Andrew Parker – In The Blink Of An Eye – how VISION sparked the big bang of evolution
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The Big Bang in animal evolution was perhaps the most dramatic event in the history of life on Earth. During this blink of an eye in such history, all the major animal groups found today evolved hard parts and became distinct shapes, simultaneously and for the first time. This happened precisely 543 million years ago, at the beginning of a period in geological history called the Cambrian, and so has become known as the 'Cambrian explosion'. (XIII)

Regardless of their external appearance and lifestyles [animals] belong to the same higher classification of animals, known as a phylum (plural phyla) because they share the same internal body plan. (2)

Revolutions in evolutionary theory have occurred since Darwin's time. Now we know that the history of life on Earth has been dominated by long periods of gradual evolution – 'micro-evolutions' – or even a complete standstill. But these periods ended abruptly as they were replaced by 'macro-evolution' – short but prolific bursts in evolutionary activity, hence a so-called 'punctuated equilibrium' model for evolutionary history. (8)

... 544 million years ago there were indeed three animal phyla with their variety of external forms, but at 538 million years ago there were thirty-eight, the same number that exists today. (9)

The Earth formed some 4,600 million years ago, and it is generally accepted that life came into existence around 3,900 million years ago, following a flurry of meteorite bombardment. But during the first 3,000 million years of life's history [...] the Earth was populated only by bacteria. (11)

The unstable concoction of chemicals ejected from the first black smokers reacted with seawater and provided conditions that could have given rise to the inorganic construction of amino acids and other prebiotic organic molecules that are the building clocks for life. (12)

... cyanobacteria [are] organisms that obtain their hydrogen from water. This was achieved by the evolution of a substance of great consequence – chlorophyll, the lifeblood of true algae and the higher plants. [...] As the cyanobacteria removed hydrogen from the Earth's water, oxygen remained and entered the atmosphere. (14)

Atmospheric oxygen not only permits breathing in higher animals but also provides a protective barrier – the ozone layer – from the sun's ultraviolet rays, which can be harmful to animal tissue. (15)

Sponges have only a few cell types modified to perform specialised functions, and the sort of cell-to-cell junctions that form sheets of tissues in higher forms are absent. [...] They are the only multicelled animals with cells capable of independent survival. (17)

The Cambrian explosion, which post-dated the Ediacaran fauna, is a milestone in evolution that can be matched in significance only by the beginning of life itself. It paved the way for the emergence of the vast diversity of life found today, whether in Australia's Great Barrier Reef or Brazil's tropical rainforests. It involved a burst of creativity, like nothing before or since, in which the blueprints for the external parts of today's animals were mapped out. Animals with teeth and tentacles and claws and jaws suddenly appeared. (25)

The 'contour lines' [of Rocky Mountains] swirl around the landscape, continuously pulling the eyes in different directions and towards different focal points. These lines are actually the boundaries of sediment layers, laid down millions of years ago by sediment in the sea settling out on the bottom, forming a new sea floor. So although a thousand meters or two above ground today, the rock that constitutes these mountains began its history underwater. As the Earth's plates moved around throughout geological time, and slowly crashed into each other, something had to give. The rocks that now form the Rocky Mountains were one of those things. They were forced up from below the water and into the air, and their chaotic movements produced the uneven patters of 'contour lines' seen on the mountains today. (26)

We now know of wonderfully preserved communities of animals where a diversity of animal phyla are represented from the Cambrian, but not before the Cambrian. [...] the internal body plans of animal phyla evolved some 120 to more than 500 million years earlier (depending on who you believe). Hence, the variety of internal body plans found in animals today really was one hidden within the bodies of worms, for tens of millions of years. Now we can really understand *what* the Cambrian explosion is. It is the sudden acquisition, 543-538 million years ago, of hard external parts by all the animal phyla found today (except the sponges, comb jellies and cnidarians). It is the simultaneous transition from the prototype worm-shaped or soft-bodied form to complex, characteristic shapes (also knows as 'phenotypes') within each phylum, and it happened in a blink of an eye on the geological timescale. (35-36)

At the turn of the twenties century, the president of the Inventors' Association resigned his position after claiming, 'Everything that could be invented has been invented.' (45)

The first mammoth appeared 150,000 years ago, into the second to last Ice Age. The mammoth spread through northern Asia, America and Europe, sharing its environment with giant ground sloths, sabre-tooth cats and big-horned bison. (52)

The Russian station at Vostok is one of the most uninhabitable in Antarctica, situated at the very centre of the continent. At Vostok the ice is drilled and cores are removed, and the ice at the bottom of a core can be up to 500,000 years old. In 1988 an American microbiologist found spores locked in part of a core containing ice 200,000 years old. Miraculously, on warming the spores live bacteria emerged, which could be cultured as if 200,000 years had never elapsed. (55)

