Alister Hardy

from THE OPEN SEA

▪ The oceans cover more than 70 per cent of our planet's surface. The majority of the Sun's photons that are available for photosynthesis fall in the sea, where, in the green cells of the phytoplankton, they drive chemical reactions 'uphill' (thermodynamically speaking) and synthesize carbon compounds that later fuel the ecosystems. Nobody had a better feel for the great rolling pastures, sunlit green meadows and waving prairies of *The Open Sea* than Alister Hardy, my first professor. His paintings for that book still adorn the corridors of the Oxford Zoology Department, and the images seem to dance with enthusiasm, just as the old man himself danced boyishly around the lecture hall, a strabismically beaming cross between Peter Pan and the Ancient Mariner. Yea, slimy things did crawl with legs upon the slimy sea—and across the blackboard in coloured chalk with Sir Alister bobbing and weaving in pursuit. In this extract, he lights up the page with his description of the remarkable phenomenon of marine phosphorescence. ▪

Some of the general phosphorescence of the sea may possibly be caused at times by bacteria, but it is usually due to vast numbers of little flagellates. The Dinoflagellates, such as *Ceratium* and *Peridinium* and the aberrant globular form *Noctiluca*, give rise to the most brilliant displays of this general lighting up of the sea. If you like fireworks it is always an entertaining experience to take a rowboat out on a dark night when some of these little flagellates are really abundant, as they often are in August and September. Every time the oar touches the sea there is a splash of flame, and as it is drawn through the water it leaves a trail of fire behind it—as does the boat itself. Let Charles Darwin give his account of such a night when on his famous voyage of the *Beagle*; it is an entry in his journal under the date of 6 December 1833:

> While sailing a little south of the Plata on one very dark night, the sea presented a wonderful and most beautiful spectacle. There was a fresh breeze, and every part of the surface, which during the day is seen as foam, now glowed with a pale light. The vessel drove before her bows two billows of liquid phosphorus, and in her wake she was followed by a milky train. As far as the eye reached, the crest of every wave was bright, and the sky above the horizon, from the reflected glare of these livid flames, was not so utterly obscure as over the vault of the heavens.

There is, of course, no need to voyage across the world to see such displays—sometimes they may be equally brilliant in our own seas. I have already described how I once saw every fish in a small shoal outlined in 'fire' and it is not at all rare to see, especially in late summer, every wave breaking on the beach with a flash of pale greenish light. The little flagellates flash with light whenever they are violently agitated. Mr George Atkinson of Lowestoft recently told me of an interesting occurrence during the first world war. A zeppelin dropped some bombs which exploded in the sea a mile or two from land; after each explosion there was a flash of phosphorescence through the sea along the shore on which he was standing.

Among the coelenterates many of the small hydroid medusae are said to be luminous, and among the larger jellyfish there is a very striking example in *Pelagia noctiluca* already referred to.

It is the comb-jellies—the Ctenophora—which give us some of the most spectacular displays of brilliant flashing light in our waters.... They are nearly all capable of emitting sudden vivid flashes. The sea is often full of very small young specimens, each of which may give off quite a bright flash. They are excellent animals to use for demonstrations of spontaneous luminescence. A plankton sample containing these animals can nearly always be relied upon to give a good show—but we must remember that they do not perform at all until they have been in the dark for almost twenty minutes. If you intend to show your friends a good display you must keep your sample of plankton completely covered with light-proof cloth, or in a light-proof cupboard, for this length of time before bringing it out for exhibition in the darkened room.

As a young student I once had an amusing demonstration of this inhibitory effect of light. I had gone over to Brightlingsea to hunt at low tide in the thick Essex mud for the rare and curious worm-like animal *Priapulus*. It was nearly dark before I had found any and it was too late to return to Oxford that night, so I put up at a very old inn where I slept in a four-poster bed in an oak-panelled room. After a strenuous day digging in the mud I retired early and soon dropped to sleep after blowing out my candle. Later in the night I was awakened by some reveller coming noisily to bed in the room next door. I opened my eyes and blinked them with astonishment, for a number of little blue lights were bobbing about in the darkness just over the end of my bed. It was as if there were a lot of little goblins dancing up and down in the air. Before coming to bed I had of course celebrated the finding of *Priapulus*—but only with a pint of bitter; clearly there must be some more objective explanation! I struck a match and lit the candle. I now saw that, level with the end of my bed, was the top of the chimney-piece on which I had placed a row of large glass jars filled with sea-water, with a little mud at the bottom of each containing my precious animals. Getting up and switching on the electric light I examined them closely and then saw that the water was full of very young ctenophores—*Pleurobrachia*, I think—actively swimming up and down. They had certainly not been flashing when I first turned out the light and got into bed; nor were there any flashes when I settled into bed for the second time—or rather not at once. I was now well awake, and it was some time before I could get off to sleep again; before I did so, after about twenty minutes in the dark, the little 'blue devils' began their dance again.

Loren Eiseley

from 'HOW FLOWERS CHANGED THE WORLD'

Rachel Carson's exact contemporary Loren Eiseley was another American scientist with a flair for lyrical writing. His style derives its poetry from the science itself, and from the author's scientifically informed imagination. This passage from an essay in *The Immense Journey* encourages the reader's poetic response to a watershed event in the history of the world, the rise of the flowering plants. All poets know that flowers are beautiful, but not all poets get the important point—also articulated by the physicist Richard Feynman:

> The beauty that is there for you is also available for me, too. But I see a deeper beauty that isn't so readily available to others. I can see the complicated interactions of the flower. The color of the flower is red. Does the fact that the plant has color mean that it evolved to attract insects? This adds a further question. Can insects see color? Do they have an aesthetic sense? And so on. I don't see how studying a flower ever detracts from its beauty. It only adds.

