Life on the Edge
Also by Jim Al-Khalili:

Black Holes, Wormholes and Time Machines
Nucleus: A Trip into the Heart of Matter
Paradox: The Nine Greatest Enigmas in Science

Also by Johnjoe McFadden:

Quantum Evolution
Human Nature: Fact and Fiction
Life on the Edge
The Coming of Age of Quantum Biology

Jim Al-Khalili
and
Johnjoe McFadden
For
Penny and Ollie
Julie, David and Kate
The winter frost has arrived early this year in Europe and there is a penetrating chill in the evening air. Buried deep within a young robin’s mind, a once vague sense of purpose and resolve grows stronger.

The bird has spent the past few weeks devouring far more than her normal intake of insects, spiders, worms and berries and is now almost double the weight that she was when her brood flew the nest back in August. This extra bulk is mostly fat reserves, which she will require as fuel for the arduous journey upon which she is about to embark.

This will be her first migration away from the spruce forest in central Sweden where she has lived for the duration of her short life and where she reared her young chicks just a few months ago. Luckily for her, the previous winter was not too harsh, for a year ago she was not yet fully grown and therefore not strong enough to undertake such a long journey. But now, with her parental responsibilities discharged until next spring, she has only herself to think about, and she is ready to escape the coming winter by heading south to seek a warmer climate.

It is a couple of hours after sunset. Rather than settle for the night, she hops in the gathering gloom to the tip of a branch near the base of the huge tree that she has made her home since the spring. She gives herself a quick shake, much like a marathon runner loosening up her muscles before a race. Her orange breast glistens in the
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moonlight. The painstaking effort and care she invested in building her nest – just a few feet away, partially hidden against the moss-covered bark of the tree trunk – is now a dim memory.

She is not the only bird preparing to depart, for other robins – both male and female – have also decided that this is the right night to begin their long migration south. In the trees all around her she hears loud, shrill singing that drowns out the usual sounds of other nocturnal woodland creatures. It is as though the birds feel compelled to announce their departure, sending out a message to the other forest inhabitants that they should think twice before contemplating invading the birds’ territory and empty nests while they are gone. For these robins most certainly plan to be back in the spring.

With a quick tilt of her head this way and that to make sure the coast is clear, she takes off into the evening sky. The nights have been lengthening with winter’s advance and she will have a good ten hours or so of flying ahead of her before she can rest again.

She sets off on a course bearing of 195° (15° to the west of due south). Over the coming days she will carry on flying in, more or less, this same direction, covering two hundred miles on a good day. She has no idea what to expect along the journey, nor any sense of how long it will take. The terrain around her spruce wood is a familiar one, but after a few miles she is flying over an alien moonlit landscape of lakes, valleys and towns.

Somewhere near the Mediterranean she will arrive at her destination; although she is not heading for any specific location, when she does arrive at a favourable spot she will stop, memorizing the local landmarks so that she can return there in the coming years. If she has the strength, she may even fly all the way across to the North African coast. But this is her first migration, and her only priority now is to escape the biting cold of the approaching Nordic winter.

She seems oblivious to the surrounding robins that are all flying in roughly the same direction, some of which will have made the journey many times before. Her night vision is superb, but she is not looking for any landmarks – as we might were we making such a
journey – nor is she tracking the pattern of the stars in the clear night sky by consulting her internal celestial map, as many other nocturnal migrating birds do. Instead, she has a rather remarkable skill and several million years of evolution to thank for her capacity to make what will become an annual autumn migration, a trip of some two thousand miles.

Migration is, of course, commonplace in the animal kingdom. Every winter, for instance, salmon spawn in the rivers and lakes of northern Europe, leaving young fry that, after hatching, follow the course of their river out to sea and into the North Atlantic, where they grow and mature; three years later, these young salmon return to breed in the same rivers and lakes where they spawned. New World monarch butterflies migrate thousands of miles southward across the entire United States in the autumn. They, or their descendants (as they will breed en route), then return north to the same trees in which they pupated in the spring. Green turtles that hatch on the shores of Ascension Island in the South Atlantic swim across thousands of miles of ocean before returning, every three years, to breed on the exact same eggshell-littered beach from which they emerged. The list goes on: many species of birds, whales, caribou, spiny lobsters, frogs, salamanders and even bees are all capable of undertaking journeys that would challenge the greatest human explorers.

How animals manage to find their way around the globe has been a mystery for centuries. We now know that they employ a variety of methods: some use solar navigation during the day and celestial navigation at night; some memorize landmarks; others can even smell their way around the planet. But the most mysterious navigational sense of all is the one possessed by the European robin: the ability to detect the direction and strength of the earth’s magnetic field, known as magnetoreception. And while we now know of a number of other creatures that possess this ability, it is the way the European robin (Erithacus rubecula) finds her way across the globe that is of greatest interest to our story.