... nucleic acid from an appropriately preserved Tasmanian tiger ('thylacine') pup has been extracted, with cloning intentions, at the Australian Museum. Here, cloning methodology, which utilises the closest living relative as a surrogate mother, is under investigation. In addition to cloning such old DNA, pitfalls to consider include its compatibility with chromosomes from a different species, followed by the acceptance of a foreign embryo by a surrogate mother. Then, if the cloning is successful, scientists must aim to avoid sterile creations. (56)

Ancient DNA has been put to another use in mapping the geographical history of disease. (56)

Cambrian life was exclusively marine (60)

Beetle exoskeleton is effectively constructed of thin layers, laid down parallel to the outer surface. If the individual layers are relatively thick and corrugated, then the beetle can withstand high temperatures. If there are many pores in the exoskeleton then wax can be secreted to prevent it drying out. A combination of both characteristics indicates an adaptation to deserts. Beetles from temperate climates tend to posses flat layers in their exoskeletons, where all the layers are thin except for a very thick outer layer which provides physical protection. The exoskeletons of cold-adapted and aquatic beetles are different again. (60)

Plants require carbon dioxide for photosynthesis. The gas is taken up through valve-like pores that occur on the surface of leaves. It is understood that the past 200 years have witnessed increased carbon dioxide levels as a result of industrial fossil fuel consumption. It is also known that plants have responded to this increase by producing fewer pores on their leaves. In fact there is a distinct inverse relationship between the concentration of carbon dioxide in the atmosphere and the density of pores on leaves. (61)

Fossils of plant life found in Jerusalem from the time of Christ were used to back up ancient texts on climate history. The climate was resolved with precision and the model of Jesus was given dark olive skin, appropriately. This contrasts with the pale, delicate complexion of previous depictions. But still the hair and beard of Jesus remained in question, and the fashion of Jesus' times became important to their reconstructions. The only useful pigments to have been preserved were not contained in 2,000-year-old hair samples, unfortunately, but those in first- and third-century frescoes of synagogues in northern Iraq. These depicted Jesus with short curly hair and a trimmed beard, a style which would be accommodated in the new reconstruction. We have to assume the hair was dark brown. (64)

The living part of nautilus occupies the first and largest chamber, which is open-ended. Each chamber thereafter has an additional character – a think tube running through its centre and through the chamber walls, terminating in the last chamber and taking on the spiral shape of the shell. Similar tubes are evident in ammonites, and in the nautilus this tube is known to contain living tissue. In terms of the body volume, the tube tissue is a minor part of the animal. But in terms of the animal's behaviour, it constitutes a major organ. The role of the tube tissue is to transport water into and out of the otherwise air-filled chambers, and so regulate buoyancy. This means that the nautilus can move vertically in the water with apparent ease. (66)

Now it is understood that mountains today were perhaps once marine reefs, as a result of movement in the Earth's plates. In fact we can construct a world atlas so accurate that it could have been used to navigate in the Cambrian, at the time the Burgess organisms lived. (79)

Angelfish live in the clear surface waters of the Amazon. They have flattened bodies with silver skin, similar to a mirror. When one fish invades another's territory, the defender leaves the shelter of reeds to do battle. Battle stance is a tilted position in the water column, with the aim of firing sunlight into the eyes of the opponent. Like Roman shields, the strong Amazonian sunlight can be concentrated into a narrow beam and directed precisely. In fact both fish in this combat take up their positions in the open water, fine-tuning their lines of fire by adjusting the tilt of their bodies. Light flashes through the water like the laser of Star Wars battles. The stakes are high. A direct hit in the eye can lead to the bursting of blood vessels and an increase in heart and breathing rates. A fish defeated in this manner is at best temporarily stunned and at worst killed. Either way, the battle is over. This is a fish living in waters where sunlight is at its most intense, and it has adapted. Acting on tis strong selection pressure, it has evolved precision mirrors. (84)

Pigments [...] are molecules that absorb certain wavelengths in white light. These wavelengths are no longer available to vision, but remaining wavelengths in the sun's spectrum are reflected from, or transmitted through, the pigments system. These are the wavelengths we see. And this is the commonest cause of colour in animals and plants they contain pigments. (89)

Pigments can cause an animal, or part of an animal, to be coloured, but this colour is not the most dazzling type. Also the colours caused by pigments do not change with the direction of viewing, or when the animal itself moves. This is because pigments disperse or reflect wavelengths equally in all directions. (90)

The skin of the chameleon or cuttlefish is packed with chromatophores – colour cells. These are simply cells packed (usually) with pigment. Each colour cell contains just one type of pigment that causes one colour. But the cell is elastic – it can change its shape. Under nervous control, it can become flat and thin, lying parallel with the surface of the animal, or short and squat. And the pigment is spread evenly throughout the cell in each case. Looking at the animal, the short, squat cells reveal only a small area of pigment, and the visual effect is negligible. But the thin, flat cells reveal much more of their pigment, and can be seen by the naked eye. Compare these two possible forms of the colour cell, considered off and on, with a coin. A coin is easily observed when lying flat, but it is more difficult to see edge on. Chameleon and cuttlefish skin is actually packed with colour cells of various hues. In comparison with a TV screen, individual cells can be considered sub-dots, collectively forming dots that can independently cause any colour. By being turned on and off, or by becoming an intermediate phase, the different sub-dots contribute to a dot that is capable of assuming any colour of varying brightness. At high magnification, imagine the skin as an assortment of juxtaposed and coloured coins. When some coins are turned on their sides, different overall colours are achieved. (93)