Feynman here spoke for all scientists (though, alas, most insect eyes don't see red), but Loren Eiseley perhaps expressed it better.

When the first simple flower bloomed on some raw upland late in the Dinosaur Age, it was wind pollinated, just like its early pine-cone relatives. It was a very inconspicuous flower because it had not yet evolved the idea of using the surer attraction of birds and insects to achieve the transportation of pollen. It sowed its own pollen and received the pollen of other flowers by the simple vagaries of the wind. Many plants in regions where insect life is scant still follow this principle today. Nevertheless, the true flower—and the seed that it produced—was a profound innovation in the world of life.

In a way, this event parallels, in the plant world, what happened among animals. Consider the relative chance for survival of the exteriorly deposited egg of a fish in contrast with the fertilized egg of a mammal, carefully retained for months in the mother's body until the young animal (or human being) is developed to a point where it may survive. The biological wastage is less—and so it is with the flowering plants. The primitive spore, a single cell fertilized in the beginning by a swimming sperm, did not promote rapid distribution, and the young plant, moreover, had to struggle up from nothing. No one had left it any food except what it could get by its own unaided efforts.

By contrast, the true flowering plants (angiosperm itself means 'encased seed') grew a seed in the heart of a flower, a seed whose development was initiated by a fertilizing pollen grain independent of outside moisture. But the seed, unlike the developing spore, is already a fully equipped *embryonic plant* packed in a little enclosed box stuffed full of nutritious food. Moreover, by featherdown attachments, as in dandelion or milkweed seed, it can be wafted upward on gusts and ride the wind for miles; or with hooks it can cling to a bear's or a rabbit's hide; or like some of the berries, it can be covered with a juicy, attractive fruit to lure birds, pass undigested through their intestinal tracts and be voided miles away.

The ramifications of this biological invention were endless. Plants traveled as they had never traveled before. They got into strange environments heretofore never entered by the old spore plants or stiff pine-cone-seed plants. The well-fed, carefully cherished little embryos raised their heads everywhere. Many of the older plants with more primitive reproductive mechanisms began to fade away under this unequal contest. They contracted their range into secluded environments. Some, like the giant redwoods, lingered on as relics; many vanished entirely.

The world of the giants was a dying world. These fantastic little seeds skipping and hopping and flying about the woods and valleys brought with them an amazing adaptability. If our whole lives had not been spent in the midst of it, it would astound us. The old, stiff, sky-reaching wooden world had changed into something that glowed here and there with strange colors, put out queer, unheard-of fruits and little intricately carved seed cases, and, most important of all, produced concentrated foods in a way that the land had never seen before, or dreamed of back in the fish-eating, leaf-crunching days of the dinosaurs.

That food came from three sources, all produced by the reproductive system of the flowering plants. There were the tantalizing nectars and pollens intended to draw insects for pollenizing purposes, and which are responsible also for that wonderful jeweled creation, the hummingbird. There were the juicy and enticing fruits to attract larger animals, and in which tough-coated seeds were concealed, as in the tomato, for example. Then, as if this were not enough, there was the food in the actual seed itself, the food intended to nourish the embryo. All over the world, like hot corn in a popper, these incredible elaborations of the flowering plants kept exploding. In a movement that was almost instantaneous, geologically speaking, the angiosperms had taken over the world. Grass was beginning to cover the bare earth until, today, there are over six thousand species. All kinds of vines and bushes squirmed and writhed under new trees with flying seeds.

The explosion was having its effect on animal life also. Specialized groups of insects were arising to feed on the new sources of food and, incidentally and unknowingly, to pollinate the plant. The flowers bloomed and bloomed in ever larger and more spectacular varieties. Some were pale unearthly night flowers intended to lure moths in the evening twilight, some among the orchids even took the shape of female spiders in order to attract wandering males, some flamed redly in the light of noon or twinkled modestly in the meadow grasses. Intricate mechanisms splashed pollen on the breasts of hummingbirds, or stamped it on the bellies of black, grumbling bees droning assiduously from blossom to blossom. Honey ran, insects multiplied, and even the descendants of that toothed and ancient lizard-bird had become strangely altered. Equipped with prodding beaks instead of biting teeth they pecked the seeds and gobbled the insects that were really converted nectar.

Across the planet grasslands were now spreading. A slow continental upthrust which had been a part of the early Age of Flowers had cooled the world's climates. The stalking reptiles and the leather-winged black imps of the seashore cliffs had vanished. Only birds roamed the air now, hot-blooded and high-speed metabolic machines.

The mammals, too, had survived and were venturing into new domains, staring about perhaps a bit bewildered at their sudden eminence now that the thunder lizards were gone, Many of them, beginning as small browsers upon leaves in the forest, began to venture out upon this new sunlit world of the grass. Grass has a high silica content and demands a new type of very tough and resistant tooth enamel, but the seeds taken incidentally in the cropping of the grass are highly nutritious. A new world had opened out for the warm-blooded mammals. Great herbivores like the mammoths, horses and bisons appeared. Skulking about them had arisen savage flesh-feeding carnivores like the now extinct dire wolves and the saber-toothed tiger.