The mechanism that enables our robin to know how far to fly,
and in which direction, is encoded in the DNA she inherited from her parents. This ability is a sophisticated and unusual one – a *sixth sense* that she uses to plot her course. For, like many other birds, and indeed insects and marine creatures, she has the ability to sense the earth’s weak magnetic field and to draw directional information from it by way of an inbuilt navigational sense, which in her case requires a novel type of chemical compass.

Magnetoreception is an enigma. The problem is that the earth’s magnetic field is very weak – between 30 and 70 microtesla at the surface: sufficient to deflect a finely balanced and almost frictionless compass needle, but only about a hundredth the force of a typical fridge magnet. This presents a puzzle: for the earth’s magnetic field to be detected by an animal it must somehow influence a chemical reaction somewhere in the animal’s body – this is, after all, how all living creatures, ourselves included, sense any external signal. But the amount of energy supplied by the interaction of the earth’s magnetic field with the molecules within living cells is less than a billionth of the energy needed to break or make a chemical bond. How, then, can that magnetic field be perceptible to the robin?

Mysteries, however small, are fascinating because there’s always the possibility that their solution may lead to a fundamental shift in our understanding of the world. Copernicus’s ponderings in the sixteenth century on a relatively minor problem concerning the geometry of the Ptolemaic geocentric model of the solar system, for instance, led him to shift the centre of gravity of the entire universe away from humankind. Darwin’s obsession with the geographical distribution of animal species and the mystery of why isolated island species of finches and mockingbirds tend to be so specialized led him to propose his theory of evolution. And German physicist Max Planck’s solution to the mystery of blackbody radiation, concerning the way warm objects emit heat, led him to suggest that energy came in discrete lumps called ‘quanta’, leading to the birth of quantum theory in the year 1900. So, could the solution to the mystery of how
birds find their way around the globe lead to a revolution in biology? The answer, bizarre as it may seem, is: yes.

But mysteries such as this are also a haunt of pseudoscientists and mystics; as the Oxford chemist Peter Atkins stated in 1976, ‘the study of magnetic field effects on chemical reactions has long been a romping ground for charlatans’. Indeed, all manner of exotic explanations, from telepathy and ancient ley lines (invisible pathways connecting various archaeological or geographical sites that are supposedly endowed with spiritual energy) to the concept of ‘morphic resonance’ invented by the controversial parapsychologist Rupert Sheldrake, have at some point been proposed as mechanisms used by migratory birds to guide them along their routes. Atkins’s reservations in the 1970s were thus understandable, reflecting a scepticism prevalent among most scientists working at that time towards any suggestion that animals might be able to sense the earth’s magnetic field. There just did not seem to be any molecular mechanism that would allow an animal to do so – at least, none within the realms of conventional biochemistry.

But in the same year that Peter Atkins voiced his scepticism, Wolfgang and Roswitha Wiltschko, a German husband-and-wife team of ornithologists based in Frankfurt, published a breakthrough paper in *Science*, one of the world’s leading academic journals, which established beyond doubt that robins can indeed detect the earth’s magnetic field. More remarkably still, they showed that the birds’ sense did not seem to work the way a normal compass does. For while compasses tell the difference between magnetic north and south poles, a robin could only distinguish between pole and equator.

To understand how such a compass might work we need to consider magnetic field lines, the invisible tracks that define the direction of a magnetic field and along which a compass needle will align itself when placed anywhere in that field – most familiar to us as the lines in the pattern mapped out by iron filings on a piece of paper placed above a bar magnet. Now imagine the whole earth as a giant bar
magnet with the field lines emerging from its south pole and radiating outwards, curving round in loops to enter its north pole (see figure 1.1). The direction of these field lines near either pole is almost vertically into or out of the ground, but they become flatter and more nearly parallel to the surface of the planet the closer they are to the equator. So a compass that measures the angle of dip between the magnetic field lines and the surface of the earth, which we call an inclination compass, can distinguish between the direction towards a pole and the direction towards the equator; but it couldn’t distinguish between north and south poles, since the field lines make the same angle with the ground at either end of the globe. The Wiltschkos’ 1976 study established that the robin’s magnetic sense worked as just such an inclination compass. The problem was that no one had a clue how any such biological inclination compass might work, because there was at that time simply no known, or even conceivable, mechanism that could account for how the angle of dip of the earth’s magnetic field could be detected within an animal’s body. The
answer turned out to be within one of the most startling scientific theories of modern times, and it had to do with the strange science of quantum mechanics.

