

Chapter 1. A deeply religious nonbeliever¹.

I don't try to imagine a personal God; it suffices to stand in awe at the structure of the world, insofar as it allows our inadequate senses to appreciate it.

Albert Einstein

The boy lay prone in the grass, his chin resting on his hands. He suddenly found himself overwhelmed by a heightened awareness of the tangled stems and roots, a forest in microcosm, a transfigured world of ants and beetles and even – though he wouldn't have known the details at the time – of soil bacteria by the billions, silently and invisibly shoring up the economy of the micro-world. Suddenly the micro-forest of the turf seemed to swell and become one with the universe, and with the rapt mind of the boy contemplating it. He interpreted the experience in religious terms and it led him eventually to the priesthood. He was ordained an Anglican clergyman and became a chaplain at my school, a teacher of whom I was fond.²

In another time and place, that boy could have been me, under the stars, dazzled by Orion, Cassiopeia and Ursa Major, tearful with the unheard music of the Milky Way, heady with the night scents of frangipani and trumpet flowers in an African garden. Why the same emotion should have led my chaplain in one direction and me in the other is not an easy question to answer.

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¹ Opening paragraphs of *The God Delusion* by Richard Dawkins

² Our sport during lessons was to sidetrack him away from scripture and towards stirring tales of Fighter Command and the Few. He had done war service in the RAF and it was with familiarity, and something of the affection that I still retain for the Church of England (at least by comparison with the competition) that I later read John Betjeman's poem:

Our padre is an old sky pilot,
Severely now they've clipped his wings,
But still the flagstaff in the Rect'ry garden
Points to Higher Things . . .

***The Mother of All Burkas*³**

One of the unhappiest spectacles to be seen on our streets today is the image of a woman, swathed in shapeless black from head to toe, peering out at the world through a tiny slit. The burka is not just an instrument of oppression of women and claustal repression of their liberty and their beauty: not just a token of egregious male cruelty and tragic female submission. I want to use the narrow slit in the veil as a symbol of something else.

Our eyes see the world through a narrow slit in the electromagnetic spectrum. Visible light is a narrow chink of brightness in the vast dark spectrum, from radio waves at the long end to gamma rays at the short end. Quite *how* narrow is hard to appreciate and a challenge to convey. Imagine a gigantic black burka, with a vision slit of approximately the standard width, say about one inch. If the length of black cloth above the slit represents the short wave end of the invisible spectrum, and if the length of black cloth below the slit represents the long wave portion of the invisible spectrum, how long would the burka have to be in order to accommodate a one inch slit to the same scale? It is hard to represent it sensibly without invoking logarithmic scales, so huge are the lengths we are dealing with. The last chapter of a book like this is no place to start tossing logarithms around, but you can take it from me that it would be the mother of all burkas. The one inch window of visible light is derisively tiny compared with the miles and miles of black cloth representing the invisible part of the spectrum, from radio waves at the hem of the skirt to gamma rays at the top of the head. What science does for us is widen the window. It opens up so wide that the black garment drops away almost completely.

Optical telescopes use glass lenses and mirrors to scan the heavens, and what they see is stars that happen to be radiating in the narrow band of wavelengths that we call visible light. But other telescopes 'see' in the X-ray, or radio wavelengths, and present to us many alternative night skies. On a smaller scale, cameras with appropriate filters can 'see' in the ultraviolet and take photographs of flowers that show an alien range of stripes and spots that are visible to, and 'designed' for, insect eyes but which our unaided eyes can't see at all. Insect eyes have a spectral window of similar width to ours, but slightly shifted up the burka: they are blind to red and they see farther into the ultraviolet than we do - into the 'ultraviolet garden' as I have called it before.

