus* to situate us exactly in the middle of the (logarithmic) spectrum of magnitudes ranging from the astronomical to the sub-atomic. I shall revert to this later in the book, when I discuss the difficulties experienced by the evolved human mind as we try to understand the extreme realms of science far from the middle ground in which our ancestors survived.

The first extract comes from Rees's 1999 book *Just Six Numbers*. A second extract from the same book explains its central theme. Modern physics has made amazing strides towards explaining the universe, heroically driving our ignorance back into the first fraction of a second after the Big Bang. But our explanations of the deep problems of existence rely on some half dozen numbers, the fundamental constants of physics, whose values we can measure but cannot derive from existing theories. They are just there; and many physicists, including Rees himself (though not, for example, Victor Stenger, a physicist for whom I also have a very high regard) believe that their precise values are crucial to the existence of a universe capable of producing biological evolution of some kind. Rees takes each of the six constants in turn, and the one I have chosen for this anthology is *N*, the ratio between the strength of the electrical force that holds atoms together and the gravitational force that holds the universe together. ■

Large Numbers and Diverse Scales

We are each made up of between 10^{28} and 10^{29} atoms. This ‘human scale’ is, in a numerical sense, poised midway between the masses of atoms and stars. It would take roughly as many human bodies to make up the mass of the Sun as there are atoms in each of us. But our Sun is just an ordinary star in the galaxy that contains a hundred billion stars altogether. There are at least as many galaxies in our observable universe as there are stars in a galaxy. More than 10^{78} atoms lie within range of our telescope.

Living organisms are configured into layer upon layer of complex structure. Atoms are assembled into complex molecules; these react, via complex pathways in every cell, and indirectly lead to the entire interconnected structure that makes up a tree, an insect or a human. We straddle the cosmos and the microworld—intermediate in size between the Sun, at a billion metres in diameter, and a molecule at a billionth of a metre. It is actually no coincidence that nature attains its maximum complexity on this intermediate scale: anything larger, if it were on a habitable planet, would be vulnerable to breakage or crushing by gravity.

We are used to the idea that we are moulded by the microworld: we are vulnerable to viruses a millionth of a metre in length, and the minute DNA double-helix molecule encodes our total genetic heritage. And it’s just as obvious that we depend on the Sun and its power. But what about the still vaster scales? Even the nearest stars are millions of times further away than the Sun, and the known cosmos extends a billion times further still. Can we understand why there is so much beyond our Solar System? In this book I shall describe several ways in which we are linked to the stars, arguing that we cannot understand our origins without the cosmic context.

The intimate connections between the 'inner space' of the subatomic world and the 'outer space' of the cosmos are illustrated by the picture in Figure 1—an *ouraborus*, described by *Encyclopaedia Britannica* as the 'emblematic serpent of ancient Egypt and Greece, represented with its tail in its mouth continually devouring itself and being reborn from itself… [It] expresses the unity of all things, material and spiritual, which never disappear but perpetually change form in an eternal cycle of destruction and re-creation'.

On the left in the illustration are the atoms and subatomic particles; this is the 'quantum world'. On the right are planets, stars and galaxies. This book will highlight some remarkable interconnections between the microscales on the left and the macroworld on the right. Our everyday world is determined by atoms and how they combine together into molecules, minerals

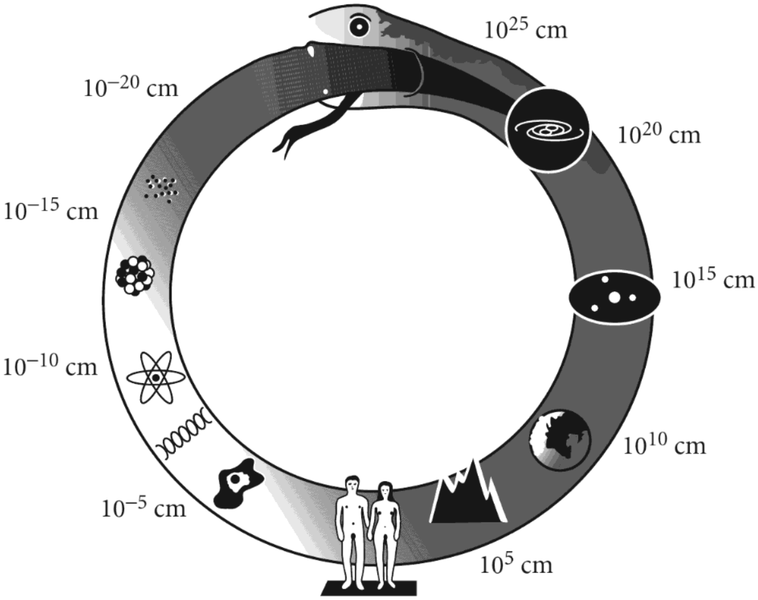

Figure 1. The *ouraborus*. There are links between the microworld of particles, nuclei and atoms (left) and the cosmos (right).

and living cells. The way stars shine depends on the nuclei within those atoms. Galaxies may be held together by the gravity of a huge swarm of subnuclear particles. Symbolized 'gastronomically' at the top, is the ultimate synthesis that still eludes us—between the cosmos and the quantum.

Lengths spanning sixty powers of ten are depicted in the *ouraborus*. Such an enormous range is actually a prerequisite for an 'interesting' universe. A universe that didn't involve large numbers could never evolve a complex hierarchy of structures: it would be dull, and certainly not habitable. And there must be long timespans as well. Processes in an atom may take a millionth of a billionth of a second to be completed; within the central nucleus of each atom, events are even faster. The complex processes that transform an embryo into blood, bone and flesh involve a succession of cell divisions, coupled with differentiation, each involving thousands of intricately orchestrated regroupings and replications of molecules; this activity never ceases as long as we eat and breathe. And our life is just one generation in humankind's evolution, an episode that is itself just one stage in the emergence of the totality of life.

The tremendous timespans involved in evolution offer a new perspective on the question 'Why is our universe so big?' The emergence of human life here on Earth has taken 4.5 billion years. Even before our Sun and its planets could form, earlier stars must have transmuted pristine hydrogen into carbon, oxygen and the other atoms of the periodic table. This has taken about ten billion years. The size of the observable universe is, roughly, the distance travelled by light since the Big Bang, and so the present visible universe must be around ten billion light-years across.

This is a startling conclusion. The very hugeness of our universe, which seems at first to signify how unimportant we are in the cosmic scheme, is actually entailed by our existence! This is not to say that there couldn't have been a smaller universe, only that we could not have existed in it. The expanse of cosmic space is not an extravagant superfluity; it's a consequence of the prolonged chain of events, extending back before our Solar System formed, that preceded our arrival on the scene.