Many bats hunt using radar. They produce pulses of ultrasound that return to the bat after rebounding from an object, just like the military radar system that detects aircraft. If, at night, the bat's radar detects an object that is small an din mid-air, it is probably a moth. That's food to a bat. But just as animals living under the sun are adapted to light, so moths are adapted to radar. They are covered in a sort of radar-absorbing fur, which reduces the signal reflected back towards the bat. When the radar source is very close, they can stall and dodge the oncoming bat. A similar cat-and-mouse game takes place underwater, where dolphins hunt fish using a comparable stimulus – they produce sonar. (94)

Following the decommissioning of armour, European armies employed warning colours op until the nineteenth century. The bright red and white uniforms, with tall headwear, provided a warning message or two. Like much of the armour before, large hat provides a false impression of body size. The larger the individual, the greater the threat perceived. And the immaculate dress itself was a clear symbol of a well-disciplined army. Then, of course, there were the regimented manoeuvres. This was an army that was prepared and knew what it was doing, at least in the eyes of the enemy. During th nineteenth century the philosophy of battle colours changed. With the introduction of accurate, long-range guns came a new form of advantage for the soldier. (95-96)

Monet provided a warning that one should beware the fixed, stereotypical image of an environment. He painted most of his landscapes many time,s but at different times of the day ... and his paintings were all unique. (98)

Beetles and birds send secret messages written in ultraviolet through the atmosphere. We know this because their ultraviolet colouration can be recorded on camera film. (99)

Just as we tan in the sun, in very shallow water the hammerhead sharks do the same. (102)

... as we plunge further down in to the sea, different wavelengths or colours are absorbed at different rates. Red, ultraviolet and violet are first to fade away, and at 200 metres sunlight is exclusively blue. [...] Below 200 metres, many animals are red. The light here is blue, and only blue. The lack of red light means that red pigments have no chance to reflect. Instead they absorb the blue light and so appear invisible. Red is a good camouflage colour in the deep. [...] The marlin is a fish that appears conspicuously coloured when our of water. But put in in the water and its hues and patters take on the roles of countershading and disruptive colouration, and the fish disappears from sight. (104)

Predatory fish can detect light that is polarised. (105)

Many beetles living on leaves are hemispherical in shape. This is a physical adaptation to light. A sphere will always cast a shadow, but from most positions a hemisphere will not. (107)

... through larger eyes pigments would appear brighter, because big eyes sample a larger segment of the pigments' multidirectional reflectance. (118)

... in addition to the direct reduction in niches at night, through the degeneration of light and shade partitions for instance, the evolution is stimulated much less at night. (120)

... where light is greatly reduced, biodiversity diminishes in unison. (128)

... deep-sea faunas are discernible for their low species diversity while sometimes displaying an amazingly high abundance for a single species. (128)

... in shallow water evolution had resulted in many species of isopods, partly in response to the increase in niches created by light. And each species was considerably different - many genetic mutations had taken place over a limited time period, so evolution had been rapid where light levels were high. (129)

... animals living on the sea floor down to depths of at least 1,000 metres are obviously well separated geographically where they occur on different plates. [...] species separated geographically today evolved from ancestors once living together on the same plate. [...] the Australian, Indian and Mexican plates (or continental slopes) were completely separated 160 million years ago. (130)

Two environments are never the same, and evolution is reflected in this. (130)

A 'species' can be considered a group of similar individuals that reproduce in their natural environment. (132)

Although there were fewer individuals in the deep-sea sediment compared with its shallow-water counterpart, the number of species was similar. The diversity of life in deep-sea sediments was equal to that in the shallow water. (132)

The deep-sea animals [...] were adapted to even the most minuscule quantities of light present in their environment – they had big eyes. The cave spider was denied *any* light and had given up the evolutionary struggle to see. (135)

In near-surface waters, such as the angelfish's Amazonian habitat, sunlight exists in the form of a beam like a spotlight, as it does on entry through the Earth's atmosphere. But below these waters the beam formation is broken, and sunlight is scattered in every direction. So here objects are illuminated equally from all directions, and no shadows are cast. A mirror in these waters vanishes from sight because in the mirror one sees only a weak reflection of the environment. The mirror becomes an optical illusion – in the direction of the mirror there appears to be only the background environment, with nothing in the way. In the ocean a silver fish is effectively a mirror. A predator looking directly at a silver-sided, or mirrored fish from below sees only a reflection of the surface. So in the direction of the fish there is ... no fish! (137)

