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BARCODES IN THE STARS

*Nor ever yet
The melting rainbow's vernal-tinctur'd hues
To me have shone so pleasing, as when first
The hand of science pointed out the path
In which the sun-beams gleaming from the west
Fall on the wat'ry cloud, whose darksome veil
Involves the orient, and that trickling show'r
Piercing thro' every crystalline convex
Of clust'ring dew-drops to their flight oppos'd,
Recoil at length where concave all behind
Th'internal surface of each glassy orb
Repells their forward passage into air;
That thence direct they seek the radiant goal
From which their course began; and as they strike
In diff'rent lines the gazer's obvious eye,
Assume a diff'rent lustre, thro' the brede
Of colours changing from the splendid rose
To the pale violet's dejected hue.*

MARK AKENSIDE,
The Pleasures of Imagination (1744)

In December 1817 the English painter and critic Benjamin Haydon introduced John Keats to William Wordsworth at dinner in his London studio, together with Charles Lamb and others of the English literary circle. On view was Haydon's new painting of Christ entering Jerusalem, attended

by the figures of Newton as a believer and Voltaire as a sceptic. Lamb, drunk, upbraided Haydon for painting Newton, 'a fellow who believed nothing unless it was as clear as the three sides of a triangle'. Newton, Keats agreed with Lamb, had destroyed all the poetry of the rainbow, by reducing it to the prismatic colours. 'It was impossible to resist him,' said Haydon, 'and we all drank "Newton's health, and confusion to mathematics".' Years later, Haydon recalled this 'immortal dinner' in a letter to Wordsworth, his fellow survivor.

And don't you remember Keats proposing 'Confusion to the memory of Newton', and upon your insisting on an explanation before you drank it, his saying, 'Because he destroyed the poetry of the rainbow by reducing it to a prism? Ah, my dear old friend, you and I shall never see such days again!

Haydon,
Autobiography and Memoirs

Three years after Haydon's dinner, in his long poem 'Lamia' (1820), Keats wrote:

*Do not all charms fly
At the mere touch of cold philosophy?
There was an awful rainbow once in heaven:
We know her woof, her texture; she is given
In the dull catalogue of common things.
Philosophy will clip an Angel's wings,
Conquer all mysteries by rule and line,
Empty the haunted air, and gnomed mine –
Unweave a rainbow . . .*

Wordsworth had better regard for science, and for Newton ('Voyaging through strange seas of thought, alone'). He also, in his preface to the *Lyrical Ballads* (1802), anticipated a time when 'The remotest discoveries of the chemist, the botanist, or mineralogist, will be as proper objects of the poet's art as any upon which it can be employed'.

His collaborator Coleridge said elsewhere that 'the souls of 500 Sir Isaac Newtons would go to the making up of a Shakespeare or a Milton'. This can be interpreted as the naked hostility of a leading Romantic against science in general, but the case of Coleridge is more complicated. He read a great deal of science and fancied himself as a scientific thinker, not least on the subject of light and colour, where he claimed to have anticipated Goethe. Some of Coleridge's scientific speculations have turned out to be plagiarisms, and he perhaps showed poor judgement over whom to plagiarize. It was not scientists in general that Coleridge anathematized, but Newton in particular. He had a high regard for Sir Humphry Davy, whose lectures he attended at the Royal Institution 'in order to renew my stock of metaphors'. He felt that Davy's discoveries, compared with Newton's, were 'more intellectual, more ennobling and empowering human nature'. His use of words like ennobling and empowering suggests that Coleridge's heart might have been in the right place with respect to science, if not with respect to Newton. But he failed to live up to his own ideals 'to unfold and arrange' his ideas in 'distinct, clear and communicable conceptions'. On the subject of the spectrum and unweaving the rainbow itself, in a letter of 1817 he became almost beside himself with confusion:

To me, I confess, Newton's positions, first, of a Ray of Light, as a physical synodical Individuum, secondly, that 7 specific individua are co-existent (by what copula?) in this complex yet divisible Ray; thirdly that the Prism is a mere mechanic Dissector of this Ray; and lastly, that Light, as the common result, is = confusion.

In another 1817 letter, Coleridge warms to his theme:

So again Colour is Gravitation under the power of Light, Yellow being the positive, blue the negative Pole, and Red the culmination

or Equator; while Sound on the other hand is Light under the power or paramountcy of Gravitation.

Perhaps Coleridge was simply born too early to be a post-modernist:

The figure/ground distinction prevalent in Gravity's Rainbow is also evident in Vineland, although in a more self-supporting sense. Thus Derrida uses the term 'subsemioticist cultural theory' to denote the role of the reader as poet. Thus, the subject is contextualized into a postcultural capitalist theory that includes language as a paradox.

This is from <http://www.cs.monash.edu.au/links/postmodern.html> where a literally infinite quantity of similar nonsense can be found. The meaningless wordplays of modish francophone *savants*, splendidly exposed in Alan Sokal and Jean Bricmont's *Intellectual Impostures* (1998), seem to have no other function than to impress the gullible. They don't even want to be understood. A colleague confessed to an American devotee of post-modernism that she found his book very difficult to understand. 'Oh, thank you very much,' he smiled, obviously delighted at the compliment. Coleridge's scientific ramblings, by contrast, seem to show some genuine, if incoherent, desire to understand the world around him. We must set him on one side as a unique anomaly, and move on.