This may seem a regression to an ancient 'anthropocentric' perspective—something that was shattered by Copernicus's revelation that the Earth moves around the Sun rather than vice versa. But we shouldn't take Copernican modesty (sometimes called the 'principle of mediocrity') too far. Creatures like us require special conditions to have evolved, so our perspective is bound to be in some sense atypical. The vastness of our universe shouldn't surprise us, even though we may still seek a deeper explanation for its distinctive features.

[…]

The Value of N *and Why it is So Large*

Despite its importance for us, for our biosphere, and for the cosmos, gravity is actually *amazingly feeble* compared with the other forces that affect atoms. Electric charges of opposite 'sign' attract each other: a hydrogen atom consists of a positively charged proton, with a single (negative) electron trapped in orbit around it. Two protons would, according to Newton's laws, attract each other gravitationally, as well as exerting an electrical force of repulsion on one another. Both these forces depend on distance in the same way (both follow an 'inverse square' law), and so their relative strength is measured by an important number, N, which is the same irrespective of how widely separated the protons are. When two hydrogen atoms are bound together in a molecule, the electric force between the protons is neutralized by the two electrons. The gravitational attraction between the protons is thirty-six powers of ten feebler than the electrical forces, and quite unmeasurable. Gravity can safely be ignored by chemists when they study how groups of atoms bond together to form molecules.

How, then, can gravity nonetheless be dominant, pinning us to the ground and holding the moon and planets in their courses? It's because gravity is *always an attraction*: if you double a mass, then you double the gravitational pull it exerts. On the other hand, electric charges can repel each other as well as attract; they can be either positive or negative. Two charges only exert twice the force of one if they are of the same 'sign'. But any everyday object is made up of huge numbers of atoms (each made up of a positively charged nucleus surrounded by negative electrons), and the positive and negative charges almost exactly cancel out. Even when we are 'charged up' so that our hair stands on end, the imbalance is less than one charge in a billion billion. But everything has the same sign of gravitational 'charge', and so gravity 'gains' relative to electrical forces in larger objects. The balance of electric forces is only slightly disturbed when a solid is compressed or stretched. An apple falls only when the combined gravity of all the atoms in the Earth can defeat the electrical stresses in the stalk holding it to the tree. Gravity is important to us because we live on the heavy Earth.

We can quantify this. In Chapter 1, we envisaged a set of pictures, each being viewed from ten times as far as the last. Imagine now a set of differently sized spheres, containing respectively 10, 100, 1000,... atoms, in other words each ten times heavier than the one before. The eighteenth would be as big as a grain of sand, the twenty-ninth the size of a human, and the fortieth that of a largish asteroid. For each thousandfold increase in mass, the volume also goes up a thousand times (if the spheres are equally dense) but the radius goes up only by ten times. The importance of the sphere's own gravity, measured by how much energy it takes to remove an atom from its gravitational pull, depends on mass divided by radius, and so goes up a factor of a hundred. Gravity starts off, on the atomic scale, with a handicap of thirty-six powers of ten; but it gains two powers of ten (in other words 100) for every three powers (factors of 1000) in mass. So gravity will have caught up for the fifty-fourth object ($54=36\times 3/2$), which has about Jupiter's mass. In any still heavier lump more massive than Jupiter, gravity is so strong that it overwhelms the forces that hold solids together.

Sand grains and sugar lumps are, like us, affected by the gravity of the massive Earth. But their *self-gravity*—the gravitational pull that their constituent atoms exert on each other, rather than on the entire Earth—is negligible. Self-gravity is not important in asteroids, nor in Mars's two small potato-shaped moons, Phobos and Deimos. But bodies as large as planets (and even our own large Moon) are not rigid enough to maintain an irregular shape: gravity makes them nearly round. And masses above that of Jupiter get crushed by their own gravity to extraordinary densities (unless the centre gets hot enough to supply a balancing pressure, which is what happens in the Sun and other stars like it). It is because gravity is so weak that a typical star like the Sun is so massive. In any lesser aggregate, gravity could not compete with the pressure, nor squeeze the material hot and dense enough to make it shine.

The Sun contains about a thousand times more mass than Jupiter. If it were cold, gravity would squeeze it a million times denser than an ordinary solid: it would be a 'white dwarf' about the size of the Earth but 330,000 times more massive. But the Sun's core actually has a temperature of fifteen million degrees—thousands of times hotter than its glowing surface, and the pressure of this immensely hot gas 'puffs up' the Sun and holds it in equilibrium.

The English astrophysicist Arthur Eddington was among the first to understand the physical nature of stars. He speculated about how much we could learn about them just by theorizing, if we lived on a perpetually cloud-bound planet. We couldn't, of course, guess how many there are, but simple reasoning along the lines I've just outlined could tell us how big they would have to be, and it isn't too difficult to extend the argument further, and work out how brightly such objects could shine. Eddington concluded that: 'When we draw aside the veil of clouds beneath which our physicist is working and let him look up at the sky, there he will find a thousand million globes of gas, nearly all with [these] masses.'

Gravitation is feebler than the forces governing the microworld by the number *N*, about 10^{36}. What would happen if it weren't quite so weak? Imagine, for instance, a universe where gravity was 'only' 10^{30} rather than 10^{36} feebler than electric forces. Atoms and molecules would behave just as in our actual universe, but objects would not need to be so large before gravity became competitive with the other forces. The number of atoms needed to make a star (a gravitationally bound fusion reactor) would be a billion times less in this imagined universe. Planet masses would also be scaled down by a billion. Irrespective of whether these planets could retain steady orbits, the strength of gravity would stunt the evolutionary potential on them. In an imaginary strong-gravity world, even insects would need thick legs to support them, and no animals could get much larger. Gravity would crush anything as large as ourselves.

Galaxies would form much more quickly in such a universe, and would be miniaturized. Instead of the stars being widely dispersed, they would be so densely packed that close encounters would be frequent. This would in itself preclude stable planetary systems, because the orbits would be disturbed by passing stars—something that (fortunately for our Earth) is unlikely to happen in our own Solar System.

But what would preclude a complex ecosystem even more would be the limited time available for development. Heat would leak more quickly from these 'mini-stars': in this hypothetical strong-gravity world, stellar lifetimes would be a million times shorter. Instead of living for ten billion years, a typical star would live for about 10,000 years. A mini-Sun would burn faster, and would have exhausted its energy before even the first steps in organic evolution had got under way. Conditions for complex evolution would undoubtedly be less favourable if (leaving everything else unchanged) gravity were stronger. There wouldn't be such a huge gulf as there is in our actual universe between the immense timespans of astronomical processes and the basic microphysical timescales for physical or chemical reactions. The converse, however, is that an even *weaker* gravity could allow even more elaborate and longer-lived structures to develop.