A hidden spooky reality

Take a straw poll today among scientists asking them what they think is the most successful, far-reaching and important theory in the whole of science and the answer will likely depend on whether you are asking someone working in the physical or the life sciences. Most biologists regard Darwin’s theory of evolution by natural selection as the most profound idea ever conceived. However, a physicist is likely to argue that quantum mechanics should have pride of place – after all, it is the foundation on which much of physics and chemistry are built and gives us a remarkably complete picture of the building blocks of the entire universe. Indeed, without its explanatory power, much of our current understanding of how the world works disappears.

Almost everyone will have heard of ‘quantum mechanics’, and the idea that this is a baffling and difficult area of science understood only by a tiny, very smart minority of humans is very much part of popular culture. Yet the truth is that quantum mechanics has been part of all our lives since the early twentieth century. The science was developed as a mathematical theory in the mid-1920s to account for the world of the very small (the microworld, as it’s called), which is to say the behaviour of the atoms that make up everything we see around us and the properties of the even tinier particles that make up those atoms. For example, in describing the rules obeyed by electrons and how they arrange themselves within atoms, quantum mechanics underpins the whole of chemistry, material science and even electronics. Despite its strangeness, its mathematical rules lie at the very heart of most of the technological advances of the past half-century. Without quantum mechanics’ explanation of how electrons move through materials, we would not have understood the behaviour of the
semiconductors that are the foundation of modern electronics, and without an understanding of semiconductors we would not have developed the silicon transistor and, later, the microchip and the modern computer. The list goes on: without the advances in our knowledge thanks to quantum mechanics there would be no lasers and so no CD, DVD or blu-ray players; without quantum mechanics we would not have smartphones, satellite navigation or MRI scanners. In fact, it has been estimated that over one-third of the gross domestic product of the developed world depends on applications that would simply not exist without our understanding of the mechanics of the quantum world.

And this is just the beginning. We can look forward to a quantum future – in all likelihood within our own lifetimes – in which near-limitless electric power may become available from laser-driven nuclear fusion; when artificial molecular machines will be carrying out a vast array of tasks in the fields of engineering, biochemistry and medicine; when quantum computers will be providing artificial intelligence; and when potentially even the sci-fi technology of teleportation will be routinely used to transmit information. The twentieth century’s quantum revolution is picking up pace in the twenty-first century and will transform our lives in unimaginable ways.

But what exactly *is* quantum mechanics? This is a question we will be exploring throughout this book; for a taster, we will start here with a few examples of the hidden quantum reality that underpins our lives.

Our first example illustrates one of the strange features of the quantum world, arguably its defining feature: wave–particle duality. We are familiar with the fact that we and all the things around us are composed of lots of tiny, discrete particles such as atoms, electrons, protons and neutrons. You may also be aware that energy, such as light or sound, comes as waves, rather than particles. Waves are spread out, rather than particulate; and they flow through space as – well, waves, with peaks and troughs like the waves of the sea. Quantum mechanics
was born when it was discovered in the early years of the twentieth century that subatomic particles can behave like waves; and light waves can behave like particles.

Although wave–particle duality is not something you need to consider every day, it is the basis of lots of very important machines, such as the electron microscopes that allow doctors and scientists to see, identify and study tiny objects too small to show up under traditional optical microscopes, such as the viruses that cause AIDS or the common cold. The electron microscope was inspired by the discovery that electrons have wave-like properties. The German scientists Max Knoll and Ernst Ruska realized that, since the wavelength (the distance between successive peaks or troughs of any wave) associated with electrons was much shorter than the wavelength of visible light, a microscope based on electron imaging should be able to pick out much finer detail than an optical microscope. This is because any tiny object or detail that has dimensions smaller than the wave falling on it will not influence or affect the wave. Think of ocean waves with wavelengths of several metres washing up against pebbles on the beach. You would not be able to learn anything about the shape or size of an individual pebble by studying the waves. You would need much shorter wavelengths, such as those produced in a ripple tank, of the type everyone encounters in school science lessons, to ‘see’ a pebble by the way that waves bounce off it or diffract around it. So, in 1931, Knoll and Ruska built the world’s first electron microscope and used it to take the first ever pictures of viruses, for which Ernst Ruska was awarded the Nobel Prize, perhaps rather belatedly, in 1986 (two years before he died).