Why, in Keats's 'Lamia', is the philosophy of rule and line 'cold', and why do all charms flee before it? What is so threatening about reason? Mysteries do not lose their poetry when solved. Quite the contrary; the solution often turns out more beautiful than the puzzle and, in any case, when you have solved one mystery you uncover others, perhaps to inspire greater poetry. The distinguished theoretical physicist Richard Feynman was charged by a friend that a scientist misses the beauty of a flower by studying it. Feynman responded:

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.

from 'Remembering Richard Feynman', *The Skeptical Inquirer* (1988)

Newton's dissection of the rainbow into light of different wavelengths led on to Maxwell's theory of electromagnetism and thence to Einstein's theory of special relativity. If you think the rainbow has poetic mystery, you should try relativity. Einstein himself openly made aesthetic judgements in science, and perhaps went too far. 'The most beautiful thing we can experience,' he said, 'is the mysterious. It is the source of all true art and science.' Sir Arthur Eddington, whose own scientific writings were noted for poetic flair, used the solar eclipse of 1919 to test General Relativity and returned from Principe Island to announce, in Banesh Hoffmann's phrase, that Germany was host to the greatest scientist of the age. I read those words with a catch in the throat, but Einstein himself took the triumph in his stride. Any other result and he would have been 'sorry for the dear Lord. The theory is correct.'

Isaac Newton made a private rainbow in a dark room. A small hole in a shutter admitted a sunbeam. In its path he placed his famous prism, which refracted (bent) the sunbeam through an angle, once as it penetrated the glass, then again as it passed through the farther facet into the air again. When the light fell on the far wall of Newton's room, the colours of the spectrum were clearly displayed. Newton was not the first to make an artificial rainbow with a prism, but he was the first to use it to demonstrate that white light is a mixture of different colours. The prism sorts them out by bending them through different angles, blue through a steeper angle than red; green, yellow and orange through

intermediate angles. Others had, understandably, thought that a prism changed the quality of the light, positively tinting it rather than separating the colours out of an existing mixture. Newton clinched the matter in two experiments in which the light passed through a second prism. In his '*experimentum crucis*', beyond the first prism he placed a slit which allowed only a small part of the spectrum to pass, say, the red portion. When this red light was again refracted by a second prism, only red light emerged. This showed that light is not qualitatively changed by a prism, merely separated out into components which would normally be mixed. In his other clinching experiment, Newton turned the second prism upside down. The spectral colours that had been fanned out by the first prism were brought together again by the second. What emerged was reconstituted white light.

The easiest way to understand the spectrum is through the wave theory of light. The thing about waves is that nothing actually travels all the way from source to destination. Such motion as there is, is local and small scale. Local motion triggers motion in the next local patch and so on, all the way along the line, like the famous football stadium wave. The original wave theory of light was in turn supplanted by the quantum theory, according to which light is delivered as a stream of discrete photons. Physicists that I have pressed admit that photons stream away from the sun in a way that football fans do not travel from one end of the stadium to the other. Nevertheless, ingenious experiments in this century have shown that even in the quantum theory photons still behave like waves too. For many purposes, including ours in this chapter, we can forget quantum theory and treat light simply as waves propagating outwards from a light source, like ripples in a pond when a pebble is thrown in. But light waves travel incomparably faster and are broadcast in three dimensions. To unweave the rainbow is to separate it into its components of different wavelengths. White light is a scrambled mixture of wavelengths, a visual cacophony. White objects reflect light of all wavelengths but, unlike

mirrors, they scatter it into incoherence as they do so. This is why you see light, but not your face, reflected from a white wall. Black objects absorb light of all wavelengths. Coloured objects, by reason of the atomic structures of their pigments or surface layers, absorb light of some wavelengths and reflect other wavelengths. Plain glass allows light of all wavelengths to pass straight through it. Coloured glass transmits light of some wavelengths while absorbing light of other wavelengths.

What is it about the bending action of a glass prism or, under the right conditions, a drop of rain, that splits white light into its separate colours? And anyway, why are light beams bent by glass and water at all? The bending results from a slowing down of the light as it moves from air into glass (or water). It speeds up again as it emerges from the glass. How can this be, given Einstein's dictum that the velocity of light is the great physical constant of the universe, and nothing can go faster? The answer is that light's legendary full speed, represented by the symbol c , is attained only in a vacuum. When light travels through a transparent substance like glass or water, it is slowed down by a factor known as the 'refractive index' of that substance. It is slowed down by air, too, but less so.

But why does slowing down translate into a change of angle? If the light beam is pointing straight into a glass block, it will continue at the same angle (dead ahead) but slowed down. However, if it breaks the surface at an oblique angle, it is deflected to a shallower angle as it starts to travel more slowly. Why? Physicists have coined a 'Principle of Least Action' which, if not entirely satisfying as an ultimate explanation, at least makes it something we can empathize with. The matter is well explained in Peter Atkins's *Creation Revisited* (1992). Some physical entity, in this case a beam of light, behaves as if it is striving for economy, trying to minimize something. Imagine yourself a lifesaver on a beach, racing to save a drowning child. Every second counts, and you must take as little time as possible to reach the child. You can run faster than you

can swim. Your course towards the child is initially over land and therefore fast, then through water and so much slower. Assuming that the child is not straight out to sea from where you are standing, how do you minimize your travel time? You could take the beeline direction, minimizing distance, but this wouldn't minimize the time taken because it leaves too much of the journey in water. You could run straight to that point on the sea's edge which is immediately opposite the child, then swim straight out to sea. This maximizes running at the expense of swimming, but even this is not quite the fastest course because of the greater total distance travelled. It is easy to see that the swiftest course is to run to the shore at a critical angle, which depends upon the ratio of your running speed to your swimming speed, then switch abruptly to a new angle for the swimming part of the journey. In terms of the analogy, swimming speed and running speed correspond to the refractive index of water and the refractive index of air. Of course light beams aren't deliberately 'trying' to minimize their travel time, but everything about their behaviour makes sense if you assume that they are doing the unconscious equivalent. The analogy can be made respectable in terms of quantum theory, but that is beyond my scope here and I recommend Atkins's book.