Gravity is the organizing force for the cosmos…[It] is crucial in allowing structure to unfold from a Big Bang that was initially almost featureless. But it is only because it is weak compared with other forces that large and long-lived structures can exist. Paradoxically, the weaker gravity is (provided that it isn't actually zero), the grander and more complex can be its consequences. We have no theory that tells us the value of *N*. All we know is that nothing as complex as humankind could have emerged if *N* were much less than 1,000,000,000,000,000,000,000,000,000,000,000,000.

Peter Atkins

from CREATION REVISITED

■ The chemist Peter Atkins writes substantial textbooks, which American university bookshops order by the cubic yard. He is also, in my opinion, one of the finest living writers of scientific literature, a master of scientific wit ('Thermodynamicists get very excited when nothing happens') and lyrical prose poetry extolling the wonders of science and the scientific world view. His literary flair is most hauntingly demonstrated in *The Creation* (second edition *Creation Revisited*):

> When we have dealt with the values of the fundamental constants by seeing that they are unavoidably so, and have dismissed them as irrelevant, we shall have arrived at complete understanding. Fundamental science then can rest. We are almost there. Complete knowledge is just within our grasp. Comprehension is moving across the face of the Earth, like the sunrise.

The extract from the same delightful book that I have chosen expounds one of the central ideas of all science—C. P. Snow's litmus test of scientific culture—the Second Law of Thermodynamics. Atkins shows how the universal downhill degradation towards disorder can be harnessed locally to drive processes uphill (the principle of the ram pump) and build up order—including life and everything that makes it worth having. Notice, by the way, that Atkins uses the word 'chaos' in its normal sense of disorder, which is rather different from a special technical sense popularized as the 'butterfly effect' (one flap of a butterfly's wing could in theory initiate a chain of events that leads to a hurricane). Important and interesting as that technical sense of 'chaos' undoubtedly is, I deplore the hijacking of the word. ■

Why Things Change

Change takes a variety of forms. There is simple change, as when a bouncing ball comes to rest, or when ice melts. There is more complex change, as in digestion, growth, reproduction, and death. There is also what appears to be excessively subtle change, as in the formation of opinions and the creation and rejection of ideas. Though diverse in its manifestations, change does in fact have a common source. Like everything fundamental, that source is perfectly simple.

Organized change, the contriving of some end, such as a pot, a crop, or an opinion, is powered by the same events that stop balls bouncing and melt ice. All change, I shall argue, arises from an underlying collapse into chaos. We shall see that what may appear to us to be motive and purpose is in fact ultimately motiveless, purposeless decay. Aspirations, and their achievement, feed on decay.

The deep structure of change is decay. What decays is not the quantity but the *quality* of energy. I shall explain what is meant by high quality energy, but for the present think of it as energy that is localized, and potent to effect change. In the course of causing change it spreads, becomes chaotically distributed like a fallen house of cards, and loses its initial potency. Energy's quality, but not its quantity, decays as it spreads in chaos.

Harnessing the decay results not only in civilizations but in all the events in the world and the universe beyond. It accounts for all discernible change, both animate and inanimate. The quality of energy is like a slowly unwinding spring. The quality spontaneously declines and the spring of the universe unwinds. The quality spontaneously degrades, and the spontaneity of the degradation drives the interdependent processes webbed around and within us, as through the interlocked gear wheels of a sophisticated machine. Such is the complexity of the interlocking that here and there chaos may temporarily recede and quality flare up, as when cathedrals are built and symphonies are performed. But these are temporary and local deceits, for deeper in the world the spring inescapably unwinds. Everything is driven by decay. Everything is driven by motiveless, purposeless decay.

As we have said, by 'quality' of energy is meant the extent of its dispersal. High-quality, useful energy, is localized energy. Low quality, wasted energy, is chaotically diffuse energy. Things can get done when energy is localized; but energy loses its potency to motivate change when it has become dispersed. The degradation of quality is chaotic dispersal.

I shall now argue that such dispersal is ultimately natural, motiveless, and purposeless. It occurs naturally and spontaneously, and when it occurs it causes change. When it is precipitate it destroys. When it is geared through chains of events it can produce civilizations.

The naturalness of the tendency of energy to spread can be appreciated by thinking of a crowd of atoms jostling. Localized energy, energy in a circumscribed region, corresponds to vigorous motion in a corner of the crowd. As the atoms jostle, they hand on their energy and induce their neighbours to jostle too, and soon the jostling disperses like the order of a shuffled pack. There is very little chance that the original corner of the crowd will ever again be found jostled back into its original activity with all the rest at rest. Random, motiveless jostling has resulted in irreversible change.

This natural tendency to disperse accounts for simple processes like the cooling of hot metal. The energy of the block, an energy captured in the vigorous vibrations of its atoms, is jostled into its surroundings. The individual jostlings may result in energy being passed in either direction; but there are so many more atoms in the world outside than in the block itself, that it is much more probable that at all later times the energy of the block will be found (or lost) dispersed.

Illusions of purpose are captured by the model. We may think that there are reasons why one change occurs and not another. We may think that there are reasons for specific changes in the location of energy (such as a change of structure, as in the opening of a flower); but at root, all there is, is degradation by dispersal.

Suppose that in some region there are many more places for energy to accumulate than elsewhere. Then jostling and random leaping results in its heaping there. If the energy began in a heap initially organized elsewhere, it will be found later in a heap in the region where the platforms are most dense. A casual observer will wonder why the energy chose to go there, conclude there must have been a purpose, and try to find it. We, however, can see that achieving being there should not be confused with choosing to go there.

Changes of location, of state, of composition, and of opinion are all at root dispersal. But if that dispersal spreads energy into regions where it can be located densely, it gives the illusion of specific change rather than mere spreading. At the deepest level, purpose vanishes and is replaced by the consequences of having the opportunity to explore at random, discovering dense locations, and lingering there until new opportunities for exploration arise.

Events are the manifestations of overriding probabilities. All the events of nature, from the bouncing of balls to the conceiving of gods, are aspects and elaborations of this simple idea. But we should not let pass without emphasis the word probability. The energy just might by chance jostle back into its original heap, and a structure reform. The energy just might, by chance, jostle its way back into the block from the world at large, and an observer see a cool block spontaneously becoming hot or a house of cards reforming. These possibilities are such remote chances that we dismiss them as wholly improbable. Yet, while improbable, they are not impossible.

The ultimate simplicity underlying the tendency to change is more effectively shrouded in some processes than in others. While cooling is easy to explain as natural, jostling dispersal, the processes of evolution, free will, political ambition, and warfare have their intrinsic simplicity buried more deeply. Nevertheless, even though it may be concealed, the spring of all creation is decay, and every action is a more or less distant consequence of the natural tendency to corruption.