... imagine a stack of thin films of different thicknesses. Imagine some that reflect blue light above others, that reflect green above yet others, that in turn reflect red. As sunlight strikes this structure, its blue rays would be reflected from the top layers, leaving the green and red rays to continue along their original path. As these rays meet with the middle layers, the green rays are reflected, leaving only red rays to continue along their path. And finally the red rays meet with the lower layers and they too are reflected. So the combined effect of all the layers is the reflection of blue, green and red rays in the same direction. And blue, green and red combine to form white, or silver (silver is a strongly directional form of white). With more layers of different thicknesses, more colours in the spectrum can be reflected. And this is how the fish skin appears silver – it contains a stack of layers of varying thickness. (137-138)

... most predators have adapted to go without a meal for weeks, even months. (141)

Light has existed on Earth from its very beginnings. Vision is an adaptation to light. It has not always existed. (141)

Around 40,000 species of seed-shrimp have been described – rather significant, considering we know of only about 8,700 species of birds and 4,100 species of mammals. (142)

In a totally dark room [...] an orange cannot be found with a blue torch. (145)

Male halophores [notched seed-shrimps] have the profiles to cause an optimal reflection of blue light at both macro- and microlevels. In terms of optics, they form extremely efficient diffraction gratings. The diffraction gratings of female halophores, on the other hand, are decidedly crude. (154)

Seed-shrimps cannot generate electricity to power miniature light bulbs. Instead they adopt a more efficient method of yielding light – they bioluminesce. Two chemicals – a luciferin and a luciferase – react with the oxygen in water, and light is emitted as a byproduct. The light is referred to as bioluminescence. Only about 20 per cent of the energy fed into a light bulb fuels light; the rest is lost as heat. Bioluminescence is less wasteful – almost all of the energy investment becomes light, and so it is knows as 'cold light.' (155)

One group of lightweight seed-shrimps, the Halocyprida, produce bioluminescence from organs in their shells. I will refer to the Halocyprida as the 'eyeless' group, since all their representatives lack eyes. The two bioluminescent chemicals are pumped from eyeless seed-shrimps into the water, where they react to form a luminescent cloud. These eyeless species gather at the ocean surface at night and bioluminesce for all they're worth. The result is a mass 'light bomb'; a patch of bioluminescence so bright it can be detected by satellites in space. And the reason for this is so as to generate a burglar alarm. The seed-shrimps are eaten by small fish, and small fish are eaten by bigger fish. Any small fish entering the light zone becomes a most conspicuous silhouette, and the alarm bells sound for the bigger fish. Not surprisingly, the eyeless seed-shrimps remain undisturbed at night. (156)

The snapping, or pistol, shrimp has one small and one large crab-like claw. The large claw is the pistol, which fires an underwater bullet of sound so loud that it can be detected by passing submarines. In fact it can even interrupt their sonar. (166)

Reference to diffraction gratings insinuates microscopically fine corrugations, where a distance approaching the wavelength of light separates neighbouring ridges. (180)

On the broken surfaces of three species [...] were remnants of diffraction gratings. Only traces of gratings had been preserved, rather like the few squares that remain in many roman mosaics, but where they did occur on a single body part, they were always exactly the same size and shape, and were orientated in the same direction. (182)

The reconstructed surfaces were taken out of the dark laboratory and placed in seawater under sunlight, and ... the colours of three Burgess Shale species shone as spectacularly as they had 515 million years ago. That was the most memorable moment of all. For the first time, the original colour of a Cambrian animal had been uncovered. An almost unimaginable piece of Cambrian history had been revealed. (184)

A standard physics textbook, Born and wolf's *Principles of Optics*, affirms that diffraction gratings were conceived in 1819, when Joseph von Fraunhofer would fine copper wire around a metal screw. Others credit the diffraction grating to the US astronomer David Rittenhouse, after his experiment of 1785. Now the date for the first diffraction grating has been pushed back a little further – some 515 million years. (185)

Eyes are the detectors that convert the light waves travelling through the atmosphere into visual images. These light waves enter the Earth's atmosphere from the sun, and bounce and reflect off objects that exist all around us. They are the same light waves that change when they strike an animal to relay information about its identity and whereabouts within the environment. Eyes pick up all th is information. Electromagnetic radiation of different wavelengths exists in the environment; colour exists only in the mind. (187)

... the eye itself is only Act One in the complete performance of seeing. Act Two involves transmitting visual information, in the manner of electrical cables, from the eye to the brain. In the Act Three an image is formed in the brain. Vision employs the eye *and* the brain of the beholder. (188)