The spectrum depends upon light of different colours being slowed by different amounts: the refractive index of a given substance, say glass or water, is greater for blue light than for red. You could think of blue light as being a slower swimmer than red, getting tangled up in the undergrowth of atoms in glass or water because of its short wavelength. Light of all colours gets less tangled up among the sparser atoms of air, but blue still travels more slowly than red. In a vacuum, where there is no undergrowth at all, light of all colours has the same velocity: the great, universal maximum c .

Raindrops have a more complicated effect than Newton's prism. Being roughly spherical, their back surface acts as a concave mirror. So they reflect the sunlight after refracting it, which is why we see the rainbow in the part of the sky opposite the sun, rather than

when looking towards the sun through rain. Imagine that you are standing with your back to the sun, looking towards a shower of rain, preferably with a leaden background. We shan't see a rainbow if the sun is higher in the sky than 42 degrees above the horizon. The lower the sun, the higher the rainbow. As the sun rises in the morning, the rainbow, if one is visible, sets. As the sun sets in the evening, the rainbow rises. So let's assume that it is early morning or late afternoon. Think about a particular raindrop as a sphere. The sun is behind and slightly above you, and light from it enters the raindrop. At the boundary of air with water it is refracted and the different wavelengths that make up the sun's light are bent through different angles, as in Newton's prism. The fanned-out colours go through the interior of the raindrop until they hit its concave far wall, where there they are reflected, back and down. They leave the raindrop again and some of them end up at your eye. As they pass from water back into air they are refracted for a second time, the different colours again being bent through different angles.

So, a complete spectrum – red, orange, yellow, green, blue, violet – leaves our single raindrop, and a similar one leaves the other raindrops in the vicinity. But from any one raindrop, only a small part of the spectrum hits your eye. If your eye gets a beam of green light from one particular raindrop, the blue light from that raindrop goes above your eye, and the red light from that particular raindrop goes below. So, why do you see a complete rainbow? Because there are lots of different raindrops. A band of thousands of raindrops is giving you green light (and simultaneously giving blue light to anybody who might be suitably placed above you, and simultaneously giving red light to somebody else below you). Another band of thousands of raindrops is giving you red light (and giving somebody else blue light . . .), another band of thousands of raindrops is giving you blue light, and so on. The raindrops delivering red light to you are all at a fixed distance from you – which is why the red band is curved (you are the centre of the circle). The raindrops delivering green light to you are also at a fixed distance

from you, but it is a shorter one. So the circle on which they sit has a smaller radius and the green curve sits inside the red curve. Then the blue curve sits inside that, and the whole rainbow is built up as a series of circles with you at the centre. Other observers will see different rainbows centred on themselves.

So, far from the rainbow being rooted at a particular 'place' where fairies might deposit a crock of gold, there are as many rainbows as there are eyes looking at the storm. Different observers, looking at the same shower from different places, will piece together their own separate rainbows using light from different collections of raindrops. Strictly speaking, even your two eyes are seeing two different rainbows. And as we drive along a road looking at 'one' rainbow, we are actually seeing a series of rainbows in quick succession. I think that if Wordsworth had realized all this, he might have improved upon 'My heart leaps up when I behold/A rainbow in the sky' (although I have to say it would be hard to improve on the lines that follow).

A further complication is that the raindrops themselves are falling, or blowing about. So any particular raindrop might pass through the band that is delivering, say, red light to you then move into the yellow region. But you continue to see the red band, as if nothing had moved, because new raindrops come to take the places of the departed ones. Richard Whelan, in his lovely *Book of Rainbows* (1997), which is the source of many of my rainbow quotations, quotes Leonardo da Vinci on the subject:

Observe the rays of the sun in the composition of the rainbow, the colours of which are generated by the falling rain, when each drop in its descent takes every colour of the bow.

Treatise on Painting (1490s)

The illusion of the rainbow itself remains rock steady, although the drops that deliver it are falling and scurrying about in the wind. Coleridge wrote,

UNWEAVING THE RAINBOW

*The steadfast rainbow in the fast-moving, fast-hurrying hail-mist.
What a congregation of images and feelings, of fantastic permanence
amidst the rapid change of tempest – quietness the daughter of storm.*

from *Anima Poetae* (published 1895)

His friend Wordsworth, too, was fascinated by the immobility of the rainbow in the face of turbulent movement of the rain itself:

*Meanwhile, by what strange chance I cannot tell,
What combination of the wind and clouds,
A large unmutilated rainbow stood
Immovable in heaven.* *The Prelude* (1815)

Part of the romance of the rainbow comes from the illusion that it is always perched on the horizon far away, a huge curve unattainably receding as we approach. But Keats's 'rainbow of the salt sand-wave' was near. And you can sometimes see a rainbow as a complete circle only a few feet in diameter, racing along the near side of a hedge as you drive by. (Rainbows look semicircular only because the horizon gets in the way of the lower part of the circle.) A rainbow looks so big partly because of an illusion of distance. The brain projects the image outwards on to the sky, aggrandizing it. You can achieve the same effect by staring at a bright lamp to 'stamp' its after-image on to your retina, then 'projecting' it into the distance by staring at the sky. This makes it look large.