Flesh eaters though these creatures were, they were being sustained on nutritious grasses one step removed. Their fierce energy was being maintained on a high, effective level, through hot days and frosty nights, by the concentrated energy of the angiosperms. That energy, thirty per cent or more of the weight of the entire plant among some of the cereal grasses, was being accumulated and concentrated in the rich proteins and fats of the enormous game herds of the grasslands.

On the edge of the forest, a strange, old-fashioned animal still hesitated. His body was the body of a tree dweller, and though tough and knotty by human standards, he was, in terms of that world into which he gazed, a weakling. His teeth, though strong for chewing on the tough fruits of the forest, or for crunching an occasional unwary bird caught with his prehensile hands, were not the tearing sabers of the great cats. He had a passion for lifting himself up to see about, in his restless, roving curiosity. He would run a little stiffly and uncertainly, perhaps, on his hind legs, but only in those rare moments when he ventured out upon the ground. All this was the legacy of his climbing days; he had a hand with flexible fingers and no fine specialized hoofs upon which to gallop like the wind.

If he had any idea of competing in that new world, he had better forget it; teeth or hooves, he was much too late for either. He was a ne'er-do-well, an in-betweener. Nature had not done well by him. It was as if she had hesitated and never quite made up her mind. Perhaps as a consequence he had a malicious gleam in his eye, the gleam of an outcast who has been left nothing and knows he is going to have to take what he gets. One day a little band of these odd apes—for apes they were—shambled out upon the grass; the human story had begun.

Apes were to become men, in the inscrutable wisdom of nature, because flowers had produced seeds and fruits in such tremendous quantities that a new and totally different store of energy had become available in concentrated form. Impressive as the slow-moving, dim-brained dinosaurs had been, it is doubtful if their age had supported anything like the diversity of life that now rioted across the planet or flashed in and out among the trees. Down on the grass by a streamside, one of those apes with inquisitive fingers turned over a stone and hefted it vaguely. The group clucked together in a throaty tongue and moved off through the tall grass foraging for seeds and insects. The one still held, sniffed, and hefted the stone he had found. He liked the feel of it in his fingers. The attack on the animal world was about to begin.

If one could run the story of that first human group like a speeded-up motion picture through a million years of time, one might see the stone in the hand change to the flint ax and the torch. All that swarming grassland world with its giant bison and trumpeting mammoths would go down in ruin to feed the insatiable and growing numbers of a carnivore who, like the great cats before him, was taking his energy indirectly from the grass. Later he found fire and it altered the tough meats and drained their energy even faster into a stomach ill adapted for the ferocious turn man's habits had taken.

His limbs grew longer, he strode more purposefully over the grass. The stolen energy that would take man across the continents would fail him at last. The great Ice Age herds were destined to vanish. When they did so, another hand like the hand that grasped the stone by the river long ago would pluck a handful of grass seed and hold it contemplatively.

In that moment, the golden towers of man, his swarming millions, his turning wheels, the vast learning of his packed libraries, would glimmer dimly there in the ancestor of wheat, a few seeds held in a muddy hand. Without the gift of flowers and the infinite diversity of their fruits, man and bird, if they had continued to exist at all, would be today unrecognizable. Archaeopteryx, the lizard-bird, might still be snapping at beetles on a sequoia limb; man might still be a nocturnal insectivore gnawing a roach in the dark. The weight of a petal has changed the face of the world and made it ours.

C. P. Snow

from the Foreword to G. H. Hardy's
A MATHEMATICIAN'S APOLOGY

C. P. Snow was better known as a novelist than as a scientist, one of rather few novelists who included sympathetically familiar portraits of scientists. The following extract is not fiction, but is from Snow's biographical Foreword to *A Mathematician's Apology*, the mathematician being the eccentric, cricket-loving G. H. Hardy, from whom we shall hear later. Snow tells the tale of how Hardy discovered the Indian mathematical genius Ramanujan and brought him to Cambridge. Hardy had earlier been a Fellow of my own college at Oxford, where he seems to have been a party to most of the low stake wagers that can still be seen in the Betting Book of the Senior Common Room. The following is typical: 'The subwarden bets Professor Hardy his fortune till death to one halfpenny that the sun will rise tomorrow (7th Feb 1923).' A couple of days later Hardy took the same bet again, but the odds had shortened significantly—for reasons at which we can only guess. This time it was only half his fortune till death, against one whole penny.

About his discovery of Ramanujan, Hardy showed no secrecy at all. It was, he wrote, the one romantic incident in his life: anyway, it is an admirable story, and one which showers credit on nearly everyone (with two exceptions) in it. One morning early in 1913, he found, among the letters on his breakfast table, a large untidy envelope decorated with Indian stamps. When he opened it, he found sheets of paper by no means fresh, on which, in a non-English holograph, were line after line of symbols. Hardy glanced at them without enthusiasm. He was by this time, at the age of thirty-six, a world famous mathematician: and world famous mathematicians, he had already discovered, are unusually exposed to cranks. He was accustomed to receiving manuscripts from strangers, proving the prophetic wisdom of the Great Pyramid, the revelations of the Elders of Zion, or the cryptograms that Bacon had inserted in the plays of the so-called Shakespeare.

So Hardy felt, more than anything, bored. He glanced at the letter, written in halting English, signed by an unknown Indian, asking him to give an opinion of these mathematical discoveries. The script appeared to consist of theorems, most of them wild or fantastic looking, one or two already well-known, laid out as though they were original. There were no proofs of any kind. Hardy was not only bored, but irritated. It seemed like a curious kind of fraud. He put the manuscript aside, and went on with his day's routine. Since that routine did not vary throughout his life, it is possible to reconstruct it. First he read *The Times* over his breakfast. This happened in January, and if there were any Australian cricket scores, he would start with them, studied with clarity and intense attention.

