Quantum biology: an introduction

A talk at the Royal Institution, London, 28 January 2015

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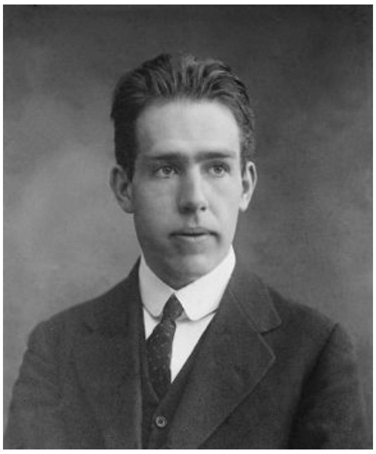
Like most trendy fads in science, quantum biology is rather old. I want to suggest that it begins on the 15th August 1932, when the Danish physicist Niels Bohr gave a talk at a very unlikely meeting, the International Congress on Light Therapy, in Copenhagen. Bohr's title was "Light and Life", and he offered some thoughts on what the new theory of quantum mechanics, which he had helped to formulate in Copenhagen during the previous decade, had to say about biology[1].



Niels Bohr (1885-1962)

Well, Bohr was the right man for the job. Not because he had any real understanding of the answer to that question, but because he wasn't someone to let ignorance get in the way of speculation. And I mean that in a good way. When smart people like Bohr are prepared to stick their necks out and say something on a topic on which they know rather little, there's always the chance that they'll spout nonsense, but a still better chance that they'll spark something valuable.

In his talk, Bohr asked "whether some fundamental traits are still missing in the analysis of natural phenomena, before we reach an understanding of life on the basis of physical experience" (by which he meant on the basis of physics). But he left this suggestion vague, and it's not really what Bohr said in his talk that matters, as much as who was listening. Bohr had been very anxious to make sure that among his audience was a young German theoretical physicist named Max Delbrück. Soon after he returned from Copenhagen to Berlin, Delbrück decided that the kind of missing trait that Bohr had alluded to might be found by studying the physical and chemical nature of genetics. Delbrück didn't mean by this that physics might explain genetics, but rather that by studying genetics he might uncover some new principle of physics.

Max Delbrück (1906-1981)

Remember that at this stage virtually nothing was known about the molecular origins of genetics. People had begun to understand how genes evolve in a population according to Darwinian principles, but they had no idea what genes were, not even that they were associated with DNA.

In 1937 Delbrück went to America, where he began to investigate the genetics of bacterial viruses, since they were a very simple form of life. This work eventually won him a Nobel Prize for his work on the genetics of viral replication. Delbrück established the idea of genetics as an information science: it was all about transmitting information.

He also helped to stimulate the interest of other physicists in biology. One of them was Erwin Schrödinger, who, in Dublin in 1944 after having fled the Nazi regime, published an extremely influential little book called *What is Life*?

Erwin Schrödinger (1887-1961)

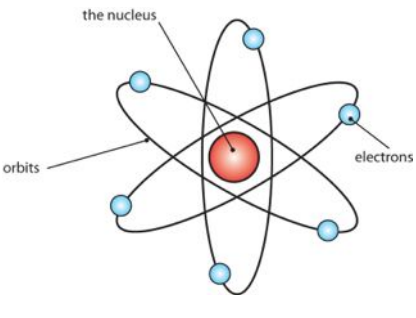
Here Schrödinger pondered the question of how an event at the atomic scale – a mutation in the molecular structure of a gene – which should be governed by the laws of quantum mechanics could potentially cause a profound and visible change in the structure of a living organism. Schrödinger speculated that these genes must be something that he called an “aperiodic crystal”: that is, an arrangement of atoms that was highly specific and not random, but neither having a regularly repeating atomic structure like a crystal. Another physicist lured into biology by Delbrück's work on replication was Francis Crick, who of course in 1953, with James Watson, showed that Schrödinger was right: that genes are made up of very specific sequences of molecular components along the double helix of DNA. According to the eminent molecular biologist Gunther Stent, Crick and Watson's discovery brought about the wedding of the "informational school" of Delbrück with the "structural school" of crystallographers looking at the atomic structures of biological molecules – and this, Stent says, made molecular biology what it is today[2].