The tendency of energy to chaos is transformed into love or war through the agency of chemical reactions. All actions are chains of reactions. From thinking to doing, in simply thinking, or in responding, the mechanism in action is chemical reaction.

At its most rudimentary, a chemical reaction is a rearrangement of atoms. Atoms in one arrangement constitute one species of molecule, and atoms in another, perhaps with additions or deletions, constitute another. In some reactions a molecule merely changes its shape; in some, a molecule adopts the atoms provided by another, incorporates them, and attains a more complex structure. In others, a complex molecule is itself eaten, either wholly or in part, and becomes the source of atoms for another.

Molecules have no inclination to react, and none to remain unreacted. There is, of course, no such thing as motive and purpose at this level of behaviour. Why, then, do reactions occur? At this level too, therefore, there can be no motive or purpose in love or war. Why then do they occur?

A reaction tends to occur if in the process energy is degraded into a more dispersed, more chaotic form. Every arrangement of atoms, every molecule, is constantly subject to the tendency to lose energy as jostling carries it away to the surroundings. If a cluster of atoms happens by chance to wander into an arrangement that corresponds to a new molecule, that transient arrangement may suddenly be frozen into permanence as the energy released leaps away. Chemical reactions are transformations by misadventure.

Atoms are only loosely structured into molecules, and explorations of rearrangements resulting in reactions are commonplace. That is one reason why consciousness has already emerged from the inanimate matter of the original creation. If atoms had been as strongly bound as nuclei, the initial primitive form of matter would have been locked into permanence, and the universe would have died before it awoke.

The frailty of molecules, though, raises questions. Why has the universe not already collapsed into unreactive slime? If molecules were free to react each time they touched a neighbour, the potential of the world for change would have been realized long ago. Events would have taken place so haphazardly and rapidly that the rich attributes of the world, like life and its own self-awareness, would not have had time to grow.

The emergence of consciousness, like the unfolding of a leaf, relies upon restraint. Richness, the richness of the perceived world and the richness of the imagined worlds of literature and art—the human spirit—is the consequence of controlled, not precipitate, collapse.

Helena Cronin

from THE ANT AND THE PEACOCK

■ We now switch from physical science to my own subject of biology. Helena Cronin's beautifully written *The Ant and the Peacock* is mostly about two special problems that arose out of Darwin's work, altruism and sexual selection. But the book begins with as elegant a word picture as you'll find of the central idea of biology itself, Darwinian evolution. ■

We are walking archives of ancestral wisdom. Our bodies and minds are live monuments to our forebears' rare successes. This Darwin has taught us. The human eye, the brain, our instincts, are legacies of natural selection's victories, embodiments of the cumulative experience of the past. And this biological inheritance has enabled us to build a new inheritance: a cultural ascent, the collective endowment of generations. Science is part of this legacy, and this book is about one of its foremost achievements: Darwinian theory itself.

[…]

A World Without Darwin

Imagine a world without Darwin. Imagine a world in which Charles Darwin and Alfred Russel Wallace had not transformed our understanding of living things. What, that is now comprehensible to us, would become baffling and puzzling? What would we see as in urgent need of explanation?

The answer is: practically everything about living things—about all of life on earth and for the whole of its history (and, probably, as we'll see, about life elsewhere, too). But there are two aspects of organisms that had baffled and puzzled people more than any others before Darwin and Wallace came up with their triumphant and elegant solution in the 1850s.

The first is design. Wasps and leopards and orchids and humans and slime moulds have a designed appearance about them; and so do eyes and kidneys and wings and pollen sacs; and so do colonies of ants, and flowers attracting bees to pollinate them, and a mother hen caring for her chicks. All this is in sharp contrast to rocks and stars and atoms and fire. Living things are beautifully and intricately adapted, and in myriad ways, to their inorganic surroundings, to other living things (not least to those most like themselves), and as superbly functioning wholes. They have an air of purpose about them, a highly organised complexity, a precision and efficiency. Darwin aptly referred to it as 'that perfection of structure and co-adaptation which most justly excites our admiration'. How has it come about?

The second puzzle is 'likeness in diversity'—the strikingly hierarchical relationships that can be found throughout the organic world, the differences and yet obvious similarities among groups of organisms, above all the links that bind the serried multitudes of species. By the mid-nineteenth century, these fundamental patterns had emerged from a range of biological disciplines. The fossil record was witness to continuity in time; geographical distribution to continuity in space; classification systems were built on what was called unity of type; morphology and embryology (particularly comparative studies) on so-called mutual affinities; and all these subjects revealed a remarkable abundance of further regularities and ever-more diversity. How could these relationships be accounted for? And whence such profligate speciation?

In the light of Darwinian theory, the answers to both questions, and to a host of other questions about the organic world, fall into place. Darwin and Wallace assumed that living things had evolved. Their problem was to find the mechanism by which this evolution had occurred, a mechanism that could account for both adaptation and diversity. Natural selection was their solution. Individuals vary and some of their variations are heritable. These heritable variations arise randomly—that is, independently of their effects on the survival and reproduction of the organism. But they are perpetuated differentially, depending on the adaptive advantage they confer.

Thus, over time, populations will come to consist of the better adapted organisms. And, as circumstances change, different adaptations become advantageous, gradually giving rise to divergent forms of life.

The key to all of this—to how natural selection is able to produce its wondrous results—is the power of many, many small but cumulative changes. Natural selection cannot jump from the primaeval soup to orchids and ants all in one go, at a single stroke. But it can get there through millions of small changes, each not very different from what went before but amounting over very long periods of time to a dramatic transformation. These changes arise randomly—without relation to whether they'll be good, bad or indifferent. So if they happen to be of advantage that's just a matter of chance. But it's not a grossly improbable chance, because the change is very small, from an organism that's not much like an exquisitely fashioned orchid to one that's ever-so-slightly more like it. So what would otherwise be a vast dollop of luck is smeared out into acceptably probable portions. And natural selection not only seizes on each of these chance advantages but also preserves them cumulatively, conserving them one after another throughout a vast series, until they gradually build up into the intricacy and diversity of adaptation that can move us to awed admiration. Natural selection's power, then, lies in randomly generated diversity that is pulled into line and shaped over vast periods of time by a selective force that is both opportunistic and conserving.