Maynard Keynes, who began his career as a mathematician and who was a friend of Hardy's, once scolded him: if he had read the stock exchange quotations half an hour each day with the same concentration he brought to the cricket scores, he could not have helped becoming a rich man.

Then, from about nine to one, unless he was giving a lecture, he worked at his own mathematics. Four hours creative work a day is about the limit for a mathematician, he used to say. Lunch, a light meal, in hall. After lunch he loped off for a game of real tennis in the university court. (If it had been summer, he would have walked down to Fenner's to watch cricket.) In the late afternoon, a stroll back to his rooms. That particular day, though, while the timetable wasn't altered, internally things were not going according to plan. At the back of his mind, getting in the way of his complete pleasure in his game, the Indian manuscript nagged away. Wild theorems. Theorems such as he had never seen before, nor imagined. A fraud of genius? A question was forming itself in his mind. As it was Hardy's mind, the question was forming itself with epigrammatic clarity: is a fraud of genius more probable than an unknown mathematician of genius? Clearly the answer was no. Back in his rooms in Trinity, he had another look at the script. He sent word to Littlewood (probably by messenger, certainly not by telephone, for which, like all mechanical contrivances including fountain pens, he had a deep distrust) that they must have a discussion after hall.

When the meal was over, there may have been a slight delay. Hardy liked a glass of wine, but, despite the glorious vistas of 'Alan St. Aubyn' which had fired his youthful imagination, he found he did not really enjoy lingering in the combination-room over port and walnuts. Littlewood, a good deal more *homme moyen sensuel*, did. So there may have been a delay. Anyway, by nine o'clock or so they were in one of Hardy's rooms, with the manuscript stretched out in front of them.

That is an occasion at which one would have liked to be present. Hardy, with his combination of remorseless clarity and intellectual panache (he was very English, but in argument he showed the characteristics that Latin minds have often assumed to be their own): and Littlewood, imaginative, powerful, humorous. Apparently it did not take them long. Before midnight they knew, and knew for certain. The writer of these manuscripts was a man of genius. That was as much as they could judge, that night. It was only later that Hardy decided that Ramanujan was, in terms of *natural* mathematical genius, in the class of Gauss and Euler: but that he could not expect, because of the defects of his education, and because he had come on the scene too late in the line of mathematical history, to make a contribution on the same scale.

It all sounds easy, the kind of judgment great mathematicians should have been able to make. But I mentioned that there were two persons who do not come out of the story with credit. Out of chivalry Hardy concealed this in all that he said or wrote about Ramanujan. The two people concerned have now been dead, however, for many years, and it is time to tell the truth. It is simple. Hardy was not the first eminent mathematician to be sent the Ramanujan manuscripts. There had been two before him, both English, both of the highest professional standard. They had each returned the manuscripts without comment. I don't think history relates what they said, if anything, when Ramanujan became famous. Anyone who has been sent unsolicited material will have a sneaking sympathy with them.

Anyway, the following day Hardy went into action. Ramanujan must be brought to England, he decided. Money was not a major problem. Trinity has usually been good at supporting unorthodox talent (the college did the same for Kapitsa a few years later). Once Hardy was determined, no human agency could have stopped Ramanujan, but they needed a certain amount of help from a superhuman one.

Ramanujan turned out to be a poor clerk in Madras, living with his wife on twenty pounds a year. But he was also a Brahmin, unusually strict about his religious observances, with a mother who was even stricter. It seemed impossible that he could break the proscriptions and cross the water. Fortunately his mother had the highest respect for the goddess of Namakkal. One morning Ramanujan's mother made a startling announcement. She had had a dream on the previous night, in which she saw her son seated in a big hall among a group of Europeans, and the goddess of Namakkal had commanded her not to stand in the way of her son fulfilling his life's purpose. This, say Ramanujan's Indian biographers, was a very agreeable surprise to all concerned.

In 1914 Ramanujan arrived in England. So far as Hardy could detect (though in this respect I should not trust his insight far) Ramanujan, despite the difficulties of breaking the caste proscriptions, did not believe much in theological doctrine, except for a vague pantheistic benevolence, any more than Hardy did himself. But he did certainly believe in ritual. When Trinity put him up in college—within four years he became a Fellow—there was no 'Alan St. Aubyn' apolausticity for him at all. Hardy used to find him ritually changed into his pyjamas, cooking vegetables rather miserably in a frying pan in his own room.

Their association was a strangely touching one. Hardy did not forget that he was in the presence of genius: but genius that was, even in mathematics, almost untrained. Ramanujan had not been able to enter Madras University because he could not matriculate in English. According to Hardy's report, he was always amiable and good-natured, but no doubt he sometimes found Hardy's conversation outside mathematics more than a little baffling. He seems to have listened with a patient smile on his good, friendly, homely face. Even inside mathematics they had to come to terms with the difference in their education. Ramanujan was self-taught: he knew nothing of the modern rigour: in a sense he didn't know what a proof was. In an uncharacteristically sloppy moment, Hardy once wrote that if he had been better educated, he would have been less Ramanujan. Coming back to his ironic senses, Hardy later corrected himself and said that the statement was nonsense. If Ramanujan had been better educated, he would have been even more wonderful than he was. In fact, Hardy was obliged to teach him some formal mathematics as though Ramanujan had been a scholarship candidate at Winchester. Hardy said that this was the most singular experience of his life: what did modern mathematics look like to someone who had the deepest insight, but who had literally never heard of most of it?