So there you have it. It wasn't just that physics that created modern biology; it was specifically *quantum* physics that did it.

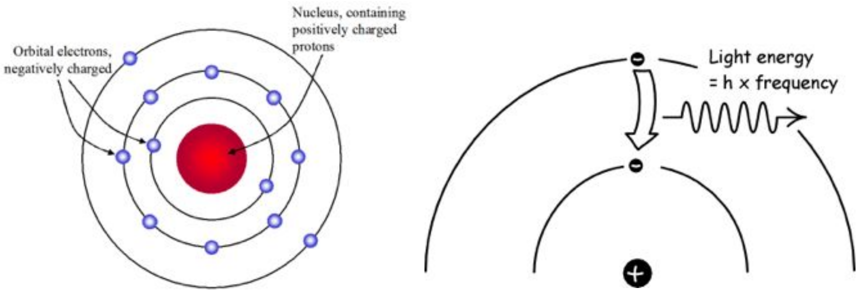
That's all very satisfactory for smug physicists. But it doesn't say anything about Bohr's intuition that quantum physics has any actual role in biology. Of course, in a trivial sense it must do, because as Bohr himself showed in the 1913 papers in which he laid out his famous theory of the quantum atom[3], quantum mechanics can explain why it is that atoms bond together to form molecules like the proteins and DNA and RNA on which all life depends. In this sense quantum theory is at the root of everything: we need it to explain why I'm standing here talking to you.

I know that quantum theory seems scary or mysterious to some people who are not so familiar with it, and here one is usually supposed to reassure you with Richard Feynman's famous quip that *no-one* understands quantum theory, and that if you think you do, it shows that you don't. But while this is true at the level I think Feynman intended, it doesn't mean that quantum theory is hard to understand. It's just hard to understand what it *means*. The challenge is not in *understanding* what quantum theory says, but in *accepting* it.

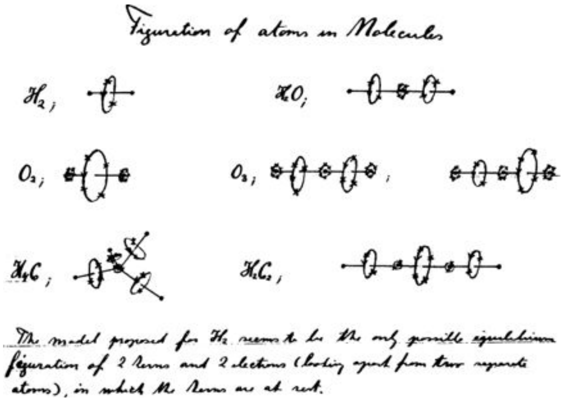
So let's see how we get on. It was known by the early twentieth century that chemical bonding is all about the electrons that atoms contain. Ernest Rutherford proposed that atoms are like little solar systems with tiny electrons orbiting a massive nucleus, and Bohr said is that those electrons can only have specific energies and no others, and therefore can only adopt some orbits but not others. They can jump from one orbit to another by absorbing or emitting energy, for example by swallowing up or spitting out a photon of light with a particular wavelength, which is related to its energy. When electrons do this, they make a quantum jump. Bohr outlined how electrons can adopt quantized orbits that link two or more atomic nuclei in a chemical bond.



The Rutherford atom



The Bohr atom, and quantum jumps



Figuration of atoms in Molecules

The model proposed for H_2 seems to be the only possible equilibrium figuration of 2 kerns and 2 electrons (looking apart from two separate atoms), in which the kerns are at rest.

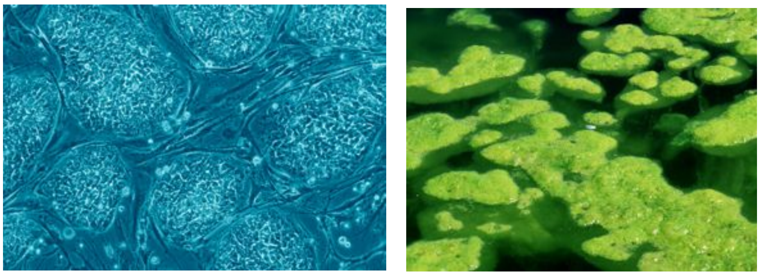
Chemical bonds as sketched by Bohr in his 1913 paper.