Our second example is even more fundamental. Why does the sun shine? Most people are probably aware that the sun is essentially a nuclear fusion reactor that burns hydrogen gas to release the heat and sunlight that sustain all life on earth; but fewer people know that it wouldn’t shine at all were it not for a remarkable quantum property that allows particles to ‘walk through walls’. The sun, and indeed all stars in the universe, is able to emit these vast amounts of energy
because nuclei of hydrogen atoms, each composed of just a single positively charged particle called a proton, are able to fuse, and as a result to release energy in the form of the electromagnetic radiation that we call sunlight. Two hydrogen nuclei have to be able to get very close in order to fuse; but the closer they get, the stronger the repulsive force between them becomes, as each carries a positive electric charge and ‘like’ charges repel. In fact, for them to get close enough to fuse, the particles have to be able to get through the subatomic equivalent of a brick wall: an apparently impenetrable energy barrier. Classical physics* – built upon Isaac Newton’s laws of motion, mechanics and gravity, which describe very well the everyday world of balls, springs, steam engines (and even planets) – would predict that this shouldn’t happen; particles should not be able to pass through walls and therefore the sun shouldn’t shine.

But particles that obey the rules of quantum mechanics, such as atomic nuclei, have a neat trick up their sleeve: they can easily pass through such barriers via a process called ‘quantum tunnelling’. And it is essentially their wave–particle duality that enables them to do this. Just as waves can flow around objects, like the pebbles on the seashore, they can also flow through objects, like the sound waves that pass through your walls when you hear your neighbour’s TV. Of course, the air that carries sound waves doesn’t actually pass through the walls itself: it’s the vibrations in the air – sound – that cause your common wall to vibrate and push on the air in your room to transmit the same sound waves to your ear. But if you could behave like an atomic nucleus then you would sometimes be able to pass, ghost-like, straight through a solid wall.† A hydrogen nucleus in the interior of the

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* Conventionally, the deterministic physical theories that preceded quantum mechanics, including special and general relativity, are collectively referred to as classical physics – as distinct from non-classical quantum mechanics.

† Although it would be wrong to think that quantum tunnelling entails the leaking through barriers of physical waves; rather, it is due to abstract mathematical waves that provide us with the probability of instantaneously finding the quantum particle on the other side of the barrier. We try in this book to provide intuitive analogies wherever possible to explain quantum phenomena, but the reality is that quantum mechanics is utterly counterintuitive and there is a danger of oversimplifying for the purposes of clarity.
sun manages to do precisely this: it can spread itself out and ‘leak’ through the energy barrier like a phantom, to get close enough to its partner on the other side of the wall to fuse. So when you are next sunning yourself on the beach, watching the waves lapping on the seashore, spare a thought for the spooky wave-like motions of quantum particles that not only allow you to enjoy the sunshine but make all life on our planet possible.

The third example is related, but illustrates a different and even weirder feature of the quantum world: a phenomenon called superposition whereby particles can do two – or a hundred, or a million – things at once. This property is responsible for the fact that our universe is richly complex and interesting. Not long after the Big Bang through which this universe came into being, space was awash with just one type of atom: the simplest in structure, hydrogen, which is made up of one positively charged proton and one negatively charged electron. It was a rather dull place, with no stars or planets and definitely no living organisms, because the elemental building blocks of everything around us, including us, consist of more than just hydrogen, including heavier elements such as carbon, oxygen and iron. Fortunately, these heavier elements were cooked up inside the hydrogen-filled stars; and their starting ingredient, a form of hydrogen known as deuterium, owes its existence to a bit of quantum magic.

The first step in the recipe is the one we’ve just described, when two hydrogen nuclei, protons, get close enough together via quantum tunnelling to release some of that energy that turns into the sunlight that warms our planet. Next, the two protons have to bind together, and this is not straightforward because the forces between them don’t provide a strong enough glue. All atomic nuclei are composed of two types of particles: protons and their electrically neutral partners, neutrons. If a nucleus has too many of one type or the other, then the rules of quantum mechanics dictate that the balance has to be redressed and those excess particles will change into the other form: protons will become neutrons, or neutrons protons, via
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a process called beta-decay. This is precisely what happens when two protons come together: a composite of two protons cannot exist and one of them will beta-decay into a neutron. The remaining proton and the newly transformed neutron can then bind together to form an object called a deuteron (the nucleus of an atom of the heavy hydrogen isotope* called deuterium), after which further nuclear reactions enable the building of the more complex nuclei of other elements heavier than hydrogen, from helium (with two protons and either one or two neutrons) through to carbon, nitrogen, oxygen, and so on.