Light perception in bacteria, animals and plants ultimately involves organic molecules that undergo a simple reaction when hit by a packet of light called photon. Light perception takes place in many single-celled animals, such as amoebae and *Euglena*, where the fluid within the cell is sensitive to light. These animals use light to orientate themselves – to distinguish up from down. In multicelled animals, independent light-sensitive cells or organs of various complexities perform the task of light perception. The most elementary forms of light-perceptive *organs* are called ocelli. These are small cups containing a light-sensitive surface backed by dark pigment. Sometimes they are capped by a rudimentary lens. The simplest multicelled animals with these structures are the jellyfish. The marginal sense organs of jellyfish in some cases include ocelli, in addition to gravity, touch, chemical, pressure and temperature receptors. Indeed, ocelli are generally the most poorly developed sense receptors in jellyfish, with lenses lacking from most groups. The pigmented patches of most jellyfish are not known to detect light, and may have evolved rather as a light barrier – to absorb light and so shield the underlying sensory cells that detect other stimuli. But in some jellyfish, where a lens covers the cup-shaped light-sensitive surface, the ability to respond to light on or light off has been established. (189)

An advantage of a cup-shaped light perceiver over a flat one lies in its curved surface. A beam of sunlight illuminates a curved surface, such as a hemisphere, in only one region. A flat surface, on the other hand, would be completely lit. So a curved surface can perceive the direction of the light surface. (189)

Nautilus [...] has a simple eye that is unique because an image is produced on its retina without the aid of a lens. (191)

The image-forming structure in the 'pinhole eye' of nautilus is a small pupil, or 'pinhole', formed in its dark iris. Light is not focused, but is received only through the pinhole, providing at least some degree of control. To gain accurate directional information, the retinal mosaic is remarkably fine so that light coming from a single point will illuminate several receptor cells. But serious disadvantages are inherent with this type of eye, which accounts for its rarity. A bright image requires a large pupil, whereas a sharp image requires a small pupil. The nautilus' solution – a large range of pupil sizes or pinholes – unfortunately results in blurred images. [...] Curved mirrors can also be successful substitutes for lenses in eyes. The scallop has many eyes just inside the edge of its shell. These eyes appear silver, like tiny mirrors – and indeed they do contain mirrors. Within each eye, a hemispherical concave mirror similar to the reflector in a car headlight lies *behind* the image-forming retina. Light passes almost unfocused *through* the transparent retina before it is reflected back, this time focused by the mirror. The light is focused precisely at the position of the retina. And now the retina absorbs the light rays, and an image is grabbed. [...] The third type of simple eye in molluscs is found in a snail. The snail has an eye separated from the skin and containing a large spherical lens. This eye is known as the camera-type. It works in the same way as a camera in that a single lens focuses light on to t film, or retina, with an adjustable iris included to alter the quantity of light passing through its 'pupil'. The general design is quite simple, but it is ideal for seeing images, and the variety of camera-type eyes to be found in other animal phyla testifies to its success. [...] The camera-type eye is the standard hardware for vision in vertebrates, both on land and underwater. Humans are one beneficiary, but in addition to bristle and molluscs it has also emerged in spiders and crustaceans within the arthropod phylum, velvet worms within a phylum all of their own, and in box jellyfish within the cnidarian phylum. (191-193)

Focusing is all about bending light rays from different parts of the environment towards a common point. There are two factors which affect the bending of light rays – the differences in materials either side of a boundary, and the angle of that boundary relative to a light ray (think of a prism). Adaptations to vision on land are different from those underwater because [...] light behaves differently in air compared to water – there is a material difference. Light does behave similarly in water and in the cornea, so it barely recognises a boundary as it enters the eye of aquatic species. In this case, the lens within the eye must be responsible for most of the focusing. But light recognises a considerable difference between the cornea and air, and it is bent as it crosses their boundary at an angle. So the cornea of land animals acts as a powerful lens in its own right. (193-194)

In eyes of vertebrates on land, between 20 and 67 per cent of the focusing power is supplied by the cornea. So the lens can be designed specifically to correct blurring and to make accommodation for different distances – nearby objects would otherwise be imagined further away from the lens than distant ones. Mammals, birds and most reptiles meet these goals by changing the shape of their lens or cornea, thereby adjusting the position of the focal plane. They use tiny muscles to pull and stretch the lens. Alternatively, fish, frogs and snakes move their lenses backwards and forwards. Lens movement can provide adjustments for water or air in some amphibious animals. (196)

In contrast to the simple eye, the compound eye has multiple openings for light to enter – hence its name – and so always consists of numerous individual units, or ocelli, called 'facets'. Other than minor appearances in the bristle worms and ark clams, the compound eye is a character of the arthropods. More precisely, compound eyes today occur in crustaceans, insects and horseshoe 'crabs' (which are actually more closely related to scorpions than true crabs). Compound eyes have evolved into sophisticated organs of sight, up to a third of the total body size in some seed-shrimps, and form images in different ways. [...] We can divide compound eyes into two basic types – apposition and superposition. The facets of apposition eyes are optically isolated from each other, so they each sample a different section of the environment. The tiny images formed within each facet are pieced together in the manner of a jigsaw puzzle to produce the complete picture. The facets of superposition eyes, on the other hand, cooperate optically so that they superimpose their light to form a single image at a common point in retina. (199-200)