The metaphor of the narrow window of light, broadening out into a spectacularly wide spectrum, serves us in other areas of science. We live near the centre of a vast museum of magnitudes, viewing the world through senses and a nervous system that are equipped to perceive and understand only a small middle range of sizes, moving at a middle range of speeds. We are at home with objects ranging in size from a few kilometres (the view from a mountaintop) to about a tenth of a millimetre (the point of a pin). Outside this range even our imagination is handicapped, and we need the help of

³ The last few pages of the book

numbers – which, fortunately, we can learn to deploy. The range of sizes, distances or speeds with which our imaginations are comfortable is a tiny band, set in the midst of a gigantic range of the possible, from the quantum scale at the smaller end to the scale of cosmology at the larger.

Our imaginations are forlornly under-equipped to cope with distances outside the small middle range of the ancestrally familiar. We try to visualize an electron as a tiny ball, in orbit around a larger cluster of balls representing protons and neutrons. That isn't what it is like at all. Electrons are not like little balls. They are not like anything we recognize. It isn't clear that 'like' even means anything when we try to fly too close to reality's further horizons. Our imaginations are not yet tooled-up to penetrate the neighbourhood of the quantum. Nothing at that scale behaves in the way matter – as we are trained to think – ought to behave. Nor can we cope with the behaviour of objects that move at some appreciable fraction of the speed of light. Common sense lets us down, because common sense evolved in a world where nothing moves very fast, and nothing is very small or very large.

At the end of a famous essay on 'Possible Worlds', the great biologist J B S Haldane wrote,

Now, my own suspicion is that the universe is not only queerer than we suppose, but queerer than we can suppose . . . I suspect that there are more things in heaven and earth than are dreamed of, or can be dreamed of, in any philosophy.

By the way, I am interested in the suggestion that the famous Hamlet speech to which Haldane was alluding is by convention wrongly spoken and understood. The normal stress is on 'your':

There are more things in heaven and earth, Horatio,
Than are dreamt of in *your* philosophy.

Indeed, the line is often plonkingly quoted with the implication that Horatio stands for shallow rationalists and sceptics everywhere. But some scholars place the stress on 'philosophy', with 'your' almost vanishing: ". . . than are dreamt of in *any philosophy*." The difference doesn't really matter for present purposes, except that the second interpretation already takes care of Haldane's 'any' philosophy.

The late Douglas Adams made a living from the strangeness of science, pushing it to the point of comedy. The following is taken from the same extempore speech in Cambridge in 1998 from which I have already quoted:-

The fact that we live at the bottom of a deep gravity well, on the surface of a gas-covered planet going around a nuclear fireball 90 million miles away and think this to be *normal* is obviously some indication of how skewed our perspective tends to be . . .

Where other science fiction writers played on the oddness of science to arouse our sense of the mysterious, Adams used it to make us laugh (those who have read *The Hitchhiker's Guide to the Galaxy* might think of the 'infinite improbability drive', for instance). Laughter is arguably the best response to

some of the stranger paradoxes of modern physics. The alternative, I sometimes think, is to cry.

Quantum mechanics, that rarefied pinnacle of twentieth century scientific achievement, makes brilliantly successful predictions about the real world. Richard Feynman compared its precision to predicting a distance as great as the width of North America to an accuracy of the width of one human hair. This predictive success seems to mean that quantum theory has got to be true in some sense. As true as anything we know, even including the most down-to-earth commonsense facts. Yet the *assumptions* that quantum theory needs to make, in order to deliver those predictions, are so mysterious that even Feynman himself was moved to remark (there are various versions of this quotation, of which the following seems to me the neatest):

If you think you understand quantum theory . . . you don't understand quantum theory.

Quantum theory is so queer that physicists resort to one or another paradoxical 'interpretation' of it. Resort is the right word. David Deutsch, in *The Fabric of Reality*, embraces the 'many worlds' interpretation of quantum theory, perhaps because the worst that you can say of it is that it is preposterously *wasteful*. It postulates a vast and rapidly growing number of universes, existing in parallel and mutually undetectable except through the narrow porthole of quantum mechanical experiments. In some of these universes I am already dead. In a small minority of them, you have a green moustache. And so on.

