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

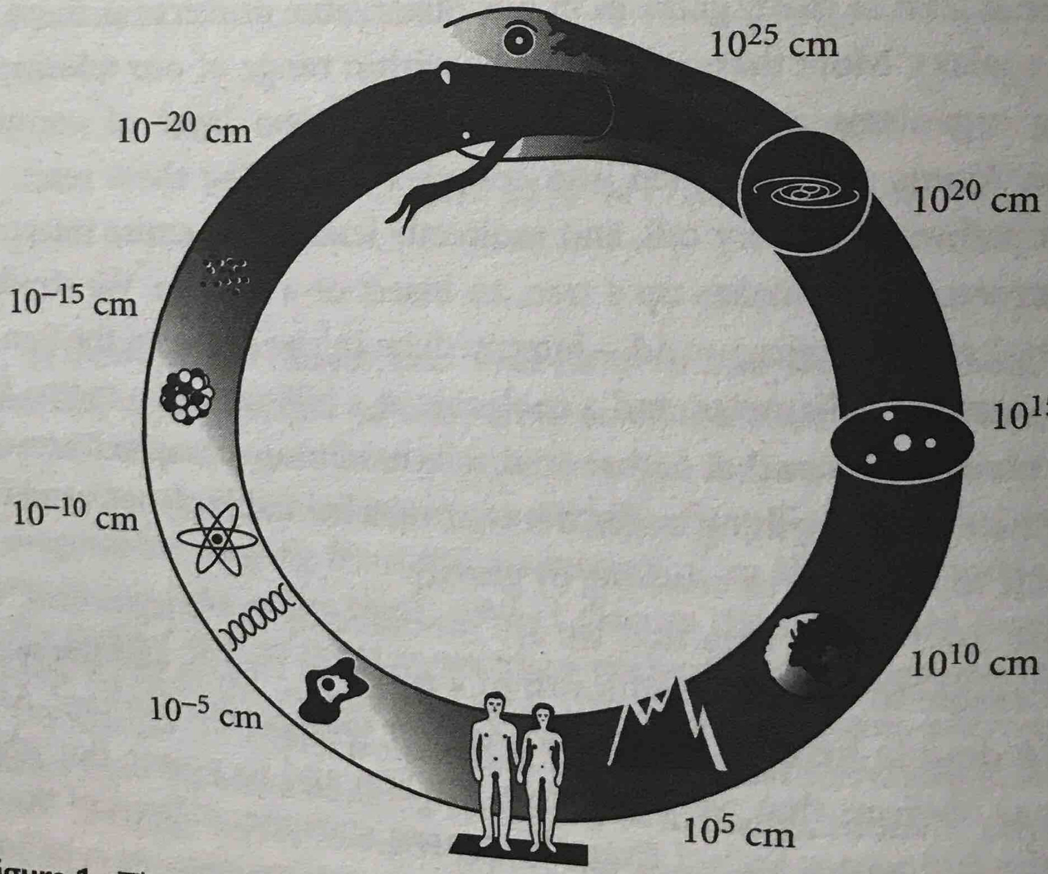

Figure 1. The *ouraborus*. There are links between the microworld of particles, nuclei and atoms (left) and the cosmos (right).

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 ($54=36\times3/2$), 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.

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.

Richard Fortey

from TRILOBITE!

■ Richard Fortey has the same virtues as a palaeontologist, and he loves his trilobites as Simpson loved his mammals and reptiles. This extract is about the wonderful crystalline eyes of the trilobites—and it is already wonderful enough to think that trilobites had eyes at all, so long ago, and to imagine the Palaeozoic coral gardens they gazed upon and the long forgotten fights and flights that their eyes initiated and mediated. Fortey reappears towards the end of this book. ■

Trilobite eyes are made of calcite. This makes them unique in the animal kingdom.