[In deep sea] rapid ascent causes nitrogen gas dissolved in the blood to decompress, forming bubbles that can block blood vessels and kill tissue. The bends leave visible depressions in the joints of bones. (204)

It is believed that the compound eyes of Cambrian arthropods shifted position from the under side to the top side of the body, and became successively incorporated in the shield or shell that covers the head. (212)

In true eyes, an image is assembled in the brain. The brain then makes a decision on how to react, and has the whole body at its disposal. (214)

... the eye has a multiple origin. It evolved on more than one occasion – the arthropod eye evolved and the chordate eye evolved, but independently and, it seems, at different points in evolutionary history. [...] now it seems *more* than possible that an eye appeared on Earth in one phylum before any others – it seems veritable. And that phylum with the first eye was the Arthropoda. (216)

[...] trilobites reigned in abundance throughout the seas. This reign ended 280 million years ago, but began 543 million years ago, at the beginning of the Cambrian explosion. Four thousand species of trilobites have been identified, and they were particularly successful during the first term of the dominion, when they flourished. [...] they were by far the most important and ubiquitous arthropods around in the Cambrian. In fact trilobites are believed to be the stem group of all arthropods – they probably wore the prototype shells, or 'exoskeletons'. From some groups of trilobites the crustaceans, and later the insects, evolved. From another group the sea spiders, and later the spiders, evolved. (216-217)

Many species of trilobites with eyes came into existence around 543 million years ago ... but not a single species before that time. The trilobites without eyes entered history a little later, in geological time. So 543 million years ago the Earth witnessed the first trilobite ... and the first eye. (224)

A patch of light-sensitive skin was used as a starting point [of eye development]. (225)

The intermediate stages, or conceptually substandard visual organs, *do* exist today because their host animals cannot handle the information loads supplied by the next conceivable stage on the road to a fully formed camera-type eye. [...] a light receptor will change by just 1 per cent of its length, width or protein density during each evolutionary step in the eye direction. But even with such a pessimistic approach, the whole sequence from light-sensitive patch to the eye of a fish would require only two thousand of these tiny modifications in sequence. [...] A study of flatworms revealed that similar proteins exist in the eyespots (not true eyes) *and* touch/chemical detectors. In the eyespots, these are the proteins that react to light, comparable to these in the retina of an eye. So a head start may be gained towards eye evolution by borrowing the proteins of other detectors. [...] [Using] a 0.005 per cent modification from one generation to the next [...] the eye of a fish could evolve from its rudimentary beginnings in less than 400,000 generations. Assuming each generation is completed within a year, this result suggests that an efficient, image-forming eye can evolve in less than a million years. (226)

The architecture of eyes alone can provide information on how animals lived. For instance, the position of the eyes in the head can reveal the position of the animal in the food chain. Eyes positioned at the sides of the head, facing sideways like those of a rabbit, can scan a wide angle and spot movement from nearly all directions. The movement pursued in this case is that of predators – eyes of this type belong mainly to plant eaters. In contrast, eyes positioned together at the front of the head, facing forward like those of an owl, see less of the environment but are better for pinpointing targets and judging the distance between them. These eyes generally belong to meat eaters. (229)

THE LAWS OF LIFE
For the survival of animals everywhere
Basic Rules
1. Every man for himself: stay alive!
1a. Avoid being eaten
1b. 'Eat'
2. For the good of one's kind.
2a. Breed
2b. Find a niche and protect it
2c. Adopt to changes in the environment
Lifestyle
1. Predator
2. Prey
Tactics
1. Conspicuousness
2. Crypsis/illusiveness
3. Genuine strength/ability (230)

The first rule of animal survival is to stay alive. The other rules, such as feeding and breeding, are academic if this first rule is not followed. [...] animals don't really receive rules – in reality the rules for their survival are the selective pressures for evolution, invisible forces acting on the genes, carrying massages for enhanced survival. And selective pressures act directly upon individuals, not species, so even the species-level survival factors are relayed through individuals. (231)

Disease is density dependent, and so it is a factor operating at the species level. On the one hand, species can become too successful for their own good. From another viewpoint, this is just evolution maintaining biodiversity, preventing one species from taking over the world. (231)

When adaptations to vision include shape and behaviour, in addition to colour, it is clear that vision is a major tactic used in the struggle for both conspicuousness and illusiveness. (232)