There are other delightful complications. I said that light from the sun enters a raindrop through the upper quadrant of the surface facing the sun, and leaves through the lower quadrant. But of course there is nothing to stop sunlight entering the lower quadrant. Under the right conditions, it can then be reflected *twice* round the inside of the sphere, leaving the lower quadrant of the drop in such a way as to enter the observer's eye, also refracted, to produce a second rainbow, 8 degrees higher than the first, with the colours reversed. Of course, for any given observer, the two rainbows are

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delivered by different populations of raindrops. One doesn't often see a double rainbow, but Wordsworth must have done so on occasion, and his heart surely leaped up even higher when he did. Theoretically, there may also be other, yet fainter rainbows arranged concentrically, but they are very seldom seen. Could anyone seriously suggest that it *spoils* it to be told what is going on inside all those thousands of falling, sparkling, reflecting and refracting populations of raindrops? Ruskin said in *Modern Painters III* (1856):

For most men, an ignorant enjoyment is better than an informed one; it is better to conceive the sky as a blue dome than a dark cavity, and the cloud as a golden throne than a sleety mist. I much question whether anyone who knows optics, however religious he may be, can feel in equal degree the pleasure or reverence which an unlettered peasant may feel at the sight of a rainbow . . . We cannot fathom the mystery of a single flower, nor is it intended that we should; but that the pursuit of science should constantly be stayed by the love of beauty, and accuracy of knowledge by tenderness of emotion.

Somehow this all lends plausibility to the theory that poor Ruskin's wedding night was ruined by the horrifying discovery that women have pubic hair.

In 1802, fifteen years before Haydon's 'immortal dinner', the English physicist William Wollaston did a similar experiment to Newton's, but his sunbeam had to pass through a narrow slit before it hit his prism. The spectrum that emerged from the prism was built up as a series of narrow strips of different wavelength. The strips smeared into each other to make a spectrum but, scattered along the spectrum, he saw narrow, dark lines in particular places. These lines were later measured and systematically catalogued by the German physicist Joseph von Fraunhofer, after whom they are now called. The Fraunhofer lines have a characteristic disposition, a fingerprint – or barcode is an even apter analogy – which depends upon the chemical nature of the substance through which

the rays have passed. Hydrogen, for example, produces its own characteristic barcode pattern of lines and spaces, sodium a different pattern, and so on. Wollaston saw only seven lines, Fraunhofer's superior instruments revealed 576, and modern spectroscopes about 10,000.

The barcode fingerprint of an element resides not just in the spacing of the lines but in their positioning against the rainbow background. The precise barcodes of hydrogen and all elements are now accurately explained by the quantum theory, but this is where I have to make my excuses and leave. Sometimes I imagine that I have some appreciation of the poetry of quantum theory, but I have yet to achieve an understanding deep enough to explain it to others. Actually, it may be that nobody really understands quantum theory, possibly because natural selection shaped our brains to survive in a world of large, slow things, where quantum effects are smothered. This point is well made by Richard Feynman, who is also supposed to have said, 'If you think you understand quantum theory – you don't understand quantum theory!' I think I have been brought closest to understanding by Feynman's published lectures, and by David Deutsch's astonishing and disturbing book, *The Fabric of Reality* (1997). (I find it additionally disturbing because I cannot tell when I am reading generally accepted physics, versus the author's own daring speculations). Whatever a physicist's doubts about how to interpret quantum theory, nobody doubts its phenomenal success in predicting detailed experimental results. And happily, for the purpose of this chapter, it is enough to know, as we have known since Fraunhofer's time, that each of the chemical elements reliably exhibits a unique barcode of characteristically spaced fine lines, branded across the spectrum.

There are two ways in which Fraunhofer lines may be seen. So far I've mentioned dark lines on a rainbow background. These are caused because an element in the path of light absorbs particular wavelengths, selectively removing them from the rainbow as seen. But an equivalent pattern of bright coloured lines against a dark

background is produced if the same element is caused to glow, as when it forms part of the make-up of a star.

Fraunhofer's refinement of Newton's unweaving was already known before the French philosopher Auguste Comte rashly wrote, of the stars:

We shall never be able to study, by any method, their chemical composition or their mineralogical structure . . . Our positive knowledge of stars is necessarily limited to their geometric and mechanical phenomena.

Cours de philosophie positive (1835)

Today, by meticulous analysis of Fraunhofer barcodes in starlight, we know in great detail what the stars are made of, although our prospects of visiting them are hardly any better than they were in Comte's time. A few years ago, my friend Charles Simonyi had a discussion with a former chairman of the US Federal Reserve Bank. This gentleman was aware that scientists had been surprised when NASA discovered what the moon was really made of. Since the moon was so much closer than the stars, he reasoned, our guesses about the stars are likely to be even more wrong. Sounds plausible but, as Dr Simonyi was able to tell him, the truth is exactly the opposite. No matter how far away the stars may be, they emit their own light, and that makes all the difference. Moonlight is all reflected sunlight (a fact which D. H. Lawrence is said to have refused to believe: it offended his poetic sensibilities), so its spectrum doesn't help us to analyse the moon's chemical nature.