The alternative '**Copenhagen interpretation**' is equally preposterous – not wasteful, just shatteringly paradoxical. Erwin Schrödinger satirized it with his parable of the cat. Schrödinger's cat is shut up in a box with a killing mechanism triggered by a quantum-mechanical event. Before we open the lid of the box, we don't know whether the cat is dead. Commonsense tells us that, nevertheless, the cat must be either alive or dead inside the box. The Copenhagen interpretation contradicts commonsense: all that exists before we open the box is a probability. As soon as we open the box, the wave function collapses to the single event: the cat is dead, or the cat is alive. Until we opened the box, it was neither dead nor alive.

The many worlds interpretation of the same events is that in some universes the cat is dead. In other universes the cat is alive. Neither interpretation satisfies human common sense or intuition. The more macho physicists don't care. What matters is that the mathematics work, and the predictions are experimentally fulfilled. Most of us are too wimpish to follow them. We seem to *need* some sort of visualization of what is 'really' going on. I understand, by the way, that Schrödinger originally proposed his cat thought-experiment in order to expose what he saw as the absurdity of the Copenhagen interpretation.

The biologist **Lewis Wolpert** believes that the queerness of modern physics is just the tip of the iceberg. Science in general, as opposed to technology, does violence to common sense. Here's a favourite example: every time you drink a glass of water, the odds are good that you will imbibe at least one

molecule that passed through the bladder of Oliver Cromwell. It's just elementary probability theory. The number of molecules per glassful is hugely greater than the number of glassfuls in the world. So every time we have a full glass, we are looking at a rather high proportion of the molecules of water that exist in the world. There is, of course, nothing special about Cromwell, or bladders. You have just breathed in a nitrogen atom that was once breathed out by the third iguanodon to the left of the tall cycad tree. Aren't you glad to be alive in a world where not only are such conjectures true but you are privileged to understand why? And publicly explain it to somebody else, not as your opinion or belief but as something that they, when they have understood your reasoning, will feel compelled to accept. Maybe this is an aspect of what Carl Sagan meant when he explained his motive in writing *The Demon-haunted World: Science as a Candle in the Dark*:

Not explaining science seems to me perverse. When you're in love, you want to tell the world. This book is a personal statement, reflecting my lifelong love affair with science.

The evolution of complex life, indeed its very existence in a universe obeying physical laws, is wonderfully surprising – or would be but for the fact that surprise is an emotion that can exist only in a brain which is the product of that very surprising process. There is an anthropic sense, then, in which our existence should not be surprising. I'd like to think that I speak for my fellow humans in insisting, nevertheless, that it is desperately surprising.

Think about it. On one planet, and possibly only one planet in the entire universe, molecules, which would normally make nothing more complicated than a chunk of rock, gather themselves together into chunks of rock-sized matter of such staggering complexity that they are capable of running, jumping, swimming, flying, seeing, hearing, capturing and eating other such animated chunks of complexity; capable in some cases of thinking and feeling, and falling in love with yet other chunks of complex matter. We now understand essentially how the trick is done, but only since 1859. Before 1859 it would have seemed very very odd indeed. Now, thanks to Darwin, it is merely very odd. Darwin seized the window of the burka and wrenched it open, letting in a flood of light whose dazzling novelty, and power to uplift the human spirit, perhaps had no precedent – unless it was the Copernican realization that the earth was not the centre of the universe.

"Tell me", the great twentieth century philosopher Ludwig Wittgenstein once asked a friend, "Why do people always say it was natural for man to assume that the Sun went round the Earth rather than that the earth was rotating?" His friend replied, "Well, obviously because it just *looks* as though the Sun is going round the Earth." Wittgenstein responded, "Well, what would it have looked like if it had looked as though the Earth was rotating?" I sometimes quote this remark of Wittgenstein in lectures, expecting the audience to laugh. Instead, they seem stunned into silence.