When eyes are positioned on the sides of the head, like those of rabbits, the wide field of view encapsulates almost the entire horizon. At first this would seem like the ideal form of vision, but to gain such a panoramic outlook, each eye sees a different picture – each approaching 180° of the horizon – and never the same object. With one eye, however, the view will be two-dimensional, and so distances are difficult to estimate. When two eyes are positioned on the front of the head, distances and the direction in which one is travelling *can* be estimated. So it follows that eyes in this arrangement can perceive the three-dimensionality of an object. Differences in the positions of images create impressions of depth, as can be demonstrated using stereograms. Each eye sees the same object but from a different angle. Stereograms probably work because the optic nerves serving slightly different regions of the two retinas converge on the same 'binocular' cell in the brain. The view of an object from two different angles is superimposed and averaged – and its depth is perceived. So animals with two eyes facing forward are said to have stereoscopic vision – they can perceive images in 3D. [...] For a prey species, staying alive first means keeping off the dinner plate and *then* eating becomes important. So it is ideal for the prey species to be surrounded by open space, where the possibility of a sudden ambush is minimised. Minimised, that is, if a 360° view of the terrain is possible – blind spots on the horizon are dangerous. We often find rabbits grazing in the middle of open fields rather than at its edges near hedgerows. And we always find them with their eyes positioned for a panoramic view: eyes positioned at the sides of the head are good for spotting predators. For a predator, in contrast, staying alive usually means eating first and worrying about *their* predators and competitors after that. Eating lively animals involves hunting. Estimating distances is a critical part of hunting – the lioness cannot begin her charge when the prey is within its safety zone, where its head start is insurmountable for the lioness. Equally, a fox cannot catch a rabbit if the rabbit is given the distance in which to each full speed. So where vision is the major sense employed by predators, two eyes at the front of the head are needed – an accurate assessment of distance is the difference between a meal and hunger. And that is just what is found in the lioness and the fox. This trend can often be found within other animal phyla with eyes. But in mid-water, things become more complicated. There is not only the horizon to worry about, there is also above and below. In mid-water, danger can approach from *all* directions. The great bearers of marine compound eyes, the crustaceans, have evolved a solution to this problem – many crustaceans have eyes positioned at the ends of moveable stalks. They can move their precision eyes to cover a wide area of their surroundings. Because of this, stalked eyes generally do not provide clues as to predator or prey, although many crustaceans, like insects on land, are often both. Today they lie somewhere in the middle of the food web where avoiding predation is finely balanced within the need to eat. [233-235]

The compound eyes of dragonflies contain several hundred or even thousand facets, not all of which are equal. There are one or two regions of the eye that contain larger facets and these are known as the acute zones, the 'sights'. Larger facets provide higher magnification and better resolution – they see with greater sensitivity. One acute zone is positioned at the top of the eye, and this is used to scan through the air and identify prey insects against the sky. When a prey insect has been spotted, the dragonfly moves into its horizon plane and tracks it with a forward facing acute zone – the prey is now locked into a line of fire. But the relevant point here is that the size and positions of the facets within the eye provide information of feeding – predation in this case. The eyes of prey can be quite different. (236)

... light detector cells in the compound eyes of ark clams and fan worms evolved from chemical detector cells that were inhibited by light. Originally, these chemical detectors were distributed over a large area of the body and, consequently, so too are the eyes today. In other words, it was most accommodating in these cases to evolve eyes all over the body. (237)

Human skin is thin and can be easily cut. For this reason, our blood has the ability to coagulate and seal up broken blood vessels, preventing blood loss and infection. Arthropod exoskeletons, on the other hands, are tough and designed to withstand the rigours of their hosts' lifestyles ... except when they are heavily attacked. The self-healing of Cambrian trilobites indicates they were so prone to attack that predation had certainly been a selection pressure during their evolution. Today animals can be found with hard shells that have functions other than to protect them against predators, such as providing support for tissues. But not only had Cambrian trilobites evolved armour, they had also evolved a self-healing mechanism to function in the event of attack by predators. Their hard shells had a role in protection against predators from the beginning. (249)

... all animal phyla suddenly evolved their hard parts simultaneously between 543 and 538 million years ago. As mentioned already, hard parts can have functions other than to provide protection against predators, but it would appear extremely coincidental for all phyla to evolve hard parts at precisely the same time to provide strength or as a barrier against osmotic stress. Multicelled animals from different phyla had been around, in soft-bodied form, for 100 million years or so before hand. And [...] physical environmental conditions that could have demanded hard parts were not the cause of the Cambrian explosion. (253)

In general the Precambrian was rather an experimental stage for predation, occupied mainly by peace-loving vegetarians that were willing enough to accept any occasional animal matter they stumbled upon. For they were developing a taste for mean. [...] If the Precambrian predators were considered passive, the second-wave of predators that swept through the early Cambrian seas were undeniably active. (259)