Modern instruments spectacularly outperform Newton's prism, but today's science of spectroscopy is the direct descendant of his unweaving of the rainbow. The spectrum of a star's emitted light, especially its Fraunhofer lines, tells us in great detail which chemical substances are present in a star. It also tells us the temperature, the pressure and the size of the star. It is the basis of an exhaustive classification of the natural history of stars. It puts our sun in its proper place in the great catalogue of stars: a Class G2V Yellow

Dwarf. To quote a popular magazine of astronomy, *Sky and Telescope*, from 1996:

To those who can read its meaning, the spectral code tells at a glance just what kind of object the star is – its color, size, and luminosity, its history and future, its peculiarities, and how it compares with the Sun and stars of all other types.

By unweaving starlight in spectroscopes we know that stars are nuclear furnaces, fusing helium out of the hydrogen that dominates their mass; then thrusting helium nuclei together in the further cascade of impurities which make up most of the rest of the elements, forging the medium-sized atoms of which we are eventually made.

Newton's unweaving paved the way for the nineteenth-century discovery that the visible rainbow, the band that we actually see, is a narrow chink in the full spectrum of electromagnetic waves. Visible light spans the wavelengths from 0.4 millionths of a metre (violet) to 0.7 millionths of a metre (deep red). A little longer than red are infrared rays, which we perceive as invisible heat radiation and which some snakes and guided missiles use to home in on their targets. A little shorter than violet are ultraviolet rays, which burn our skin and give us cancer. Radio waves are much longer than red light. Their wavelengths are measured in centimetres, metres, even thousands of metres. Between them and infrared waves on the spectrum lie microwaves, which we use for radar and for high-speed cooking. Shorter than ultraviolet rays are X-rays, which we use for seeing bone through flesh. Shortest of all are gamma rays, with a wavelength measured in trillionths of a metre. There is nothing special about the narrow band of wavelengths that we call light, apart from the fact that we can see it. For insects, visible light is shifted bodily along the spectrum. Ultraviolet is for them a visible colour ('bee purple'), and they are blind to red (which they might call 'infra yellow'). Radiation all along the larger spectrum can be unwoven in the same kind of way as the rainbow, although the par-

ticular instrument we use for the unweaving – a radio tuner instead of a prism, for instance – is different in different parts of the spectrum.

The colours that we actually experience, the subjective sensations of redness and blueness, are arbitrary labels that our brains tie to light of different wavelengths. There is nothing intrinsically 'long' about redness. Knowing how red and blue look doesn't help us remember which wavelength is longer. I regularly have to look it up, whereas I never forget that soprano sounds have a shorter wavelength than bass. The brain needs convenient internal labels for the different parts of the physical rainbow. Nobody knows if my sensation of redness matches yours, but we can easily agree that the light that I call red is the same as the light that you call red and that, if a physicist measures it, it will be found to have a long wavelength. My subjective judgement is that violet looks redder than blue does, even though it lies further away on the spectrum from red. Probably you agree. The apparent reddish tinge in violet is a fact about nervous systems, not a fact about the physics of spectrums.

Hugh Lofting's immortal Doctor Dolittle flew to the moon and was startled to see a dazzling range of new colours, as different from our familiar colours as red is from blue. Even in fiction we can be sure that this would never happen. The hues that would greet any traveller to another world would be a function of the brains that they bring with them from the home planet.*

* Colour is a rich source of philosophical speculation, which is often scientifically under-informed. A laudable attempt to rectify this is C. L. Hardin's 1988 book, *Color for Philosophers: Unweaving the Rainbow*. I am embarrassed to say that I discovered this book, and in particular its excellent subtitle, only after mine had gone off to the publishers. Doctor Dolittle, by the way, may be hard to find, as he is now often banned by pompously correct librarians. They worry about the racism in *The Story of Doctor Dolittle*, but this was all but universal in the 1920s. In any case it is offset by the Doctor's splendid fight against the slave trade in *Doctor Dolittle's Post Office*, and, more profoundly, by the stand that all the Doctor Dolittle books make against the vice of speciesism which is as unquestioned today as racism was in earlier times.

We know now in some detail how the eye informs the brain about the wavelengths of light. It is a three-colour code, as used in colour television. The human retina has four kinds of light-sensitive cell: three kinds of 'cones' plus the 'rods'. All four are similar and have surely diverged from a common ancestor. One of the things it is easy to forget about any sort of cell is how intricately complicated even a single cell is, much of the complexity being built up of fine-folded internal membranes. Each tiny rod or cone contains a deep stack of membranes, packed like a tall column of books. Threaded back and forth through each book is a long, thin molecule, a protein called rhodopsin. Like many proteins, rhodopsin behave as an enzyme, catalysing a particular chemical reaction by providing correctly shaped place for particular molecules to slot in.

It is the three-dimensional form of an enzyme molecule which gives it its catalytic property, serving as a carefully shaped, albeit slightly flexible, template for other molecules to fit in and meet one another — otherwise they'd have to rely on bumping into each other by chance (which is why enzymes so dramatically speed up chemical reactions). The elegance of this system is one of the key things that makes life possible, but it does raise a problem. Enzyme molecules are often capable of coiling into more than one shape, and usually only one of them is desirable. Much of the work of natural selection over the millions of years has been to find 'decisive' or 'single-minded' molecules whose 'preference' for their favoured shape is much stronger than their tendency to coil into any other shape. Molecules with two alternative shapes can be a tragic menace. 'Mad cow disease', sheep scrapie and their human counterparts Kuru and Creutzfeldt-Jakob disease, are caused by proteins called prions which have two alternative shapes. They normally fold into one of the two shapes, and in this configuration they do a useful job. But occasionally they adopt the alternative shape. And then a terrible thing happens. The presence of one protein with the alternative shape induces others to come over to the rogue persuasion. An epidemic of misshapen proteins sweeps through the

body like a cascade of falling dominoes. A single misshapen protein can infect a new body and trigger a new domino run. The consequence is death from spongy holes in the brain, because the protein in its alternative shape cannot do its normal job.