R. A. Fisher

from THE GENETICAL THEORY OF NATURAL SELECTION

My overwhelming impression on opening any page of Darwin is of being ushered into the presence of a great intellect. I feel the same sense of reverential hush when I read Darwin's great twentieth-century succes-

sor R. A. Fisher. I think it is right to include Fisher in this collection, even though his writing is more difficult than Darwin's, especially to non-mathematicians (in which large category Darwin would have been the first to place himself). The opening pages of Fisher's *The Genetical Theory of Natural Selection* lack the explicit mathematics of later parts of the book, but you can tell that the biologist in whose presence we find ourselves was a mathematician first. Fisher was one of the three great founders of population, mathematical, and evolutionary genetics, one of the half dozen or so founders of the neo-Darwinian Modern Synthesis, and arguably the founder of modern statistics. Alas, I never met him, but as an undergraduate I once encountered the eccentric Oxford geneticist E. B. Ford escorting an old gentleman with a very white beard and very thick glasses through the Museum, and I like to think that this must have been Ford's mentor and hero, Sir Ronald Fisher. ■

Difficulties Felt by Darwin

The argument based on blending inheritance and its logical consequences, though it certainly represents the general trend of Darwin's thought upon inheritance and variation, for some years after he commenced pondering on the theory of Natural Selection, did not satisfy him completely. Reversion he recognized as a fact which stood outside his scheme of inheritance, and that he was not altogether satisfied to regard it as an independent principle is shown by his letter to Huxley already quoted. By 1857 he was in fact on the verge of devising a scheme of inheritance which should include reversion as one of its consequences. The variability of domesticated races, too, presented a difficulty which, characteristically, did not escape him. He notes (pp. 77, 78, *Foundations*) in 1844 that the most anciently domesticated animals and plants are not less variable, but, if anything more so, than those more recently domesticated; and argues that since the supply of food could not have been becoming much more abundant progressively at all stages of a long history of domestication, this factor cannot alone account for the great variability which still persists. The passage runs as follows:

> If it be an excess of food, compared with that which the being obtained in its natural state, the effects continue for an improbably long time; during how many ages has wheat been cultivated, and cattle and sheep reclaimed, and we cannot suppose their *amount* of food has gone on increasing, nevertheless these are amongst the most variable of our domestic productions.

This difficulty offers itself also to the second supposed cause of variability, namely changed conditions, though here it may be argued that the conditions of cultivation or nurture of domesticated species have always been changing more or less rapidly. From a passage in the *Variation of Animals and Plants* (p. 301), which runs:

> Moreover, it does not appear that a change of climate, whether more or less genial, is one of the most potent causes of variability; for in regard to plants Alph. De Candolle, in his *Geographie Botanique*, repeatedly shows that the native country of a plant, where in most cases it has been longest cultivated, is that where it has yielded the greatest number of varieties.

it appears that Darwin satisfied himself that the countries in which animals or plants were first domesticated, were at least as prolific of new varieties as the countries into which they had been imported, and it is natural to presume that his inquiries under this head were in search of evidence bearing upon the effects of changed conditions. It is not clear that this difficulty was ever completely resolved in Darwin's mind, but it is clear from many passages that he saw the necessity of supplementing the original argument by postulating that the causes of variation which act upon the reproductive system must be capable of acting in a delayed and cumulative manner so that variation might still be continued for many subsequent generations.

Particulate Inheritance

It is a remarkable fact that had any thinker in the middle of the nineteenth century undertaken, as a piece of abstract and theoretical analysis, the task of constructing a particulate theory of inheritance, he would have been led, on the basis of a few very simple assumptions, to produce a system identical with the modern scheme of Mendelian or factorial inheritance. The admitted non-inheritance of scars and mutilations would have prepared him to conceive of the hereditary nature of an organism as something nonetheless definite because possibly represented inexactly by its visible appearance. Had he assumed that this hereditary nature was completely determined by the aggregate of the hereditary particles (genes), which enter into its composition, and at the same time assumed that organisms of certain possible types of hereditary composition were capable of breeding true, he would certainly have inferred that each organism must receive a definite portion of its genes from each parent, and that consequently it must transmit only a corresponding portion to each of its offspring. The simplification that, apart from sex and possibly other characters related in their inheritance to sex, the contributions of the two parents were equal, would not have been confidently assumed without the evidence of reciprocal crosses; but our imaginary theorist, having won so far, would scarcely have failed to imagine a conceptual framework in which each gene had its proper place or locus, which could be occupied alternatively, had the parentage been different, by a gene of a different kind. Those organisms (homozygotes) which received like genes, in any pair of corresponding loci, from their two parents, would necessarily hand on genes of this kind to all of their offspring alike; whereas those (heterozygotes) which received from their two parents genes of different kinds, and would be, in respect of the locus in question, cross-bred, would have, in respect of any particular offspring, an equal chance of transmitting either kind. The heterozygote when mated to either kind of homozygote would produce both heterozygotes and homozygotes in a ratio which, with increasing numbers of offspring, must tend to equality, while if two heterozygotes were mated, each homozygous form would be expected to appear in a quarter of the offspring, the remaining half being heterozygous. It thus appears that, apart from dominance and linkage, including sex linkage, all the main characteristics of the Mendelian system flow from assumptions of particulate inheritance of the simplest character, and could have been deduced *a priori* had any one conceived it possible that the laws of inheritance could really be simple and definite.

The segregation of single pairs of genes, that is of single factors, was demonstrated by Mendel in his paper of 1865. In addition Mendel demonstrated in his material the fact of dominance, namely that the heterozygote was not intermediate in appearance, but was almost or quite indistinguishable from one of the homozygous forms. The fact of dominance, though of the greatest theoretical interest, is not an essential feature of the factorial system, and in several important cases is lacking altogether. Mendel also demonstrated what a theorist could scarcely have ventured to postulate, that the different factors examined by him in combination, segregated in the simplest possible manner, namely independently. It was not till after the rediscovery of Mendel's laws at the end of the century that cases of linkage were discovered, in which, for factors in the same linkage group, the pair of genes received from the same parent are more often than not handed on together to the same child. The conceptual framework of loci must therefore be conceived as made of several parts, and these are now identified, on evidence which appears to be singularly complete, with the dark-staining bodies or chromosomes which are to be seen in the nuclei of cells at certain stages of cell division.

The mechanism of particulate inheritance is evidently suitable for reproducing the phenomenon of reversion, in which an individual resembles a grandparent or more remote ancestor, in some respect in which it differs from its parents; for the ancestral gene combination may by chance be reproduced. This takes its simplest form when dominance occurs, for every union of two heterozygotes will then produce among the offspring some recessives, differing in appearance from their parents, but probably resembling some grandparent or ancestor.