In the limited world in which our brains evolved, small objects are more likely to move than large ones, which are seen as the background to movement. As the world rotates, objects that seem large because they are

near – mountains, trees and buildings, the ground itself – all move in exact synchrony with each other, relative to heavenly bodies such as the sun and stars. Because the sun and stars seem small by comparison, our evolved brains project an illusion of movement onto them rather than the mountains and trees in the foreground.

The point I now want to develop is that the way we see the world, and the reason why we find some things intuitively easy to grasp and others hard, is that *our brains are themselves evolved organs*: on-board computers, evolved to help us survive in a world – I shall call it Middle World – where the objects that mattered to our survival were neither very large nor very small; a world where things either stood still or moved slowly compared with the speed of light; and where the very improbable could safely be treated as impossible. Our mental burka window is narrow because it didn't *need* to be any wider in order to assist our ancestors to survive.

Science has taught us, against all evolved intuition, that apparently solid things like crystals and rocks are really composed almost entirely of empty space. The familiar illustration represents the nucleus of an atom as a fly in the middle of a sports stadium. The next atom is right outside the stadium. The hardest, solidest, densest rock, then, is 'really' almost entirely empty space, broken only by tiny particles so far apart that they shouldn't count. So why do rocks look and feel solid and hard and impenetrable?

I won't try to imagine how Wittgenstein might have answered that question. But, as an evolutionary biologist, I would answer it like this. Our brains have evolved to help our bodies find their way around the world on the scale at which those bodies operate. We never evolved to navigate the world of atoms. If we had, our brains probably *would* perceive rocks as full of empty space. Solid objects such as rocks feel hard and impenetrable to our hands because other such objects, including our hands, can't penetrate them. The reason they can't penetrate them is unconnected with the sizes and separations of the particles that constitute matter. Instead, it has to do with the force fields that are associated with those widely spaced particles. It is useful for our brains to *construct* notions like solidity and impenetrability, because such notions help us to navigate our bodies through the world in which we live, a world in which objects – which we call solid – cannot occupy the same space as each other.

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Having evolved in Middle World, we find it intuitively easy to grasp ideas like: "When a person moves, at the sort of medium velocity at which Middle World objects do move, and hits another solid Middle World object like a wall, his progress is painfully arrested." Our brains are not equipped to imagine what it would be like to be a neutrino passing through a wall, in the vast interstices of which that wall 'really' consists. Nor can our understanding cope with what happens when things move at close to the speed of light.

Unaided human intuition, evolved and schooled in Middle World, even finds it hard to believe Galileo when he tells us that a cannon ball and a feather, given no air friction, would hit the ground at the same instant. That is because, in Middle World, air friction is always there. If we had evolved in a vacuum, we would *expect* a feather and a cannonball to hit the ground simultaneously. We are evolved denizens of Middle World, and that limits what we are capable of imagining. The narrow window of our burka permits us, unless we are especially gifted or peculiarly well educated, to see only Middle World.

There is a sense in which we animals have to survive not just in Middle World but in the micro world of atoms and electrons too. The very nerve impulses with which we do our thinking and our imagining depend upon activities in Micro World. But no action that our wild ancestors ever had to perform, no decision that they ever had to take, would have been assisted by an understanding of Micro World. If we were bacteria, constantly buffeted by thermal movements of molecules, it would be different. But we Middle Worlders are too big to notice Brownian motion. Similarly, our lives are dominated by gravity but are almost oblivious to the force of surface tension. A small insect would reverse that priority.

Steve Grand, in *Creation: life and how to make it*, is almost scathing about our pre-occupation with matter itself. We have this tendency to think that only solid, material 'things' are 'really' things at all. 'Waves' of electromagnetic fluctuation in a vacuum seem 'unreal'. Victorians thought that waves had to be waves 'in' some material medium. No such medium was known, so they invented one and named it the luminiferous ether. But we find 'real' matter comfortable to our understanding only because our ancestors evolved to survive in Middle World where matter is a useful fiction.