Calcite is one of the most abundant minerals. The white cliffs of Dover are calcite; the bluffs along the Mississippi river are largely calcite; the mountains stacked like giant termite mounds in Guilin Province, China, are composed of calcite that has resisted millennia of weathering. Limestones (which are calcite) have been used to build many of the most monumental and enduring buildings: the sublime crescents of Bath, the pyramids of Gizeh, the amphitheatres and Corinthian columns of classical times. Polished slabs composed of calcite deck the floors of Renaissance churches in Italy, still grace the interiors of Hyatt–Regency hotels, or conference halls, or wherever architects wish to suggest the dignity that only real rock seems to confer. Rubbly limestone builds our rockeries; its finer, whiter counterpart provides the raw material from which great sculpture grows. Only silica sand seems as ubiquitous. Surely one could expect no surprises from a substance so common and so familiar. Yet it was calcite transformed that allowed the trilobite to see.

The purest forms of calcite are transparent. In building stones and decorative slabs it is the impurities and fine crystal masses that provide the colour and design: the yellows and greys and fine mottling.

The dark red of the *scaglio rosso* so typical of Italian church floors is a deep stain of ferric iron. Purge calcite of all these impurities and it is colourless. But it may not be transparent even then. Chalk is almost pure calcite, but it is a mass of tiny grains—fossil fragments most of them—which scatter and reflect the light: hence its almost indecent whiteness. When the Seven Sisters on the southern English coast emerge from a sea mist it is like observing a line of undulating starched sheets, so frigid is their purity. But when a calcite crystal grows more slowly in nature, then it may acquire its perfect crystal form, and be glassy clear. The chemical composition, calcium carbonate ($CaCO_3$), is simple as minerals go. As the crystal grows the constituent atoms stack together in a lopsided way, and do not allow other stray atoms to intrude to cloud its mineral exactitude. Layer builds on layer to reveal the crystalline form, the macrocosm of the gem reflecting exactly the microcosm of atomic sructure. As with the handiwork of a master mason, there is no mistake permissible in the atomic brickwork. Large, fine crystals often grow in mineral veins. These are often rejected by miners in search of rarer booty, for precious metals sometimes hide in grey and opaque minerals that seem dull by comparison with calcite's perfectly formed spar. Some of these crystals are sharply pointed and then are described as dog's tooth spar, looking much like the zig-zag ornament favoured by Norman craftsmen over church doors; others, blunt-tipped, are termed nail head spar. But the clearest crystal, transparent as a toddler's motives, is Iceland spar.

Look into a crystal of Iceland spar and you can see the secret of the trilobite's vision. For trilobites used clear calcite crystals to make lenses in their eyes; in this they were unique. Other arthropods have mostly developed 'soft' eyes, the lenses made of cuticle similar to that constructing the rest of the body. Within this limitation there is enormous variety: many-lensed eyes like those of the fly; large complex eyes such as those of most spiders; eyes that can see in the dark; eyes that function best in brilliant sunshine. The octopus among the molluscs has an eye that is famously like that of backbone-bearing animals, and provides one of the best examples of convergent evolution in the animal kingdom. Most of us will have contemplated the sorry eyes of a dead fish, and remarked the comparison with our own, large, focusing eyes. Trilobites alone have used the transparency of calcite as a means of transmitting light. The trilobite eye is in continuity with the rest of its shelly armour. It sits on top of the cheek of the animal, an *en suite* eyeglass, tough as clamshell.

The science of the eye demands a little explanation. It all depends on the optical properties of calcite, and this depends in turn on its crystallography. If you break a large piece of crystalline calcite it will fracture in a fashion related to its fine atomic structure: such cleavage of the mineral does the bidding of the invisible arrangement of matter itself. You are left with a regular, six-sided chunk of the mineral in your hand, termed a rhomb. Neither foursquare like a cube, nor rectangular like a chunk of chocolate, the sides of a rhomb lean away from the perpendicular. The geometry of mineral shape can be described quite simply by the orientation of a few main axes passing through the centre of the crystal: the simplest case is the cube, in which axes passing through the centre of the faces and meeting at the middle are all at right angles and all the same length. These axes are termed *a*, *b*, and *c*, respectively, a case of science for once taking the simplest route to make a name. In the structure of calcite, one major axis has three axes perpendicular to it set at 120 degrees from one another, hence the configuration of the rhomb. The clear calcite of this not-quite-a-cube treats light in a peculiar way. If a beam of light is shone at the sides of the rhomb it splits in two; this is known as double refraction. The rays of light so produced are the 'ordinary' and the 'extraordinary' rays: their course is determined, just like the shape of the rhomb, by the stacking of the individual atoms. There is a huge specimen of Iceland spar on the first floor of London's Natural History Museum through which you may peer to see two images of a Maltese cross, one generated by the extraordinary, and the other by the ordinary rays. But there is one direction, and one direction only, in which light is not subjected to this optical splitting. This is where a ray of light approaches along the *c* crystallographic axis; from this direction it does not split into two rays at all but passes straight through.