The key point is that the deuteron owes its existence to its ability to exist in two states simultaneously, by virtue of quantum superposition. This is because the proton and neutron can stick together in two different ways that are distinguished by how they spin. We will see later how this concept of ‘quantum spin’ is actually very different from the familiar spin of a big object, such as a tennis ball; but for now we will go with our classical intuition of a spinning particle and imagine both the proton and the neutron spinning together within the deuteron in a carefully choreographed combination of a slow, intimate waltz and a faster jive. It was discovered back in the late 1930s that within the deuteron these two particles are not dancing together in either one or the other of these two states, but in both states at the same time – they are in a blur of waltz and jive simultaneously – and it is this that enables them to bind together.†

An obvious response to this statement is: ‘How do we know?’ Surely, atomic nuclei are far too small to be seen, so might it not be more reasonable to assume that there is something missing in our understanding of nuclear forces? The answer is no, for it has been

* All chemical elements come in different varieties called isotopes. An element is defined by the number of protons in the nuclei of its atoms: hydrogen has one, helium two, and so on. But the number of neutrons the nucleus contains can vary. Thus, hydrogen comes in three varieties (isotopes): the atoms of normal hydrogen contain just a single proton, while those of the heavier isotopes, deuterium and tritium, also contain one and two neutrons, respectively.
† Technically, the deuteron owes its stability to a feature of the nuclear force that holds the proton and neutron together called the ‘tensor interaction’, which forces the pair to be in a quantum superposition of two angular momentum states, called S-wave and D-wave.
confirmed in many laboratories over and over again that if the proton and neutron were performing the equivalent of either a quantum waltz or a quantum jive, then the nuclear ‘glue’ between them would not be quite strong enough to bind them together; it is only when these two states are superimposed on top of each other – the two realities existing at the same time – that the binding force is strong enough. Think of the two superposed realities as a little like mixing two coloured paints, blue and yellow, to make a combined resultant colour, green. Although you know the green is made up of the two primary constituent colours, it is neither one nor the other. And different ratios of blue and yellow will make different shades of green. Likewise, the deuteron binds when the proton and neutron are mostly locked in a waltz, with just a tiny amount of jive thrown in.

So if particles couldn’t jive and waltz simultaneously our universe would have remained a soup of hydrogen gas and nothing more – no stars would shine, none of the other elements would have formed and you would not be reading these words. We exist because of the ability of protons and neutrons to behave in this quantum counterintuitive way.

Our last example takes us back into the world of technology. The nature of the quantum world can be exploited not only to view tiny objects like viruses but also to see inside our bodies. Magnetic resonance imaging (MRI) is a medical scanning technique that generates marvellously detailed images of soft tissue. MRI scans are routinely used to diagnose disease and particularly to detect tumours inside internal organs. Most non-technical accounts of MRI avoid mentioning the fact that the technique depends on the weird way that the quantum world works. MRI uses big powerful magnets to align the axes of spinning nuclei of hydrogen atoms within the patient’s body. These atoms are then zapped with a pulse of radio waves, which forces the aligned nuclei to exist in that strange quantum state of spinning in both directions at once. It is pointless even trying to visualize what this entails, because it is so far removed from our everyday experience! What is important is that when the atomic nuclei relax
back to their initial state – the state they were in before they received the pulse of energy that jolted them into a quantum superposition – they release this energy, which is picked up by the electronics in the MRI scanner and used to create those beautifully detailed images of your inner organs.

So if you do ever find yourself lying in an MRI scanner, perhaps listening to music piped through your headphones, take a moment to ponder the counterintuitive quantum behaviour of subatomic particles that makes this technology possible.

Quantum biology

What does all this quantum weirdness have to do with the flight of the European robin as she navigates across the globe? Well, you will remember that the Wiltschkos’ research in the early 1970s established that the robin’s magnetic sense worked in the same way as an inclination compass. This was extraordinarily puzzling because, at the time, no one had a clue how a biological inclination compass might work. However, around the same time a German scientist called Klaus Schulten became interested in how electrons were transferred in chemical reactions involving free radicals. These are molecules that have lone electrons in their outer electron shell, in contrast to most electrons, which are paired up in atomic orbitals. This is important when considering that weird quantum property of spin, since paired electrons tend to spin in opposite directions, so their total spin cancels to zero. But, without a spin-cancelling twin, the lone electrons in free radicals have a net spin that gives them a magnetic property: their spin can be aligned with a magnetic field.

Schulten proposed that pairs of free radicals generated by a process known as a fast triplet reaction could have their corresponding electrons ‘quantum entangled’. For subtle reasons that should become clear later on, such a delicate quantum state of the two separated electrons is highly sensitive to the direction of any external magnetic field. Schulten then went on to propose that the enigmatic
avian compass might be using this kind of quantum entanglement mechanism.