Prions have caused some confusion because they spread like self-replicating viruses, yet they are proteins, and proteins aren't supposed to be self-replicating. Textbooks of biology would have it that self-replication is the unique privilege of polynucleotides (DNA and RNA). However, prions are self-replicating only in the peculiar sense of one misshapen rogue molecule 'persuading' its already existing neighbours to flip into the same shape.

In other cases, enzymes with two alternative shapes turn their switchability to good account. Switchability is, after all, the essential property of transistors, diodes and the other high-speed electronic gates that make the logical operations of computers — IF, NOT, AND, OR and the like — possible. There are 'allosteric' proteins that flip from state to state in a transistor-like way, not through infectious 'persuasion' by a neighbour, as in prions, but only IF some biologically useful condition is met, AND NOT under certain other conditions. Rhodopsin is one of these 'transistor' proteins which make good use of their property of having two alternative shapes. Like a photocell, it flips from one state to the other when it is hit by light. It automatically clicks back to the previous shape after a brief recovery period. In one of its two shapes it is a powerful catalyst, but not in the other. So, when light causes it to snap into its active shape, this initiates a special chain reaction and a rapid turnover of molecules. It is as if the light had switched on a high-pressure tap.

The end product of the resulting chemical cascade is a stream of nerve impulses which are relayed to the brain via a series of nerve cells, each of which is a long thin tube. Nerve impulses, too, are rapidly catalysed chemical changes. They sweep along the long thin tubes like fizzing trails of gunpowder. Each fizzing sweep is discrete and separate from the others, so they arrive at the far end

of the tube like a series of short, sharp reports – nerve impulses. The rate at which the nerve impulses arrive – which may be hundreds per second – is a coded representation of (in this case) the intensity of light falling on the rod or cone cell. As far as a single nerve cell is concerned, the difference between strong stimulation and weak is the difference between a high-speed machine gun and intermittent rifle fire.

So far, what I have said applies to the rods and all three kinds of cone. Now for the ways in which they differ. Cones respond only to bright light. Rods are sensitive to dim light and are needed for night vision. Rods are found all over the retina, and are nowhere particularly crowded, so they are no good for resolving small detail. You can't read with them. You read with cones, which are extremely densely packed in one particular part of the retina, the fovea. The denser the packing, of course, the finer the detail that can be resolved.

Rods are not involved in colour vision because they all have the same wavelength sensitivity as each other. They are most sensitive to yellow light in the middle of the visible spectrum, less sensitive nearer the two ends of the spectrum. This does not mean that they report all light to the brain as yellow. That isn't even a meaningful thing to say. All nerve cells report to the brain as nerve impulses, and that's all. If a rod fires rapidly, this could either mean that there is a lot of red or blue light, or that there is somewhat less yellow light. The only way for the brain to resolve the ambiguity is to have simultaneous reports from more than one kind of cell, differentially sensitive to different colours.

This is where the three kinds of cone come in. The three kinds of cone have three different flavours of rhodopsin. All of them respond to light of all wavelengths. But one kind is most sensitive to blue light, another is most sensitive to green light, and the third is most sensitive to red light. By comparing the firing rates of the three kinds of cone – in effect, subtracting them from each other – the nervous system is able to reconstruct the wavelengths of light

hitting the relevant part of the retina. Unlike the case of vision by rods alone, the brain is not confused between dim light of one colour and bright light of another colour. The brain, because it receives reports from more than one kind of cone, is able to compute the true colour of the light.

As I said when recalling Doctor Dolittle on the moon, the colours that we finally think we see are labels used for convenience by the brain. I used to be disappointed when I saw 'false colour' images, say, satellite photographs of earth, or computer-constructed images of deep space. The caption tells us that the colours are arbitrary codes, say, for different types of vegetation, in a satellite picture of Africa. I used to think false colour images were a kind of cheat. I wanted to know what the scene 'really' looked like. I now realize that everything I think I see, even the colours of my own garden through the window, are 'false' in the same sense: arbitrary conventions used, in this case by my brain, as convenient labels for wavelengths of light. Chapter 11 argues that all our perceptions are a kind of 'constrained virtual reality' constructed in the brain. (Actually, I am *still* disappointed by false colour images!)

We can never know whether the subjective sensations that different people associate with particular wavelengths are the same. We can compare opinions about what colours seem to be mixtures of which. Most of us agree to find it plausible that orange is a mixture of red and yellow. Blue-green's status as a mixture is conveyed by the compound word itself, though not by the word turquoise. It is controversial whether different languages agree on how they partition the spectrum. Some linguists aver that the Welsh language does not divide the green and blue region of the spectrum in the same way as English does. Instead, Welsh is said to have a word corresponding to part of green, and another word corresponding to the other part of green plus part of blue. Other linguists and anthropologists say that this is a myth, no more true than the equally seductive allegation that the Inuit ('Eskimos') have 50 different words for snow. These sceptics claim experimental

evidence, obtained by presenting a large range of coloured chips to native speakers of many languages, that there are strong universals in the way humans partition the spectrum. Experimental evidence is, indeed, the only way to settle the question. It matters nothing that, at least to this English speaker, the story about the Welsh partitioning of blue and green feels implausible. There is nothing in physics to gainsay it. The facts, whatever they are, are facts of psychology.