... all those wonderful colours we see around us, wherever we are, do not actually exist. In the environment there is no colour, only objects that happen to deflect different types of electromagnetic radiation. Roses are not beaming out reds, not do leaves generate greens. Perhaps the only chance we have of dealing with this truth lies with ultraviolet. To birds and insects there is even more happening in the environment, even more colour. Their palette also contains ultraviolet – they are communicating with private wavelengths, oblivious to us. But birds and insects could not comprehend that some other animals cannot detect ultraviolet light. So in turn we should remember that not all animals see images nor understand what *we* mean by colour. That's not to say that light and colour are not a big part of the lives of *all* animals. The word 'colour' can be found in the dictionaries of all animals living where light exists. Although not all are conscious of the fact, light is a major selection pressure acting on *everyone* ... or at least it is today. Plants are governed by very different rules to those of animals, yet even many plant colours are adaptation to animals vision. Leaves generally have to be green because their component chlorophyll deflects that wavelengths that we interpret as green (those wavelengths not used for photosynthesis) – that is incidental colour. But many plants produce flowers that display a vast array of colours to attract pollinating insects, and also colourful fruits to attract seed-dispersing mammals and birds. In fact, animals with eyes may even provide the main selection pressure in the evolution of some plant groups. For instance, the flowers of the *Ophrys* orchids have evolved to mimic females of different species of *Campsoscolia* wasps in terms of colour and shape. This mimicry is so effective that the male *Campsoscolia* wasps are deceived and attempt to mate with the flowers, but succeed only in transporting pollen. (261-262)

Colour is the logical animal adaptation to light, and the external colour of an animal living in an environment with light is usually an evolutionary response to that light. (265)

The [...] colour, shape and behavioural characteristics are not directly an adaptation to sunlight, but rather adaptations to the presence of animals with eyes. (266)

Of course mating is another important behavioural and evolutionary consideration, leading to sexual selection. Sexual selection acts in unison with predator-driven evolution, or natural selection. When the threat of predation is relaxed, bright mating colours will evolve in guppies via sexual selection. But all of this evolution is driven by vision, whether the vision of other guppies or of their predators. (266)

The Cambrian explosion is really all about defences to visually oriented predation. So when that first eye appeared, the potential for proto-trilobites to rule the world was recognised in the selective pressures acting on other animals. [...] So as selective pressures for active predatory lifestyles mounted on the proto-trilobites, so did selective pressures for countermeasures build up on the other multicelled animals. [...] Evolution is a balance, and the balance will not continue to tilt one way. With the exception of extinction, it continuously levels. (277)

... it seems the evolution of hard parts everywhere, and ultimately the evolution of body forms of multicelled animals, was driven by active predators. This process was the Cambrian explosion. But it was triggered by the evolution of the eye. (279)

A sense is the ability to detect and be conscious of the outside world. A sense involves a stimulus and a detector. Excluding eyes and vision now, detectors are usually one of two types – chemical or mechanical. Magnetic detectors also exist, which track the direction of the Earth's magnetic field. The magnetic sense is best known in insects and chordates, such as the homing pigeon, which can determine its geographical position by using a 'magnetic map'. Some fishes, notably sharks, use the magnetic sense to hunt prey, but usually this sense is employed for orientation purposes. [...] Chemical detectors detect chemicals and give rise to the sense of taste or smell. They contain nerve fibres that produce electrical impulses when contacted by specific chemicals. In its most rudimentary form, a nerve fibre terminates at the outer surface of the host animal and is free to be stimulated by chemicals that contact the animal. [...] Mechanical receptors are so called because they sense physical movement in the environment. They contain nerve fibres that produce electrical impulses when they are themselves moved. This happens as a consequence of contacting an object or movement in the surrounding water or air. Mechanical receptors are responsible for the senses of touch, hearing/vibration detection, and gravity, temperature and pressure sensitivity. (281-283)

The evolution of receptors for stimuli other than vision can theoretically show a linear progression, but a light perceiver with an inadequate lens has little advantage over one with no lens. The theoretical intermediate states of a lens increase light perception only slightly, but when a complete, fully focusing lens is formed, the increase suddenly becomes vast. (284)

... although vision can be found in only six of the thirty-eight phyla today, over 95 per cent of all animal species, taking account of all phyla, have eyes. (289)

'What triggered the evolution of the eye?' [...] Logic suggests the solution must lie in an event which led to an increase in light levels at the Earth's surface just prior to the Cambrian. (291)

... indeed the geologists have revealed an increase in sunlight levels at the Earth's surface precisely at the very end of the Precambrian. Due to its direct relationship with the Earth's magnetic field, an increase in luminosity is proportional to an increase in the elements carbon-14 and beryllium-10 preserved in the rocks. And temperatures increased on Earth at the time too. (292)

Cambrian life was exclusive marine. (292)

Some meteorologists suggest that a blanket fog (with various possible sources, including volcanic activity) cloaked the Earth's surface in the Precambrian, thus cloaking out a high proportion of sunlight like a giant umbrella. (292)

... we should consider changes in sea transparency. In terms of quality of light, or colours, today the sea acts as a narrow filter. Only a restricted range of wavelengths – mainly in the blue region – pierce seawater well, and the rest are absorbed or scattered. But change the mineral content of the sea and this filter may move within the spectrum or even wide. Could there have been an event at the Earth's surface that released minerals previously locked in rocks? (295)

... a mineral change in the water is the most likely explanation for increased light transmission in general (297)