We haven’t mentioned quantum entanglement yet because it is probably the strangest feature of quantum mechanics. It allows particles that were once together to remain in instant, almost magical, communication with each other, despite being separated by huge distances. For example, particles that were once close but are later separated so far apart as to be located at opposite sides of the universe can, in principle at least, still be connected. In effect, prodding one particle would prompt its distant partner to jump *instantaneously.*

Entanglement was shown by the quantum pioneers to follow naturally from their equations, but its implications were so extraordinary that even Einstein, who gave us black holes and warped space-time, refused to accept it, deriding it as ‘spooky action at a distance’. And it is indeed this spooky action at a distance that so often intrigues ‘quantum mystics’ who make extravagant claims for quantum entanglement, for example that it accounts for paranormal ‘phenomena’ such as telepathy. Einstein was sceptical because entanglement appeared to violate his theory of relativity, which stated that no influence or signal can ever travel through space faster than the speed of light. Distant particles should not, according to Einstein, possess instantaneous spooky connections. In this, Einstein was wrong: we now know empirically that quantum particles really can have instantaneous long-range links. But, just in case you are wondering, quantum entanglement can’t be invoked to validate telepathy.

The idea that the weird quantum property of entanglement was involved in ordinary chemical reactions was considered outlandish in the early 1970s. At the time, many scientists were with Einstein in doubting whether entangled particles really existed at all, as no one had yet detected them. But over the decades since then, many ingenious laboratory experiments have confirmed the reality of these

* We should clarify that quantum physicists do not use this sort of simplistic language. More correctly, two distant yet entangled particles are said to be non-locally connected because they are parts of the same quantum state. But then, saying it like that doesn’t help much, does it?
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spooky connections; and the most famous of them was conducted as early as 1982 by a team of French physicists led by Alain Aspect at the University of Paris-South.

Aspect’s team generated pairs of photons (particles of light) with entangled polarization states. Light polarization is probably most familiar to us through wearing polarized sunglasses. Every photon of light has a kind of directionality, its angle of polarization, which is a bit like the property of spin that we introduced earlier.* The photons in sunlight come with all possible polarization angles, but polarized sunglasses filter them, allowing through only those photons that have one particular polarization angle. Aspect generated pairs of photons with polarization directions that were not only different – let’s say that one was pointing up and the other down – but entangled; and, like our previous dancing partners, neither of the entangled pair was actually pointing one way or another: they were both pointing in both directions simultaneously, until they were measured.

Measurement is one of the most mysterious – and certainly the most argued about – aspects of quantum mechanics, as it relates to the question that we are sure has occurred to you already: why don’t all objects we see do all these weird and wonderful things that quantum particles can do? The answer is that, down in the microscopic quantum world, particles can behave in these strange ways, like doing two things at once, being able to pass through walls, or possessing spooky connections, only when no one is looking. Once they are observed, or measured in some way, they lose their weirdness and behave like the classical objects that we see around us. But then, of course, this only throws up another question: what is so special about measurement that allows it to convert quantum behaviour to classical behaviour?† The answer to this question is crucial to

* However, since light can be thought of as a wave as well as a particle, the notion of polarization (unlike quantum spin) can be more easily understood as the direction in which a light wave oscillates.
† Again, in striving for clarity we are deliberately being overly simplistic here. Measuring a certain property of a quantum particle, say its position, means we are no longer uncertain about where it is – in a sense, it is brought into focus and ceases to be fuzzy. However, this
our story, because measurement lies on the borderline between the quantum and classical worlds, the quantum edge, where we, as you will have guessed from the title of this book, are claiming life also lies.

We will be exploring quantum measurement throughout this book and we hope that you will gradually get to grips with the subtleties of this mysterious process. For now, we will just consider the simplest interpretation of the phenomenon and say that when a quantum property, such as polarization state, is measured by a scientific instrument then it is instantly forced to forget its quantum abilities, such as pointing in many directions simultaneously, and must take on a conventional classical property, such as pointing in a single direction only. So, when Aspect measured the polarization state of one of any pair of entangled photons, by observing whether it could pass through a polarized lens, it instantly lost its spooky connection with its partner and adopted just a single polarization direction. And so did its partner, instantly, no matter how far away it was; at least, that’s what the equations of quantum mechanics predicted, which was of course exactly what made Einstein uneasy.

Aspect and his team carried out their famous experiment for pairs of photons that had been separated by several metres in his laboratory, far enough away that not even an influence travelling at the speed of light – and relativity tells us that nothing can travel faster than the speed of light – could have passed between them to coordinate their angles of polarization. Yet the measurements on paired particles were correlated: when one photon’s polarization was pointing up, the other’s was found to point down. Since 1982, the experiment has been repeated even for particles separated by
does not mean it now behaves like a classical particle. Due to Heisenberg’s Uncertainty Principle it now no longer has a fixed velocity. Indeed, a particle in a definite position will, at that moment in time, be in a superposition of moving at all possible speeds in all possible directions. And as for quantum spin, since this property is only found in the quantum world, measuring it certainly does not make the particle behave classically.
hundreds of miles, and they still possess that spooky entangled connection that Einstein couldn’t accept.