On the other hand, even we Middle Worlders can see that a whirlpool is a 'thing' with something like the reality of a rock, even though the matter in the whirlpool is constantly changing. In a desert plain in Tanzania, in the shadow of the volcano Ol Donyo Lengai, there is a dune made of volcanic ash from an eruption in 1969. It is carved into shape by the wind. But the beautiful thing is that it *moves* bodily. It is what is technically known as a barchan (pronounced bahkahn). The entire dune walks across the desert in a westerly direction at a speed of about 17 metres per year. It retains its crescent shape and moves in the direction of the horns. The wind blows sand up the shallow slope on the other side. Then, as each sand grain hits the top of the ridge, it cascades down the steeper slope on the inside of the crescent.

Actually, even a barchan is more of a 'thing' than a wave. A wave *seems* to move horizontally across the open sea, but the molecules of water move vertically. Similarly, sound waves may travel from speaker to listener, but molecules of air don't: that would be a wind, not a sound. Steve Grand points out that you and I are more like a wave than a permanent 'thing'. He invites his reader to think . . .

. . . of an experience from your childhood. Something you remember clearly, something you can see, feel, maybe even smell, as if you

were really there. After all, you really were there at the time, weren't you? How else would you remember it? But here is the bombshell: you *weren't* there. Not a single atom that is in your body today was there when that event took place . . . Matter flows from place to place and momentarily comes together to be you. Whatever you are, therefore, you are not the stuff of which you are made. If that doesn't make the hair stand up on the back of your neck, read it again until it does, because it is important.

'Really' isn't a word we should use with simple confidence. If a neutrino had a brain which had evolved in neutrino-sized ancestors, it would say that rocks 'really' do consist mostly of empty space. We have brains that evolved in medium-sized ancestors, which couldn't walk through rocks, so our 'really' is a 'really' in which rocks are solid. 'Really', for an animal, is whatever its brain needs it to be, in order to assist its survival. And because different species live in such different worlds, there will be a discomfoting variety of 'reallys'.

What we see of the real world is not the unvarnished real world but a *model* of the real world, regulated and adjusted by sense data, a model that is constructed so that it is useful for dealing with the real world. The nature of that model depends on the kind of animal we are. A flying animal needs a different kind of world model from a walking, a climbing or a swimming animal. Predators need a different kind of model from prey, even though they may seem to be moving through the same world. A monkey's brain must have software capable of simulating a three-dimensional maze of branches and trunks. A water boatman's brain doesn't need 3-D software, since it lives on the surface of the pond in an Edwin Abbott Flatland. A mole's software for constructing models of the world will be customized for underground use. A naked mole rat probably has similar world-representing software similar to a mole's. But a squirrel, although it is a rodent like the mole rat, probably has world-representing software much more like a monkey's.

I've speculated, in *The Blind Watchmaker* and elsewhere, that bats may 'see' colour with their ears. The world-model that a bat needs, in order to navigate through three dimensions catching insects, must surely be similar to the model that a swallow needs in order to perform much the same task. The fact that the bat uses echoes to input the currently updated variables to its model, while the swallow uses light, is incidental. Bats, I suggest, use perceived hues such as 'red' and 'blue' as internal labels for some useful aspect of echoes, perhaps the acoustic texture of surfaces; just as swallows use the same perceived hues to label long and short wavelengths of light. The point is that the nature of the model is governed by how it is to be *used* rather than by the sensory modality involved. The lesson of the bats is this. The general form of the mind model – as opposed to the variables that are constantly being inputted by sensory nerves – is an adaptation to the animal's way of life, no less than its wings, legs and tail are.