Anyway, they produced together five papers of the highest class, in which Hardy showed supreme originality of his own (more is known of the details of this collaboration than of the Hardy–Littlewood one). Generosity and imagination were, for once, rewarded in full.

This is a story of human virtue. Once people had started behaving well, they went on behaving better. It is good to remember that England gave Ramanujan such honours as were possible. The Royal Society elected him a Fellow at the age of 30 (which, even for a mathematician, is very young). Trinity also elected him a Fellow in the same year. He was the first Indian to be given either of these distinctions. He was amiably grateful. But he soon became ill. It was difficult, in war-time, to move him to a kinder climate.

Hardy used to visit him, as he lay dying in hospital at Putney. It was on one of those visits that there happened the incident of the taxi-cab number. Hardy had gone out to Putney by taxi, as usual his chosen method of conveyance. He went into the room where Ramanujan was lying. Hardy, always inept about introducing a conversation, said, probably without a greeting, and certainly as his first remark: 'I thought the number of my taxicab was 1729. It seemed to me rather a dull number.' To which Ramanujan replied: 'No, Hardy! No, Hardy! It is a very interesting number. It is the smallest number expressible as the sum of two cubes in two different ways.'

That is the exchange as Hardy recorded it. It must be substantially accurate. He was the most honest of men; and further, no one could possibly have invented it.

Max F. Perutz

'A PASSION FOR CRYSTALS'

X-ray crystallography is the subtle technique by which we know the three-dimensional structure of large biological molecules. Pioneered by William and Lawrence Bragg (the only father and son team to share a Nobel Prize), it was developed further by the physicist J. D. ('Sage') Bernal and then brought to triumphant fruition by a group of younger physicists turned biologist mentored by Bernal or by the younger Bragg. Max Perutz and Dorothy Hodgkin were two of the several Nobel-prizewinning crystallographers associated with Bernal. Here Perutz, in *I wish I'd made you angry earlier*, paints a picture of Dorothy Hodgkin, and of her science. Perutz, originally from Austria, was one of the leading lights of that extraordinary powerhouse of scientific achievement, which he helped to found, the MRC Laboratory of Molecular Biology at Cambridge. Dorothy Hodgkin was Oxford's most distinguished crystallographer. To my regret, I scarcely knew her, but I remember seeing her around the Oxford science labs, an awe-inspiring figure of serene dignity but with tragically arthritic hands. Perutz gives us a warm and affectionate portrait, as befits the gentle and reflective author and his equally gentle subject, both scientists of enormous distinction and becoming modesty.

In October 1964, the *Daily Mail* carried a headline 'Grandmother wins Nobel Prize'. Dorothy Hodgkin won it 'for her determination by X-ray techniques of the structures of biologically important molecules'.

She used a physical method first developed by W. L. Bragg, X-ray crystallography, to find the arrangements of the atoms in simple salts and minerals. She had the courage, skill, and sheer willpower to extend the method to compounds that were far more complex than anything attempted before. The most important of these were cholesterol, vitamin D, penicillin, and vitamin B_{12}. Later, she was most famous for her work on insulin, but this reached its climax only five years after she had won the prize.

In the early 1940s, when Howard Florey and Ernest Chain had isolated penicillin from Alexander Fleming's mould, some of the best chemists in Britain and the United States tried to find its chemical constitution. They were taken aback when a handsome young woman, using not chemistry but X-ray analysis, then still mistrusted as an upstart physical technique, had the face to tell them what it was. When Dorothy Hodgkin insisted that its core was a ring of three carbon atoms and a nitrogen which was believed to be too unstable to exist, one of the chemists, John Cornforth, exclaimed angrily, 'If that's the formula of penicillin, I'll give up chemistry and grow mushrooms'. Fortunately he swallowed his words and won the Chemistry Prize himself 30 years later. Hodgkin's formula proved right and was the starting-point for the synthesis of chemically modified penicillins that have saved many lives.

Pernicious anaemia used to be deadly until the early 1930s when it was discovered that it could be kept in check by liver extracts. In 1948, the active principle, vitamin B_{12}, was isolated from liver in crystalline form, and chemists began to wonder what its formula was. The first X-ray diffraction pictures showed that the vitamin contained over a thousand atoms, compared to penicillin's thirty-nine; it took Hodgkin and an army of helpers eight years to solve its structure. Like penicillin, vitamin B_{12} showed chemical features not encountered before, such as a strange ring of nitrogens and carbon atoms surrounding its central cobalt atom and a novel kind of bond from the cobalt atom to the carbon atoms of a sugar ring that provided the clue to the vitamin's biological function. The Nobel Prize was awarded to Hodgkin not just for determining the structures of several vitally important compounds, but also for extending the bounds of chemistry itself.

In 1935 Dorothy Crowfoot, as she then was, put a crystal of insulin in front of an X-ray beam and placed a photographic film behind it. That night, when she developed the film, she saw minute, regularly arranged spots forming a diffraction pattern that held out the prospect of solving insulin's structure. Later that night she wandered around the streets of Oxford, madly excited that she might be the first to determine the structure of a protein, but next morning she woke with a start: could she be sure that her crystals really were insulin rather than some trivial salt? She rushed back to the lab before breakfast. A simple spot test on a microscope slide showed that her crystals took up a stain characteristic for protein, which revived her hopes. She never imagined that it would take her thirty-four years to solve that complex structure, nor that once solved it would have practical application. It has recently enabled genetic engineers to change the chemistry of insulin in order to improve its benefits for diabetics.