Aspect’s experiment was still a few years away when Schulten proposed that entanglement was involved in the avian compass, and the phenomenon was still controversial. Also, Schulten had no idea how such an obscure chemical reaction could allow a robin to see the earth’s magnetic field. We say ‘see’ here because of another peculiarity discovered by the Wiltschkos. Despite the European robin being a nocturnal migrant, activation of its magnetic compass required a small amount of light (around the blue end of the visible spectrum), hinting that the bird’s eyes played a significant role in how it worked. But, aside from vision, how did its eyes also help provide a magnetic sense? With or without a radical pair mechanism, this was a complete mystery.

The theory that the avian compass had a quantum mechanism languished in the scientific back drawer for more than twenty years. Schulten moved back to the US where he set up a very successful theoretical chemical physics group at the University of Illinois at Urbana-Champaign. But he never forgot his outlandish theory, and continually rewrote a paper proposing candidate biomolecules (molecules that are made by living cells) that might generate the radical pairs necessary for the fast triplet reaction. But none really fitted the bill: either they couldn’t generate radical pairs or they weren’t present in birds’ eyes. But in 1998 Schulten read that an enigmatic light receptor, called cryptochrome, had been found in animal eyes. This immediately set his scientific alarm bell ringing, because cryptochrome was known to be a protein that could potentially generate radical pairs.

A talented PhD student called Thorsten Ritz had recently joined Schulten’s group. As an undergraduate at the University of Frankfurt, Ritz had heard Schulten give a talk on the avian compass and was hooked. When the opportunity arose, he jumped at the chance of doing a PhD in Schulten’s lab, working initially on photosynthesis. When the cryptochrome story broke he shifted to working
on magnetoreception, and in 2000 he wrote a paper with Schulten entitled ‘A model for photoreceptor-based magnetoreception in birds’, describing how cryptochrome could provide the avian eye with a quantum compass. (We will revisit this subject more fully in chapter 6.) Four years later, Ritz teamed up with the Wiltschkos to perform a study of European robins that provided the first experimental evidence in support of this theory that birds use quantum entanglement to navigate around the globe. Schulten, it seemed, had been right all along. Their 2004 paper, published in the prestigious UK-based journal *Nature*, sparked a huge amount of interest and the avian quantum compass instantly became the poster child for the new science of quantum biology.

*Figure 1.2: Attendees at the 2012 Surrey workshop on quantum biology. From left to right: the authors, Jim Al-Khalili and Johnjoe McFadden; Vlatko Vedral, Greg Engel, Nigel Scrutton, Thorsten Ritz, Paul Davies, Jennifer Brookes and Greg Scholes.*
If quantum mechanics is normal, why should we be excited about quantum biology?

We earlier described quantum tunnelling and quantum superposition both in the heart of the sun and in technological devices such as electron microscopes and MRI scanners. So why should we be surprised if quantum phenomena turn up in biology? Biology is, after all, a kind of applied chemistry, and chemistry is a kind of applied physics. So isn’t everything, including us and other living creatures, just physics when you really get down to the fundamentals? This is indeed the argument of many scientists who accept that quantum mechanics must, at a deep level, be involved in biology; but they insist that its role is trivial. What they mean by this is that since the rules of quantum mechanics govern the behaviour of atoms, and biology ultimately involves the interaction of atoms, then the rules of the quantum world must also operate at the tiniest scales within biology – but only at those scales, with the result that they will have little or no effect on the scaled-up processes important to life.

These scientists are, of course, at least partly right. Biomolecules such as DNA or enzymes are made of fundamental particles like protons and electrons whose interactions are governed by quantum mechanics. But then, so is the structure of the book you are reading or the chair you are sitting on. The way you walk or talk or eat or sleep or even think must ultimately depend on quantum mechanical forces governing electrons, protons and other particles, just as the operation of your car or your toaster depends, ultimately, on quantum mechanics. But, by and large, you don’t need to know that. Car mechanics aren’t required to attend college courses on quantum mechanics, and most biology curricula don’t include any mention of quantum tunnelling, entanglement or superposition. Most of us can get by without knowing that, at a fundamental level, the world operates according to an entirely different set of rules from those that we are familiar with. The weird quantum stuff that happens at the level
of the very small doesn’t usually make a difference to the big stuff like cars or toasters that we see and use every day.