Theodosius Dobzhansky

from MANKIND EVOLVING

■ One of Fisher's co-founders of the neo-Darwinian Modern Synthesis was the Russian American geneticist Theodosius Dobzhansky (1900–75). Less mathematical than Fisher, he was a fine researcher, and the author of one of the most influential of the founding texts of the Synthesis, *Genetics and the Origin of Species*. The passage I have chosen is from one of his later books, *Mankind Evolving* (1962), which influenced me when I was an undergraduate and heard him give a lecture at Oxford as the guest of E.B. Ford. Dobzhansky's chapter is a lucid exposition of how genes interact with environment in the determination of the variation among human individuals. The stress, importantly, is on the word variation. 'Nature versus nurture' is a topic that frequently inspires rather boring writing. Dobzhansky's chapter is an honourable exception. ■

Equal but Dissimilar

> My idea of society is that while we are born equal, meaning that we have a right to equal opportunity, all have not the same capacity.
>
> MAHATMA GANDHI

'I have made the four winds that every man might breathe there-of like his brother during his time. I have made every man like his brother, and I have forbidden that they do evil; it was their hearts which undid that which I had said.' This utterance, ascribed to the Egyptian god Re, antedates by some four and a half thousand years the Declaration of Independence, which states: 'We hold these truths to be self-evident, that all men are created equal.' But, surely, Re as well as Thomas Jefferson knew that brothers very often look and act unlike. Brothers, though dissimilar, are yet equal in their rights to share in the patrimony of their fathers.

A newborn infant is not a blank page; however, his genes do not seal his fate. His reactions to the world around him will differ in many ways from those of other infants, including his brothers. My genes have indeed determined what I am, but only in the sense that, given the succession of environments and experiences that were mine, a carrier of a different set of genes might have become unlike myself.

It is sometimes said that the genes determine the limits up to which, but not beyond which, a person's development may advance. This only confuses the issue. There is no way to predict all the phenotypes that a given genotype might yield in every one of the infinity of possible environments. Environments are infinitely diversified, and in the future there will exist environments that do not exist now. The infant now promenading in his perambulator under my window may become many things. To be sure, he is not likely to grow eight feet tall, but we do not know how to obtain the evidence needed to determine how tall he may grow in some environments that may be contrived to stimulate growth. It is an illusion that there is something fundamental or intrinsic about limits, particularly upper limits. Every statistician knows that limits are elusive and hard to determine, most of all when the environmental conditions are not specified.

Even at the risk of belaboring the obvious, let it be repeated that heredity cannot be called the 'dice of destiny'. Variations in body build, in physiology, and in mental traits are in part genetically conditioned, but this does not make education and social improvements any less necessary, or the hopes of benefits to be derived from these improvements any less well founded. What genetic conditioning does mean is that there is no single human nature, only human natures with different requirements for optimal growth and self-realization. The evidence of genetic conditioning of human traits, especially mental traits, must be examined with the greatest care.

FAMILY RESEMBLANCES

Heredity is said to cause the resemblance between children and their parents. This definition is good as far as it goes, but it does not go far enough. Mendel found that some of the progeny of two dominant heterozygous parents will differ from them because of homozygosis for recessive genes. Heredity may thus make children different from their parents. Hence heredity is better described as the transmission of self-reproducing entities, genes. The oldest and simplest method of studying heredity is, nevertheless, to observe resemblances and differences within and between families. Galton was the pioneer of systematic studies of this sort.

In *Hereditary Genius* Galton (1869) studied 300 families which produced one or more eminent men, the eminence being defined as attainment of a position of influence or renown, such as was achieved by about one person in 4,000, or 0.025 per cent, in the English population. Galton's eminent men were statesmen, judges, military commanders, church dignitaries, and famous writers and scientists. Table 1 shows that the incidence of eminence is higher in relatives of eminent men than in the general population, and that close relatives of eminent men are more likely to achieve eminence than more remote relatives.

Table 1. Numbers of eminent male relatives per 100 eminent men in 19th-century England *(after Galton)*

Relation	*Number eminent*	*Relation*	*Number eminent*
Father	31	Grandson	14
Brother	41	First cousin	13
Son	48	Great grandfather	3
Uncle	18	Great uncle	5
Nephew	22	Great grandson	3
Grandfather	17	Great nephew	10

Clearly, eminence 'runs in families'. But does it follow that possession of a certain genetic endowment is necessary or sufficient to attain eminence? Surely having influential relatives is helpful, even in societies with class barriers less rigid than those of nineteenth-century England. Galton was not oblivious of this possibility. But he dismissed it because he defined the genetic endowment of eminent men as that which, 'when left to itself, will, urged by an inherent stimulus, climb the path that leads to eminence, and has strength to reach the summit—one which, if hindered or thwarted will fret and strive until the hindrance is overcome, and it is again free to follow its labor-loving instinct.'

This sounds perilously close to circular reasoning. Galton's clinching argument seems whimsical at present, but it was taken seriously a century ago. Class barriers are less rigid in the United States than in England; it should be easier to achieve eminence in the former than in the latter country; one might accordingly expect that the United States will produce more men of genius than England; in point of fact, the opposite is true; therefore, according to Galton, to become eminent one must inherit genes that are more frequent in the English than in the American population.

His observations, though not his conclusions, have been repeatedly confirmed in different countries by investigators studying the pedigrees and descendants of persons of varying degrees of eminence, from the indisputable eminence of geniuses such as Darwin or J. S. Bach to the relatively puny eminence of the persons 'starred' in *American Men of Science* or included in various 'Who's Who' directories.

Although it has been found nearly everywhere that eminence runs in families, it is just at this point that one must proceed with the greatest caution. The environmental bias in the data is patent—other things being equal, a son may find his way smoothest if he follows the calling in which his father excelled. But to reject the data as throwing no light at all on genetic conditioning is unreasonable: notable development of certain special abilities does occur in persons who are possessors of special genetic endowments. The data on inheritance of musical talent are particularly abundant and convincing.

Among the fifty-four known male ancestors, relatives, and descendants of J. S. Bach, forty-six were professional musicians, and among these seventeen were composers of varying degrees of distinction. Granted that in many parts of the world it is customary for members of a family to seek their livelihood in the same profession; granted also that growing up in a family of musicians is propitious for becoming a musician; it is still quite unlikely that the genetic equipment of the Bachs had nothing to do with their musicianship. The recurrence of marked musical ability among the relatives of great musicians is so general a rule that exceptions are worthy of notice. No musical talent is known among the 136 ancestors and relatives of Schumann. Although the composer was married to a virtuoso pianist, none of their eight children possessed great musical ability. Such exceptions do not disprove that musicianship is genetically conditioned; they only show that its genetic basis is complex.

[…]

NATURE AND NURTURE IN CONDOMINIUM

In 1924, with nature-versus-nurture polemics close to their peak, J. B. Watson, the leader of the school of behaviorism in psychology and one of the staunchest partisans of the nurture hypothesis, wrote the following fighting lines:

> Give me a dozen healthy infants, well formed, and my own special world to bring them up in, and I'll guarantee to take any one at random and train him to become any type of specialist I might select—doctor, lawyer, artist, merchant-chief, and yes, even beggar and thief, regardless of his talents, penchants, tendencies, abilities, vocations, and race of his ancestors.