Unlike birds, which have excellent colour vision, many mammals have no true colour vision at all. Others, including certain kinds of partially colour-blind humans, use a two-colour system based on two kinds of cones. High-quality colour vision with a three-colour system may have evolved in our primate ancestors as an aid to finding fruits in the green forest. It has even been suggested, by the Cambridge psychologist John Mollon, that the three-colour system 'is a device invented by certain fruiting trees in order to propagate themselves': an imaginative way of calling attention to the fact that trees benefit from attracting mammals to eat their fruits and spread the seeds. Some New World monkeys go in for weird arrangements in which different individuals within a species have different combinations of two-colour systems, and are thereby specialized to see different things. Nobody knows whether or how this benefits them, but it may be suggestive that bomber crews in the Second World War liked to include at least one colour-blind member, who could penetrate certain kinds of camouflage on the ground.

Unweaving the wider rainbow, moving to other parts of the electromagnetic spectrum, we separate station from station on the radio dial, we insulate conversation from conversation in the network of cellular telephones. Without sensitive unweaving of the electromagnetic rainbow, we'd hear everybody's conversation simultaneously, and all the frequencies on the broadcasting dial, in a white babel of noise. In a different way, and with the assistance of special-purpose computers, unweaving the rainbow underlies

Magnetic Resonance Imaging, the spectacular technique by which doctors today can discern the three-dimensional structure of our internal organs.

When a source of waves is itself moving relative to its detector, something special happens. There is a 'Doppler shift' of wavelengths as detected. This is easy to notice in the case of sound waves because they travel slowly. A car's engine note is of a distinctly higher pitch when it is approaching than when receding. This is why we hear the characteristic dual-tone eee-aaah when a car whizzes past. The Dutch scientist Buys Ballott in 1845 first verified Doppler's prediction by hiring a brass band to play on an open railway wagon as it sped past his audience. Light waves travel so fast that we notice the Doppler shift only if we are moving very fast towards the source of light (in which case the light is shifted towards the blue end of the spectrum) or away from it (in which case the light is red-shifted). This is true of distant galaxies. The fact that they are fast receding from us was first discovered because of the Doppler shift in their light. It is redder than it should be, shifted consistently towards the longwave, red end of the spectrum.

How do we know that the light coming from a distant galaxy is red-shifted? How do we know that it wasn't red when it set out? You can tell by using the Fraunhofer lines as markers. Each element, remember, signs its name in a unique barcode of lines. The spacing between the lines is characteristic like a fingerprint, but so is the precise position of each line along the rainbow. Light from a distant galaxy shows barcodes that have familiar spacing patterns. This very familiarity is what tells us that other galaxies are made of the same range of stuffs as our own. But the whole pattern is shifted a fixed distance towards the longwave end of the spectrum: it is redder than it should be. In the 1920s, the American astronomer Edwin Hubble (after whom the Hubble Space Telescope is now named) discovered that distant galaxies have red-shifted spectra. Those galaxies with the most pronounced red shift are also the most distant — as estimated from the faintness of their light.

Hubble's famous conclusion (although it had been suggested by others before) was that the universe is expanding, and from any given observation point the galaxies seem to recede at ever-increasing speed.

When we look at a distant galaxy, we are looking far back into the past, for the light has taken billions of years to reach us. It has become faint, which is how we know it has come a great distance. The speed with which our galaxy is racing apart from the other galaxy has had the effect of shifting the spectrum towards the red end. The relationship between distance and velocity of receding is a lawful one (it obeys 'Hubble's law'). By extrapolating this quantitative relationship backwards we can estimate when the universe began expanding. Using the language of the now prevailing 'Big Bang' theory, the universe began in a gigantic explosion between ten billion and 20 billion years ago. All this we infer from unweaving the rainbow. Further developments of the theory, supported by all available evidence, suggest that time itself began in this mother of all cataclysms. You probably don't understand, and I certainly don't, what it can possibly mean to say that time itself began at a particular moment. But once again that is a limitation of our minds, which were only ever designed to cope with slow, rather large objects on the African savannahs, where events come well behaved and in order, and every one has a before. An event that has no before terrifies our poor reason. Maybe we can appreciate it only through poetry. Keats, thou shouldst be living at this hour.

And are there eyes out there in the galaxies, looking back at us? Back is the word, for they can see us only in our past. The inhabitants of a world 100 million light years distant might at this moment see, if they could see anything at all on our planet, red-shifted dinosaurs lunging over the rose-tinted plains. Alas, even if there are other creatures in the universe, and even if they have eyes, it is unlikely that, however powerful their telescopes, they will have the resolving power to see our planet, let alone individual

inhabitants of it. We ourselves have never seen another planet outside our solar system. We didn't even know about all the planets in our own solar system until recent centuries. Neptune and Pluto are too faint to be seen by the naked eye. The only reason we knew which way to point the telescope was by calculations from minute perturbations in the orbits of nearer planets. In 1846, two mathematical astronomers, J. C. Adams in England and U. J. J. Leverrier in France, were independently puzzled by a discrepancy between the actual position of the planet Uranus and where it theoretically should have been. Both calculated that the perturbation could have been caused by the gravity of an invisible planet of a particular mass in a particular place. The German astronomer J. G. Galle duly pointed his telescope in the right direction and discovered Neptune. Pluto was discovered in the same way, as late as 1930 by the American astronomer C. W. Tombaugh, alerted by its (much smaller) gravitational effects on the orbit of Neptune. John Keats would have appreciated the excitement those astronomers felt:

*Then felt I like some watcher of the skies
When a new planet swims into his ken;
Or like stout Cortez when with eagle eyes
He stared at the Pacific – and all his men
Look'd at each other with a wild surmise –
Silent upon a peak in Darien.*

'On First Looking into Chapman's Homer' (1816)

I have had a special affection for these lines ever since they were quoted to me by a publisher on first reading the manuscript of *The Blind Watchmaker*.