The way that calcite treats light might have remained no more than an odd fact to be trotted out as an esoteric answer in tests of general knowledge. But what the selectivity of the *c* axis guarantees is that light

* Shape
&
one spot
↳ c-axis

approaching from the angle at which it points is specially favoured. If a crystal is elongated in parallel to the *c* axis into the shape of a prism light will still pass unrefracted through the crystal along the long axis of the prism. But light approaching the same prism from other angles will be split into ordinary and extraordinary rays, which will in turn be deflected to reach the edge of the prism, where they might be partly internally reflected, or refracted yet again. When the prism is long enough the *only* light to pass clearly through to the far side of the prism is that which approaches from the direction of the *c* crystallographic axis. To put it the other way round, the light that such a crystal 'sees' approaches from one particular direction. It is an astonishing fact that trilobites have hijacked the special properties of calcite for their own ends. They have crystal eyes.

The eyes of trilobites are composed of elongate prisms of clear calcite. Most eyes have many such prisms stacked side by side. By comparison with dozens of other kinds of arthropods the prisms obviously functioned as individual lenses, in just the same way as a fly's eye is a honeycomb of hexagons, each one a lens—or the dragonfly's, or the lobster's. The trilobite carries on its head another example of such an arthropod compound eye—an eye composed of numerous small ocular units, which had to collaborate to paint a portrait of the world. Each component unit is a lens. The unique difference is that the trilobite's lenses are composed of a rock-forming mineral. It would be no less than the truth to say that the trilobite could give you a stony stare. One is reminded of the strange lines from that strangest of Shakespeare's plays, *The Tempest*:

> Full fathom five thy father lies:
> Of his bones are coral made:
> Those are pearls that were his eyes:
> Nothing of him that doth fade,
> But doth suffer a sea-change
> Into something rich and strange.

light
bounces off
pearls

If to travel back to the time of the trilobite is a historical sea-change then there can be nothing stranger than the calcareous eyes of the trilobite. And pearls are chemically the same as the trilobite's unblinking lenses, being yet another manifestation of calcium carbonate, although pearls are exquisite reflectors of light rather than transmitters of it. The weirdness of Shakespeare's line results from his suggestions of pearly opacity, the hints of a corpse transformed; dead, yet seeing. The trilobite saw the submarine world with eyes tessellated into a mosaic of calcified lenses; unlike the dead seafarer, his stony eyes read the world through the medium of the living rock.

paradox

Colin Blakemore

from THE MIND MACHINE

■ The theme of eyes continues with the next extract by Colin Blakemore, British physiologist and head of the Medical Research Council, who always seems to me to be an incongruous (in the nicest possible way) combination of glamorous whiz kid and eminent elder statesman of science. The use of 'Grandma' as the object perceived in this hypothetical story of a photon is not as arbitrary as it sounds, by the way, but is an in-joke. Ever since the American neurophysiologist Jerry Lettvin epitomized highly specific pattern-detecting neurones as 'grandmother detectors', scientists have used 'Lettvin's grandmother' as an affectionate shorthand for the idea. It is Blakemore's witty tribute to Lettvin to use this vivid image without actually spelling out its history. ■

Sight Unseen

A single atom of gas, baking in the unimaginable heat at the surface of the sun, suddenly shifts from one energy state to another, and spits out the surplus energy as a photon—the smallest, indivisible unit of light. This tiny pellet of energy is thrown into space at the highest speed that Einstein could conceive of. Eight minutes or so after its birth, our chosen photon slows down a little as it hits the atmosphere of the Earth and a fraction of a second later it reaches the surface. It strikes the wrinkled skin of an old woman but, as chance has it, the wavelength of our charmed photon of light is such that it is not captured by the pigments of her skin. It is reflected, and 10 microseconds later it shoots into a tiny black hole, just 3 millimetres across. This hole is the pupil of a man's eye.