Watson's challenge was pure rhetoric—nobody has made an experiment according to his specifications. Now, more than a third of a century after Watson, we can deal more easily with his verbiage. Notice that the experiment would have to be done on healthy and well-formed individuals; this at once makes a considerable portion of mankind ineligible, since much poor health and malformation are plainly genetically conditioned. Is not normality here defined as developmental plasticity and educability? Notice further that Watson would have trained his normal subjects regardless of their talents, penchants, abilities, etc. But what are these things? If they are products of upbringing, they need not be mentioned in this context at all; if they have, at least in part, a genetic basis, then it is probably easier to train some persons to be doctors and others artists or merchant chiefs, etc.

Many, perhaps most, human infants could be trained, either as lawyers, or beggars, or thieves, etc., by suitably manipulating their environment. But this does not contradict the existence of genetic diversity, so that in a given environment some persons will probably become lawyers and others thieves. Or, to put it another way, different environments may be needed to make lawyers or thieves of different individuals. Or, again, those who are in fact lawyers could perhaps have become thieves, and the actual thieves could have become lawyers, if the circumstances of their lives had been different. In short, nature is not sovereign over some traits and potentialities and nurture over others; they share all traits in condominium.

G. C. Williams

from ADAPTATION AND NATURAL SELECTION

■ As Fisher was perhaps the first to realize clearly, evolution, at bottom, consists of the changing frequencies of genes in gene pools. It was left to the distinguished American biologist George C. Williams to apply the same insight clearly to adaptation, the tendency of living organisms to look as though they were designed for a purpose. Before Williams's 1966 book *Adaptation and Natural Selection*, the *cui bono* question (for whose benefit do adaptations evolve?) was likely to be answered by some vague nonsense about 'the good of the species'. Darwin, who knew better, would have said 'for the good of the individual in the struggle for survival and reproduction against rival members of the same species'. It was Williams, especially in the passage extracted here, who powerfully emphasized that 'for the good of the gene' was the answer that most naturally flowed from neo-Darwinism. Adaptations are 'for the benefit of' the genes responsible for the difference between individuals that possess them and individuals that don't. This is the central idea to which I later gave the title The Selfish Gene—although as it happened my original influence came from W. D. Hamilton (see below) rather than Williams. The extract reproduced here is Williams's vivid and persuasive way of expressing the argument. ■

The essence of the genetical theory of natural selection is a statistical bias in the relative rates of survival of alternatives (genes, individuals, etc.). The effectiveness of such bias in producing adaptation is contingent on the maintenance of certain quantitative relationships among the operative factors. One necessary condition is that the selected entity must have a high degree of permanence and a low rate of endogenous change, relative to the degree of bias (differences in selection coefficients). Permanence implies reproduction with a potential geometric increase.

Acceptance of this theory necessitates the immediate rejection of the importance of certain kinds of selection. The natural selection of phenotypes cannot in itself produce cumulative change, because phenotypes are extremely temporary manifestations. They are the result of an interaction between genotype and environment that produces what we recognize as an individual. Such an individual consists of genotypic information and information recorded since conception. Socrates consisted of the genes his parents gave him, the experiences they and his environment later provided, and a growth and development mediated by numerous meals. For all I know, he may have been very successful in the evolutionary sense of leaving numerous offspring. His phenotype, nevertheless, was utterly destroyed by the hemlock and has never since been duplicated. If the hemlock had not killed him, something else soon would have. So however natural selection may have been acting on Greek phenotypes in the fourth century BC, it did not of itself produce any cumulative effect.

The same argument also holds for genotypes. With Socrates' death, not only did his phenotype disappear, but also his genotype. Only in species that can maintain unlimited clonal reproduction is it theoretically possible for the selection of genotypes to be an important evolutionary factor. This possibility is not likely to be realized very often, because only rarely would individual clones persist for the immensities of time that are important in evolution. The loss of Socrates' genotype is not assuaged by any consideration of how prolifically he may have reproduced. Socrates' genes may be with us yet, but not his genotype, because meiosis and recombination destroy genotypes as surely as death.

It is only the meiotically dissociated fragments of the genotype that are transmitted in sexual reproduction, and these fragments are further fragmented by meiosis in the next generation. If there is an ultimate indivisible fragment it is, by definition, 'the gene' that is treated in the abstract discussions of population genetics. Various kinds of suppression of recombination may cause a major chromosomal segment or even a whole chromosome to be transmitted entire for many generations in certain lines of descent. In such cases the segment or chromosome behaves in a way that approximates the population genetics of a single gene. In this book I use the term *gene* to mean 'that which segregates and recombines with appreciable frequency'. Such genes are potentially immortal, in the sense of there being no physiological limit to their survival, because of their potentially reproducing fast enough to compensate for their destruction by external agents.

Francis Crick

from LIFE ITSELF

■ The salient feature of Mendelian genetics, the one that equips it to undergird the neo-Darwinian synthesis, is that it is digital. A given gene (Gregor Mendel himself didn't use the word) either passes to a given offspring (grand-offspring etc.) or it does not. There are no half measures, and genes never blend with one another. Heredity is all-or-none. That's digital. But what neither Mendel nor anyone else before 1953 knew was that genes themselves are digital, within themselves. A gene is a sequence of code letters, drawn from an alphabet of precisely four letters, and the genetic code is universal throughout all known living things. Life is the execution of programs written using a small digital alphabet in a single, universal machine language. This realization was the hammer blow that knocked the last nail into the coffin of vitalism and, by extension, of dualism. The hammer was wielded, with undisguised youthful relish, by James Watson and Francis Crick. Their famous one-page paper in *Nature* of 1953 concludes with what may be the greatest piece of calculated understatement ever: 'It has not escaped our notice that the specific pairing we have postulated immediately suggests a possible copying mechanism for the genetic material.'

The quality of mind that enabled Watson and Crick to race ahead of their laboratory-based rival Rosalind Franklin is well demonstrated by that sentence, and it is shown again in the extract I have chosen from Crick's book *Life Itself: Its Origin and Nature* (1981). Watson and Crick were not only concerned with finding out how things actually are—although that was of course their ultimate goal. They also kept in mind the way DNA ought to be if it was to do its job as the genetic molecule, and this gave them a short cut, which was ignored by the painstaking Rosalind Franklin. Watson said something similar in *Avoid Boring People* (see below): 'Knowing why is more important than learning what.' Crick exemplified this again and again in after years, as we learn from Matt Ridley's biography. At times it led him astray, as when he was seeking the genetic code and was temporarily seduced by a brilliantly neat idea about an ideally economical one. Nature, it turned out, was less elegant than Crick's mind, but it is in general true that deep cogitation on the way nature ought to be constitutes a good prelude to the eventual investigation of the way it actually is. Only a prelude, however: the ultimate test of an idea is not its elegance but how well it explains reality. ■

Nucleic Acids and Molecular Replication

Now that we have described the requirements for a living system in rather abstract terms, we must examine more closely how the various processes are carried out in the organisms we find all around us. As we have seen, the absolutely central requirement is for some rather precise method of replication and, in particular, for copying a long linear macromolecule put together from a standard set of subunits. On earth this role is played by one or the other of the two great families of nucleic acids, the DNA family and the RNA family. The general plan of these molecules is extremely simple, so simple indeed that it strongly suggests that they go right back to the very beginning of life.