Why not? Footballs don’t pass through walls; people don’t have spooky connections (despite the bogus claims of telepathy); and, sadly, you cannot be both at the office and at home at the same time. Yet the fundamental particles inside a football, or a person, can do all of these things. Why is there a fault line, an edge, between the world that we see and the world that physicists know really exists beneath its surface? This is one of the deepest problems in the whole of physics, and one that relates to the phenomenon of quantum measurement we introduced a little earlier. When a quantum system interacts with a classical measuring device, such as the polarizing lens in Alain Aspect’s experiment, it loses its quantum weirdness and behaves like a classical object. But the measurements carried out by physicists cannot be responsible for the way the world we see around us appears. So what is it that carries out the equivalent quantum-behaviour-destroying function outside the physics laboratory?

The answer has to do with the way particles are arranged and how they move within large (macroscopic) objects. Atoms and molecules tend to be randomly scattered and vibrating erratically inside inanimate solid objects; in liquids and gases they are also in a constant state of random motion due to heat. These randomizing factors – scattering, vibrations and motion – cause the wavy quantum properties of particles to dissipate very quickly. So it is the combined action of all the quantum constituents of a body that performs the ‘quantum measurement’ on each and all of them, thereby making the world we see around us look normal. To observe the quantum weirdness you either have to go to unusual places (such as the interior of the sun), peer deep into the microworld (with instruments like electron microscopes) or carefully line up the quantum particles so that they are marching in step (as happens to the spins of hydrogen nuclei within your body when it is inside an MRI scanner – until the magnet is turned off, when the spin orientation of the nuclei is randomized again, cancelling out the quantum
coherence once more). The same kind of molecular randomization is responsible for the fact that we can get by without quantum mechanics most of the time: all the quantum weirdness is washed away inside the randomly orientated and constantly moving molecular interiors of the visible inanimate objects that we see around us.

Most of the time . . . but not always. As Schulten discovered, the speed of the fast triplet chemical reaction could only be accounted for when that delicate quantum property of entanglement was involved. But the fast triplet reaction is just that: fast. And it only involves a couple of molecules. For it to be responsible for bird navigation it would have to have a lasting effect on an entire robin. So the claim that the avian magnetic compass was quantum entangled was a wholly different level of proposition from the claim that entanglement was involved in an exotic chemical reaction involving just a couple of particles; and it was met with considerable scepticism. Living cells were thought to be composed mostly of water and biomolecules in a constant state of molecular agitation that would be expected to instantly measure and scatter those weird quantum effects. By ‘measure’ here we do not of course mean that water molecules or biomolecules perform a measurement in the sense that we might measure the weight or the temperature of an object and then make a permanent record of this value on paper or on a computer’s hard drive, or even only in our brain. What we are talking about here is what happens when a water molecule bumps into one of a pair of entangled particles: its subsequent motion will be affected by the state of that particle, so that if you were to study the water molecule’s subsequent motion you could deduce some of the properties of the particle it had bumped into. So, in this sense, the water molecule has carried out a ‘measurement’ because its motion provides a record of the state of the entangled pair, whether or not anyone is there to examine it. This kind of accidental measurement is usually sufficient to destroy entangled states. So the claim that delicately arranged quantum entangled states could survive in the warm and complex
introduction of living cells was thought by many to be an outlandish idea, verging on madness.

Yet in recent years our knowledge of such things has made huge strides – and not only in connection with birds. Quantum phenomena such as superposition and tunnelling have been detected in lots of biological phenomena, from the way plants capture sunlight to the way that all our cells make biomolecules. Even our sense of smell or the genes that we inherit from our parents may depend on the weird quantum world. Research papers on quantum biology are now appearing regularly in the pages of the world’s most prestigious scientific journals; and there exists a small but growing number of scientists who insist that aspects of quantum mechanics do indeed play a non-trivial, indeed crucial, role in the phenomenon of life, and that life is in a unique position to sustain these weird quantum properties at the edge between the quantum and classical worlds.

That these scientists are indeed few in number was made clear to us when we hosted an international workshop on quantum biology at the University of Surrey in September 2012 that was attended by most of those working in the field and managed to fit them all into a small lecture theatre. But the field is growing rapidly, driven by the excitement of discovering roles for quantum mechanics in everyday biological phenomena. And one of the most exciting areas of research – the one that might have huge implications for the development of new quantum technologies – is the recent unravelling of the mystery of how quantum weirdness manages to survive in hot, wet and messy living bodies.

But to fully appreciate the significance of these findings we must first ask a deceptively simple question: what is life?