J B S Haldane, in the article on 'possible worlds' that I quoted above, had something relevant to say about animals whose world is dominated by smell. He noted that dogs can distinguish two very similar volatile fatty acids –

caprylic acid and caproic acid – each diluted to one part in a million. The only difference is that caprylic acid's main molecular chain is two carbon atoms longer than the main chain of caproic acid. A dog, Haldane guesses, would probably be able to place the acids

. . . in the order of their molecular weights by their smells, just as a man could place a number of piano wires in the order of their lengths by means of their notes.

There is another fatty acid, capric acid, which is just like the other two except that it has yet two more carbon atoms in its main chain. A dog that had never met capric acid would perhaps have no more trouble imagining its smell than we would have trouble imagining a trumpet playing one note higher than we have heard a trumpet play before. It seems to me entirely reasonable to guess that a dog, or a rhinoceros, might treat mixtures of smells as harmonious chords. Perhaps there are discords. Probably not melodies, for melodies are built up of notes that start or stop abruptly with accurate timing, unlike smells. Or perhaps dogs and rhinos smell in colour. The argument would be the same as for the bats.

Once again, the perceptions that we call colours are tools used by our brains to label important distinctions in the outside world. Perceived hues – what philosophers call qualia – have no intrinsic connection with lights of particular wavelengths. They are labels which are *available* to the brain, when it constructs its model of reality, to make distinctions that are especially salient to the animal concerned. In our case, or that of a bird, that means light of different wavelengths. In a bat's case, I have speculated, it might be surfaces of different echoic properties or textures, perhaps red for shiny, blue for velvety. And in a dog's or a rhino's case, why should it not be smells? The power to imagine the alien world of a bat or a rhino, a pond skater or a mole, a bacterium or a bark beetle, is one of the privileges science grants us when it tugs at the black cloth of our burka and shows us the wider range of what is out there for our delight.

The metaphor of Middle World – of the intermediate range that the narrow slit in our burka permits us to see – applies to yet other scales or 'spectrums'. We can construct a scale of improbabilities, with a similarly narrow window through which our intuition and imagination are capable of going. At one extreme of the spectrum of improbabilities, are those would-be events that we call impossible. Miracles are events that are extremely improbable. A statue of a madonna could wave its hand at us. The atoms that make up its crystalline structure are all vibrating back and forth. Because there are so many of them, and because there is no agreed preference in their direction of motion, the hand, as we see it in Middle World, stays rock steady. But the atoms in the hand *could* all just *happen* to move in the same direction at the same time. And again. And again. In this case the hand would move, and we'd see it waving at us. It could happen, but the odds against are so great that, if you had set out writing the number at the origin of the universe, you still would not have written enough zeroes to this day. The power to calculate such odds – the power to quantify the impossible rather

than just throw up our hands in despair – is another example of the liberating benefactions of science to the human spirit.

Evolution in Middle World has equipped us poorly to handle very improbable events. But in the vastness of astronomical space, or geological time, events that seem impossible in Middle World turn out to be inevitable. Science flings open the narrow window through which we are accustomed to viewing the spectrum of possibilities. We are liberated by calculation and reason to visit regions of possibility that had once seemed out of bounds. We have already made use of this widening of the window in Chapter 4, where we considered the improbability of the origin of life and how even a seemingly impossible chemical event must come to pass given enough planet years to play with; and where we considered the spectrum of possible universes, each with its own set of laws and constants, and the anthropic necessity of finding ourselves in one of the minority of friendly places.

How should we interpret Haldane's "Queerer than we can suppose"? Queerer than can, *in principle*, be supposed? Or just queerer than *we* can suppose, given the limitation of our brains' evolutionary apprenticeship in Middle World? Could we, by training and practice, emancipate ourselves from Middle World, tear off our black burka, and achieve some sort of intuitive – as well as just mathematical – understanding of the very small, the very large, the very fast, and the very improbable? I genuinely don't know the answer, but I am thrilled to be alive at a time when humanity is pushing against the limits of understanding. Even better, we may eventually discover that there are no limits.