Dorothy Crowfoot was born in Cairo in 1910. Her father, J. W. Crowfoot, was Education Officer in Khartoum and an archaeologist; her mother too was an archaeologist, with a particular interest in the history of weaving. When Dorothy was a child, they lived next door to the Sudan Government chemist, Dr A. F. Joseph. It was 'Uncle Joseph's' early encouragement that excited her interest in science. Later he introduced her to the Cambridge Professor of Physical Chemistry, T. Martin Lowry, who advised her to work with J. D. Bernal.

When Dorothy Crowfoot was 24 and working in Cambridge with Bernal on crystals of another protein, the digestive enzyme pepsin, Bernal made his crucial discovery of their rich X-ray diffraction patterns.. But, on the day that he did, her parents had taken her to London to consult a specialist about persistent pains in her hands. He diagnosed the onset of the rheumatoid arthritis that was to cripple her hands and feet, but never slowed her determined pursuit of science.

At Oxford, Dorothy Hodgkin used to labour on the structure of life in a crypt-like room tucked away in a corner of Ruskin's Cathedral of Science, the Oxford Museum. Her Gothic window was high above, as in a monk's cell, and beneath it was a gallery reachable only by a ladder. Up there she would mount her crystals for X-ray analysis, and descend precariously, clutching her treasure with one hand and balancing herself on the ladder with the other. For all its gloomy setting, Hodgkin's lab was a jolly place. As Chemistry Tutor at Somerville College, she always had girls doing crystal structures for their fourth year and two or three research students of either sex working for their PhDs. They were a cheerful lot, not just because they were young, but because her gentle and affectionate guidance led most of them on to interesting results. Her best-known pupil, however, made her name in a career other than chemistry: Margaret Roberts, later Margaret Thatcher, worked as a fourth-year student on X-ray crystallography in Dorothy Hodgkin's laboratory.

In 1937, Dorothy had married the historian Thomas Hodgkin. Some women intellectuals regard their children as distracting impediments to their careers, but Dorothy radiated motherly warmth even while doing scientific work. Concentration came to her so easily that she could give all her attention to a child's chatter at one moment and switch to complex calculation the next.

She pursued her crystallographic studies, not for the sake of honours, but because this was what she liked to do. There was magic about her person. She had no enemies, not even among those whose scientific theories she demolished or whose political views she opposed. Just as her X-ray cameras bared the intrinsic beauty beneath the rough surface of things, so the warmth and gentleness of her approach to people uncovered in everyone, even the most hardened scientific crook, some hidden kernel of goodness. She was once asked in a BBC radio interview whether she felt handicapped in her career by being a woman. 'As a matter fact,' she replied gently, 'men were always particularly nice and helpful to me *because* I was a woman.' At scientific meetings she would seem lost in a dream, until she suddenly came out with some penetrating remark, usually made in a diffident tone of voice, and followed by a little laugh, as if wanting to excuse herself for having put everyone else to shame.

Dorothy Hodgkin's uncanny knack of solving difficult structures came from a combination of manual skill, mathematical ability, and profound knowledge of crystallography and chemistry. It often led her and her alone to recognise what the initially blurred maps emerging from X-ray analysis were trying to tell. She was a great chemist; a saintly, gentle, and tolerant lover of people; and a devoted protagonist of peace.

Francis Crick

from WHAT MAD PURSUIT

Francis Crick's autobiography is called *What Mad Pursuit*. I wrote the following for its jacket blurb:

> Francis Crick's is the dominant intellect from the heroic age of molecular biology when authors-per-paper could be counted on one hand and

> heroic individual intelligence could still dominate. We expect brilliance from his book and we get it, together with mature wisdom. What we may not expect—but also get—is a generous and charming modesty that belies the famous opening sentence of an alternative volume. This modesty is personal and does not preclude a justified pride, almost arrogance, on behalf of a discipline—molecular biology—that earned the right to be arrogant by cutting the philosophical claptrap, getting its head down, and in short order solving many of the outstanding problems of life. Francis Crick seems to epitomize the ruthlessly successful science that he did so much to found.

The 'alternative volume' I had in mind was, of course, *The Double Helix*. Here I have reprinted Crick's own personal response to the discovery of the double helix and to its aftermath, ending with a delightful anecdote about Jim Watson trying to explain DNA after dinner. ■

What was it like to live with the double helix? I think we realized almost immediately that we had stumbled onto something important. According to Jim, I went into the Eagle, the pub across the road where we lunched every day, and told everyone that we'd discovered the secret of life. Of that I have no recollection, but I do recall going home and telling Odile that we seemed to have made a big discovery. Years later she told me that she hadn't believed a word of it. 'You were always coming home and saying things like that,' she said, 'so naturally I thought nothing of it.' Bragg was in bed with flu at the time, but as soon as he saw the model and grasped the basic idea he was immediately enthusiastic. All past differences were forgiven and he became one of our strongest supporters. We had a constant stream of visitors, a contingent from Oxford that included Sydney Brenner, so that Jim soon began to tire of my repetitious enthusiasm. In fact at times he had cold feet, thinking that perhaps it was all a pipe dream, but the experimental data from King's College, when we finally saw them, were a great encouragement. By summer most of our doubts had vanished and we were able to take a long cool look at the structure, sorting out its accidental features (which were somewhat inaccurate) from its really fundamental properties, which time has shown to be correct.