The photon slips past the transparent window that covers the front of his eye, through the lens within it and on, between the particles of the gelatinous mass behind the lens, even across the membranes and cytoplasm of the nerve cells of the retina in the back of the eye. But time is running out. It penetrates a strange, thin cell at the back of the retina and its existence ends as it strikes a single molecule of pigment inside that cell, which captures the photon, destroying it by stealing its energy.

'Hello, Grandma.' The man, whose retina has caught our hero, the photon, has recognised his grandmother. He sees her wrinkled face and her blue gingham dress.

She smiles and opens her mouth. As she exhales, the folds of her larynx vibrate as the air rushes past them. Her breath rushes around her moving tongue as it darts skilfully back and forth within her mouth, occasionally touching her lips or her teeth. She is speaking. The rich mixture of tones and noises pulses through the air towards her grandson's head. Some of the vibrating particles in the air are caught by the crevices of his outer ear and funnelled into the narrow tube that leads to his eardrum. They beat on it, setting up a rhythm in a chain of minute bones, which rattle at another membrane, setting up waves in the liquid inside a tiny coiled tube. And these vibrations, in turn, tickle hairs on tiny specialised nerve cells that stand like a regiment of sharp-eared soldiers along the length of the tube. 'Hello dear.' The man hears his grandmother speaking.

This everyday scene sets the stage for a detective story. The detective is the human brain; the story is our perception of the world around us.

KNOWLEDGE FROM MOLECULES AND WAVES

To the inner eye and ear of the conscious mind, our senses give us windows through which we see, hear, touch, taste, and smell the physical world.

The job of the sense organs is to convert light, sound, heat, pressure, and molecules into the tiny electrical impulses that scurry along nerve fibres—their currency of communication. We are blissfully unaware of the machinery of nerves within our sense organs and our brains; all that we know directly is the impression of reality. Perception is an invention of nerve cells inside our heads.

For more than 2000 years, philosophers and scientists have been deceived by the apparent simplicity of perception. The great Greek geometer, Euclid, who lived about 300 BC, thought that we see the world because light flows *out* of the eyes, like an invisible hand, feeling the reality of the physical world. But Plato, who lived 100 years earlier, realised that knowledge—even knowledge of the outside world—comes from *within*. He described a fable, told by Socrates, about people living in a strange underground world:

> Behold! Human beings living in an underground den, which has a mouth open towards the light…Here they have been from their childhood…Above and behind them a fire is blazing at a distance, and between the fire and the prisoners there is a raised path; and you will see, if you look, a low wall built along the path, like the screen which marionette players have in front of them, over which they show the puppets.

Socrates described the way in which the human beings trapped in the cave could see the people and objects that were out of sight behind the wall only by virtue of the flickering shadows of them thrown on the opposite wall of the cave by the light of the fire. In such a frightful world, Socrates said that 'the truth would be literally nothing but the shadows of the images'. He went on to explain his allegory: 'The prison-house is the world of sight, the light of the fire is the sun.' And so it is; our understanding of the world around us comes from the merest echoes of reality—the photons of light that bombard the eye, the vibrations in the air that strike the ear, the floating molecules that rush into the nostrils.

Aristotle, the first great biologist, wrote that each sense organ 'receives the form of the object without its matter'. The immaterial qualities (such as colour, shape and smell) of physical things in the world strike the sense organs and evoke the perception of the world. Galileo's eyes, peering through his telescope at the heavens, changed our entire understanding of the universe, yet he wrote, in 1623, fourteen years before he lost his sight, that sensations 'are nothing more than names when separated from living beings, just as tickling and titillation are nothing but names in the absence of such things as noses and armpits'.

PICTURES IN THE HEAD

How, then, can nerve cells create our knowledge of the world? To start to answer that question, we can peer backwards in time and downwards through the animal world to simple creatures with no more than a few thousand neurons to help them find their food, avoid their enemies and manage their lives. Any animal that moves must understand something of the world around it. Many simple animals *detect* light but learn little from it: they merely move towards or away from the light, depending on their particular style of life. The light-sensitive nerve cells in the human retina, on which those photons that enter the pupil fall, can also do nothing more than signal the intensity of light. All the richness of our visual perceptions, all the information needed to recognise a grandmother's face, comes from those tiny cells in the retina that know nothing but the number of photons hitting them.