But are there planets orbiting other stars? An important question, this, whose answer affects our estimate of the ubiquity of life in the universe. If there is only one star in the universe that has planets, that star has to be our sun and we are very very alone. At the other extreme, if every star is the centre of a solar system, the

number of planets potentially available for life will exceed all counting. Almost whatever the odds of life on any one planet, if we find planets orbiting one other typical star as well as the sun, we feel sensibly less lonely.

Planets are too close to their suns, and too smothered by their brightness, for our telescopes normally to see them. The main way we know that other stars have planets – and the discovery waited till the 1990s – is, once again, through orbital perturbations, this time detected via Doppler shifts in coloured light. Here's how this works. We think of the sun as the centre about which planets orbit. But Newton tells us that two bodies orbit each other. If two stars are of similar mass – they're called a binary pair – the two swing round each other like a pair of dumb-bells. The more unequal they are, the more it seems the lighter one orbits the heavier one, which almost stays still. When one body is much larger than the other, for instance the sun versus Jupiter, the heavier one just wobbles a bit while the lighter one whizzes round like a terrier circling its master on a walk.

It is such wobbles in the positions of stars that betray the presence of otherwise invisible planets orbiting them. But the wobbles themselves are too small to be seen directly. Our telescopes cannot resolve such small changes in position; less so, indeed, than they can resolve the planets themselves. Again, it is unweaving the rainbow that comes to the rescue. As a star wobbles back and forth under the influence of an orbiting planet, the light from it reaches us red-shifted when the star is moving away, blue-shifted when it is moving towards us. Planets give themselves away by causing minute, but measurable, red/blue oscillations in the light reaching us from their parent stars. In the same way, inhabitants of distant planets might just detect the presence of Jupiter by watching the sun's rhythmic changes of hue. Jupiter is probably the only one of our sun's planets large enough to be detectable in this way. Our humble planet is too tiny to make gravitational ripples for aliens to notice.

They might, however, be aware of us through unweaving the rainbow of radio and television signals that we ourselves have been pumping out for the past few decades. The swelling spherical bubble of vibrations, now more than a light-century across, has enveloped a significant number of stars though an insignificant proportion of those that populate the universe. Carl Sagan, in his novel *Contact*, has darkly noted that in the vanguard of images announcing earth to the rest of the universe will be Hitler's speech opening the 1936 Olympic Games in Berlin. No reply has so far been picked up, no message of any kind from any other world.

We have never been given any direct reason to suppose that we have company. In very different ways, the possibility that the universe is teeming with life, and the opposite possibility that we are totally alone, are equally exciting. Either way, the urge to know more about the universe seems to me irresistible, and I cannot imagine that anybody of truly poetic sensibility could disagree. I am ironically amused by how much of what we have discovered so far is a direct extrapolation of unweaving the rainbow. And the poetic beauty of what that unweaving has now revealed, from the nature of the stars to the expansion of the universe, could not fail to catch the imagination of Keats; would be bound to send Coleridge into a frenzied reverie; would make Wordsworth's heart leap up as never before.

The great Indian astrophysicist Subrahmanyan Chandrasekhar said, in a lecture in 1975:

This 'shuddering before the beautiful', this incredible fact that a discovery motivated by a search after the beautiful in mathematics should find its exact replica in Nature, persuades me to say that beauty is that to which the human mind responds at its deepest and most profound.

How much more sincere that sounds than Keats's better-known expression of a superficially similar emotion:

UNWEAVING THE RAINBOW

'Beauty is truth, truth beauty,' – that is all
Ye know on earth, and all ye need to know.

'Ode on a Grecian Urn' (1820)

Keats and Lamb should have raised their glass to poetry, and to mathematics, and to the poetry of mathematics. Wordsworth would have needed no encouragement. He (and Coleridge) had been inspired by the Scottish poet James Thomson, and might have recalled Thomson's 'To the Memory of Sir Isaac Newton' (1727):

... *Even Light itself, which every thing displays,
Shone undiscovered, till his brighter mind
Untwisted all the shining robe of day;
And, from the whitening undistinguished blaze,
Collecting every ray into his kind,
To the charmed eye educed the gorgeous train
Of parent colours. First the flaming red
Sprung vivid forth; the tawny orange next;
And next delicious yellow; by whose side
Fell the kind beams of all-refreshing green.
Then the pure blue, that swells autumnal skies,
Ethereal played; and then, of sadder hue,
Emerged the deepened indigo, as when
The heavy-skirted evening droops with frost;
While the last gleamings of refracted light
Died in the fainting violet away.
These, when the clouds distil the rosy shower,
Shine out distinct adown the watery bow;
While o'er our heads the dewy vision bends
Delightful, melting on the fields beneath.
Myriads of mingling dyes from these result,
And myriads still remain – infinite source
Of beauty, ever flushing, ever new.*

BARCODES IN THE STARS

*Did ever poet image aught so fair,
Dreaming in whispering groves by the hoarse brook?
Or prophet, to whose rapture heaven descends?
Even now the setting sun and shifting clouds,
Seen, Greenwich, from thy lovely heights, declare
How just, how beauteous the refractive law.*