For a number of years after that, things were fairly quiet. I named my family's Cambridge house in Portugal Place 'The Golden Helix' and eventually erected a simple brass helix on the front of it, though it was a single helix rather than a double one. It was supposed to symbolize not DNA but the basic idea of a helix. I called it golden in the same way that Apuleius called his story 'The Golden Ass', meaning beautiful. People have often asked me whether I intend to gild it, but we never got further than painting it yellow.

Finally one should perhaps ask the personal question—am I glad that it happened as it did? I can only answer that I enjoyed every moment of it, the downs as well as the ups. It certainly helped me in my subsequent propaganda for the genetic code. But to convey my own feelings, I cannot do better than quote from a brilliant and perceptive lecture I heard years ago in Cambridge by the painter John Minton in which he said of his own artistic creations, 'The important thing is to be there when the picture is painted'. And this, it seems to me, is partly a matter of luck and partly good judgement, inspiration, and persistent application.

There was in the early fifties a small, somewhat exclusive biophysics club at Cambridge, called the Hardy Club, named after a Cambridge zoologist of a previous generation who had turned physical chemist. The list of those early members now has an illustrious ring, replete with Nobel laureates and Fellows of the Royal Society, but in those days we were all fairly young and most of us not particularly well known. We boasted only one F.R.S.—Alan Hodgkin—and one member of the House of Lords—Victor Rothschild. Jim was asked to give an evening talk to this select gathering. The speaker was customarily given dinner first at Peterhouse. The food there was always good but the speaker was also plied with sherry before dinner, wine with it, and, if he was so rash as to accept them, drinks after dinner as well. I have seen more than one speaker struggling to find his way into his topic through a haze of alcohol. Jim was no exception. In spite of it all he managed to give a fairly adequate description of the main points of the structure and the evidence supporting it, but when he came to sum up he was quite overcome and at a loss for words. He gazed at the model, slightly bleary-eyed. All he could manage to say was 'It's so beautiful, you see, so beautiful!' But then, of course, it was.

Carl Sagan

from THE DEMON-HAUNTED WORLD

Carl Sagan inspired a whole generation of young scientists, especially in America, and his death from cancer in 1996 was a grievous loss to science and the whole world of reality-based thinking. Open any one of his books and you need go no further than the Table of Contents to experience the tingling of the poetic nerve endings that will continue throughout the book: The shores of the cosmic ocean...One voice in the cosmic fugue...The harmony of worlds...The backbone of night...The edge of forever...Who speaks for Earth? Carl Sagan himself would be a good candidate for the answer to the last question. Quite apart from his contributions to public understanding and appreciation of science, Sagan's own research contributions to planetary science would have been fully enough to ensure his election to the National Academy of Sciences, and it is widely believed that envy at his massive success in communicating science to the millions was the direct cause of his being blackballed for election to the Academy. Parallel to his poetic evocations of the universe, Sagan was also an influential voice against superstition and paranormal mumbo jumbo of all kinds. Debunking is often thought to be a killjoy activity: unsexy, necessary but poor box-office. I have never understood this attitude although I have often encountered it. Carl Sagan eloquently belies it in his marvellous book *The Demon-Haunted World* from which the following excerpt is taken.

[Science] is more than a body of knowledge; it is a way of thinking. I have a foreboding of an America in my children's or grandchildren's time—when the United States is a service and information economy; when nearly all the key manufacturing industries have slipped away to other countries; when awesome technological powers are in the hands of a very few, and no one representing the public interest can even grasp the issues; when the people have lost the ability to set their own agendas or knowledgeably question those in authority; when, clutching our crystals and nervously consulting our horoscopes, our critical faculties in decline, unable to distinguish between what feels good and what's true, we slide, almost without noticing, back into superstition and darkness. The dumbing down of America is most evident in the slow decay of substantive content in the enormously influential media, the 30-second sound bites (now down to 10 seconds or less), lowest common denominator programming, credulous presentations on pseudoscience and superstition, but especially a kind of celebration of ignorance.

[...]

We've arranged a global civilization in which most crucial elements—transportation, communications, and all other industries; agriculture, medicine, education, entertainment, protecting the environment; and even the key democratic institution of voting—profoundly depend on science and technology. We have also arranged things so that almost no one understands science and technology. This is a prescription for disaster. We might get away with it for a while, but sooner or later this combustible mixture of ignorance and power is going to blow up in our faces.

A Candle in the Dark is the title of a courageous, largely Biblically based, book by Thomas Ady, published in London in 1656, attacking the witch-hunts then in progress as a scam 'to delude the people'. Any illness or storm, anything out of the ordinary, was popularly attributed to witchcraft. Witches must exist, Ady quoted the 'witchmongers' as arguing, 'else how should these things be, or come to pass?' For much of our history, we were so fearful of the outside world, with its unpredictable dangers, that we gladly embraced anything that promised to soften or explain away the terror. Science is an attempt, largely successful, to understand the world, to get a grip on things, to get hold of ourselves, to steer a safe course. Microbiology and meteorology now explain what only a few centuries ago was considered sufficient cause to burn women to death.

Ady also warned of the danger that 'the Nations [will] perish for lack of knowledge'. Avoidable human misery is more often caused not so much by stupidity as by ignorance, particularly our ignorance about ourselves. I worry that, especially as the millennium edges nearer, pseudoscience and superstition will seem year by year more tempting, the siren song of unreason more sonorous and attractive. Where have we heard it before? Whenever our ethnic or national prejudices are aroused, in times of scarcity, during challenges to national self-esteem or nerve, when we agonize about our diminished cosmic place and purpose, or when fanaticism is bubbling up around us—then, habits of thought familiar from ages past reach for the controls.