DNA and RNA are rather similar—molecular cousins, you might say—so let us describe DNA first and then how RNA differs from it. One chain of DNA consists of a uniform backbone, the sequence of atoms repeating over and over again, with a side-group joined on at every repeat. Chemically the backbone goes…phosphate-sugar phosphate-sugar…etc., repeating many thousands or even millions of times. The sugar is not the sugar you have on your breakfast table but a smaller one called deoxyribose—that is, ribose with one 'oxy' group missing (hence the name DNA, standing for *D*eoxyribo*N*ucleic *A*cid—'nucleic' because it is found in the nucleus of higher cells, and 'acid' because of the phosphate groups, each of which in normal conditions carries a negative charge). Each sugar has a side-group joined to it. The side-groups differ, but there are only four main types of them. These four side-groups of DNA (for technical reasons called *bases*) are conveniently denoted by their initial letters, A, G, T and C (standing for *A*denine, *G*uanine, *T*hymine and *C*ytosine, respectively). Because of their exact size and shape and the nature of the chemical constituents, A will pair neatly with T, G with C. (A and G are big, T and C are smaller, so each pair consists of one big one with one smaller one.)

Both DNA and RNA rather easily form two-chain structures, in which the two chains lie together, side by side, twisted around one another to form a double helix and linked together by their bases. At each level there is a base-pair, formed between a base on one chain paired (using the pairing rules) with a base on the other. The bonds holding these pairs together are individually rather weak, though collectively

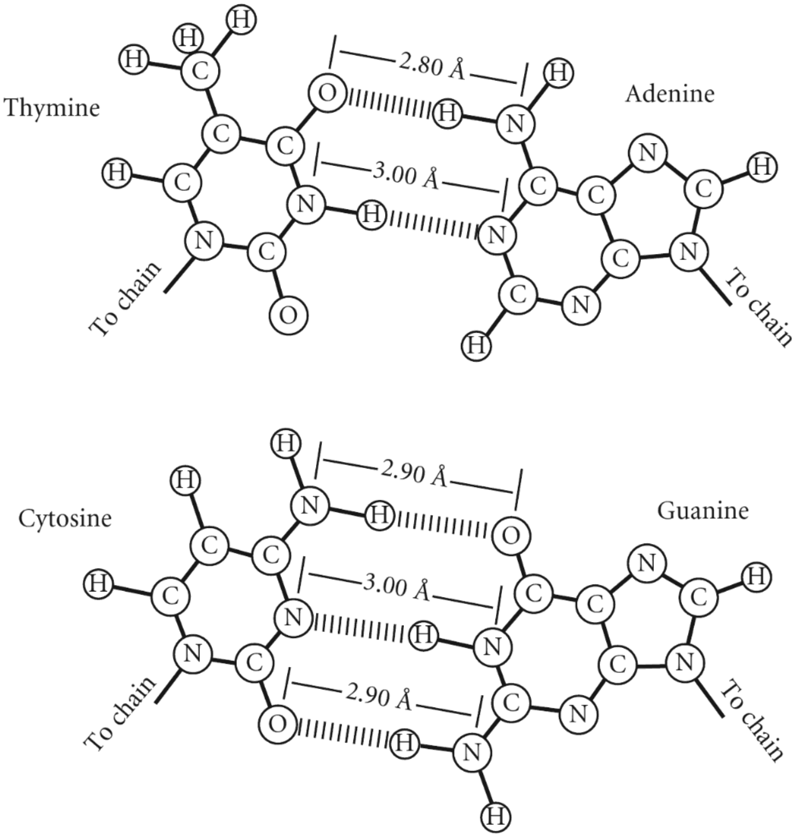

Figure 2. The base-pairs which are the secret of the DNA structure. The bases are held together by weak hydrogen bonds, shown by the interrupted lines. Thymine always pairs with adenine; cytosine with guanine.

they make a double helix reasonably stable. But if the structure is heated the increased thermal agitation will jostle the chains apart, so that they separate and float away from each other in the surrounding water.

The genetic message is conveyed by the exact base-sequence along one chain. Given this sequence, then the sequence of its complementary companion can be read off, using the base-pairing rules (A with T, G with C). The genetic information is recorded twice, once on each chain. This can be useful if one chain is damaged, since it can be repaired using the information—the base-sequence—of the other chain.

There is one unexpected peculiarity. In the usual double helix the two backbones of the two chains are not approximately parallel but antiparallel. If the sequence of the atoms in one backbone runs up, that in the other runs down. This does cause certain complications, but not as much as one might expect. At bottom it springs from the type of symmetry possessed by the double helix. This is produced by the pseudosymmetry of the base-pairing. It happens to be the convenient way for these particular chemicals to fit neatly together.

It is easy to see that a molecule of this type, consisting of a pair of chains whose irregular elements (the bases) fit together, is ideal for molecular replication, especially since the two chains can be rather easily separated from each other by mild methods. This is because the bonds *within* each chain, holding each chain together, are strong chemical bonds, fairly immune to normal thermal battering, whereas the two chains cling to each other by rather weak bonds so that they can be prized apart without too much difficulty and without breaking the individual backbones. The two chains of DNA are like two lovers, held tightly together in an intimate embrace, but separable because however closely they fit together each has a unity which is stronger than the bonds which unite them.

Because they fit together so precisely, each chain can be regarded as a mold for the other one. Conceptually the basic replication mechanism is very straightforward. The two chains are separated. Each chain then acts as a template for the assembly of a new companion chain, using as raw material a supply of four standard components. When this operation has been completed we shall have two pairs of chains instead of one, and since to do a neat job the assembly must obey the base-pairing rules (A with T, G with C), the base-sequences will have been copied exactly. We shall end up with two double helices where we only had one before. Each daughter double helix will consist of one old chain and one newly synthesized chain fitting closely together, and more important, the base-sequence of these two daughters will be identical to that of the original parental DNA.

The basic idea could hardly be simpler. The only rather unexpected feature is that the two chains are not identical but complementary. One could conceive an even simpler mechanism in which like paired with like, so that the two paired chains were identical, but the nature