The candle flame gutters. Its little pool of light trembles. Darkness gathers. The demons begin to stir.

There is much that science doesn't understand, many mysteries still to be resolved. In a Universe tens of billions of light years across and some ten or fifteen billion years old, this may be the case forever. We are constantly stumbling on surprises. Yet some New Age and religious writers assert that scientists believe that 'what they find is all there is'. Scientists may reject mystic revelations for which there is no evidence except somebody's say-so, but they hardly believe their knowledge of Nature to be complete.

Science is far from a perfect instrument of knowledge. It's just the best we have. In this respect, as in many others, it's like democracy. Science by itself cannot advocate courses of human action, but it can certainly illuminate the possible consequences of alternative courses of action.

The scientific way of thinking is at once imaginative and disciplined. This is central to its success. Science invites us to let the facts in, even when they don't conform to our preconceptions. It counsels us to carry alternative hypotheses in our heads and see which best fit the facts. It urges on us a delicate balance between no-holds-barred openness to new ideas, however heretical, and the most rigorous sceptical scrutiny of everything—new ideas and established wisdom. This kind of thinking is also an essential tool for a democracy in an age of change.

One of the reasons for its success is that science has built-in, error-correcting machinery at its very heart. Some may consider this an overbroad characterization, but to me every time we exercise self-criticism, every time we test our ideas against the outside world, we are doing science. When we are self-indulgent and uncritical, when we confuse hopes and facts, we slide into pseudoscience and superstition.

Every time a scientific paper presents a bit of data, it's accompanied by an error bar—a quiet but insistent reminder that no knowledge is complete or perfect. It's a calibration of how much we trust what we think we know. If the error bars are small, the accuracy of our empirical knowledge is high; if the error bars are large, then so is the uncertainty in our knowledge. Except in pure mathematics nothing is known for certain (although much is certainly false).

Moreover, scientists are usually careful to characterize the veridical status of their attempts to understand the world—ranging from conjectures and hypotheses, which are highly tentative, all the way up to laws of Nature which are repeatedly and systematically confirmed through many interrogations of how the world works. But even laws of Nature are not absolutely certain. There may be new circumstances never before examined—inside black holes, say, or within the electron, or close to the speed of light—where even our vaunted laws of Nature break down and, however valid they may be in ordinary circumstances, need correction.

Humans may crave absolute certainty; they may aspire to it; they may pretend, as partisans of certain religions do, to have attained it. But the history of science—by far the most successful claim to knowledge accessible to humans—teaches that the most we can hope for is successive improvement in our understanding, learning from our mistakes, an asymptotic approach to the Universe, but with the proviso that absolute certainty will always elude us.

We will always be mired in error. The most each generation can hope for is to reduce the error bars a little, and to add to the body of data to which error bars apply. The error bar is a pervasive, visible self-assessment of the reliability of our knowledge. You often see error bars in public opinion polls (‘an uncertainty of plus or minus three per cent’, say). Imagine a society in which every speech in the *Congressional Record*, every television commercial, every sermon had an accompanying error bar or its equivalent.

One of the great commandments of science is, ‘Mistrust arguments from authority’. (Scientists, being primates, and thus given to dominance hierarchies, of course do not always follow this commandment.) Too many such arguments have proved too painfully wrong. Authorities must prove their contentions like everybody else. This independence of science, its occasional unwillingness to accept conventional wisdom, makes it dangerous to doctrines less self-critical, or with pretensions to certitude.

Because science carries us toward an understanding of how the world is, rather than how we would wish it to be, its findings may not in all cases be immediately comprehensible or satisfying. It may take a little work to restructure our mindsets. Some of science is very simple. When it gets complicated, that's usually because the world is complicated—or because *we're* complicated. When we shy away from it because it seems too difficult (or because we've been taught so poorly), we surrender the ability to take charge of our future. We are disenfranchised. Our self-confidence erodes.

But when we pass beyond the barrier, when the findings and methods of science get through to us, when we understand and put this knowledge to use, many feel deep satisfaction. This is true for everyone, but especially for children—born with a zest for knowledge, aware that they must live in a future moulded by science, but so often convinced in their adolescence that science is not for them. I know personally, both from having science explained to me and from my attempts to explain it to others, how gratifying it is when we get it, when obscure terms suddenly take on meaning, when we grasp what all the fuss is about, when deep wonders are revealed.

In its encounter with Nature, science invariably elicits a sense of reverence and awe. The very act of understanding is a celebration of joining, merging, even if on a very modest scale, with the magnificence of the Cosmos. And the cumulative worldwide build-up of knowledge over time converts science into something only a little short of a trans-national, trans-generational meta-mind.

'Spirit' comes from the Latin word 'to breathe'. What we breathe is air, which is certainly matter, however thin. Despite usage to the contrary, there is no necessary implication in the word 'spiritual' that we are talking of anything other than matter (including the matter of which the brain is made), or anything outside the realm of science. On occasion, I will feel free to use the word. Science is not only compatible with spirituality; it is a profound source of spirituality. When we recognize our place in an immensity of light years and in the passage of ages, when we grasp the intricacy, beauty and subtlety of life, then that soaring feeling, that sense of elation and humility combined, is surely spiritual. So are our emotions in the presence of great art or music or literature, or of acts of exemplary selfless courage such as those of Mohandas Gandhi or Martin Luther King Jr. The notion that science and spirituality are somehow mutually exclusive does a disservice to both.