This quantum theory of atomic bonding has got a lot more sophisticated since then, and it now gives a very detailed description of the shapes and properties of molecules. It explains, for example, why grass is green and blood is red – questions that John Donne asked in the 17th century. They have these particular colours because of the energies of the electrons' quantum states in chlorophyll and haemoglobin. So certainly in this sense, molecular biology depends on quantum physics.

But when we talk about quantum effects in nature and science, we generally mean something different. Quantum mechanics is notorious for producing effects that defy everyday intuition. Particles can behave like waves and can be in two places or states at once, they can pass through walls and apparently communicate with one another instantly over vast distances. We tend to be insulated from actually experiencing these odd behaviours on the whole, either because they only appear under rather specialized conditions such as at very low temperatures or because their operation at the scale of single atoms and molecules becomes washed out and averaged away for objects at everyday scales that contain trillions upon trillions of atoms. This is why we can generally rely on the pre-quantum classical mechanics of Galileo and Newton to explain and describe how things behave in our world.

Quantum biology explores the possibility that some of these strange quantum effects happen in biological systems, where they might in fact be essential to the way the system does its job. This seems on the whole to be surprising and unexpected. If physicists want to study quantum effects of this sort, they often need extremely sophisticated equipment. They might have to cool the experiment down with liquid helium to within a few degrees of absolute zero, to work under a vacuum more empty than that of interstellar space, and to take great pains to eliminate any disturbances coming from the environment. In contrast, biology – the world of the living cell – is warm, wet and messy. Cells are little bags of countless different types of molecule, all colliding, interacting and reacting. Expecting to encounter quantum effects here is a bit like expecting to be able to sit down and meditate peacefully in the middle of Waterloo Station during rush hour.

Quantum physics…

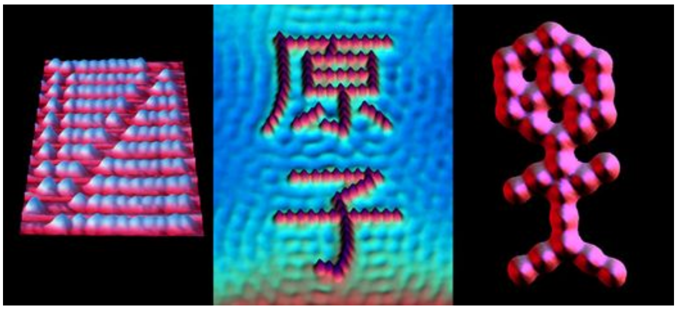


… and quantum biology?

And yet – it happens. There is good evidence that quantum effects do matter in biology. I'm going to tell you about some of them. But I want to stress that, to what extent they matter – whether they happen at all, and if they do, whether they are biologically relevant – is something that is still being intensively debated. These effects seem well attested in some cases, uncertain in others, and extremely speculative in others. This is natural; quantum biology is in its infancy, and we still can't say whether it amounts to just a ragbag of oddities and quirks of nature or a profound aspect of how life happens.

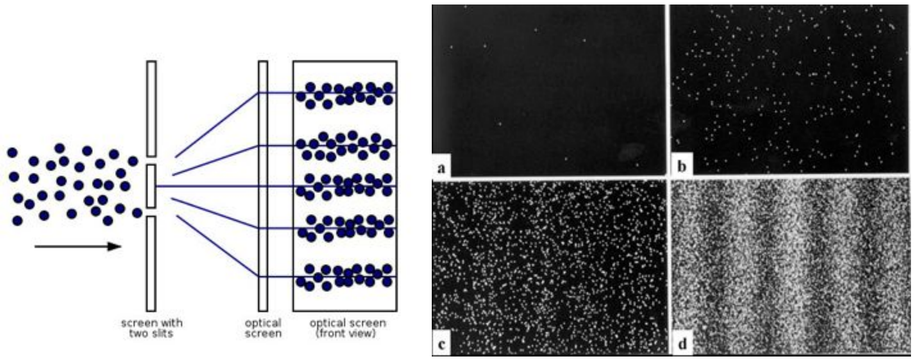
Tunnelling

Let me start with waves. Wave-particle duality is one of the least helpful expressions in quantum theory, but what it seeks to convey is that very small particles seem in some experiments to show the characteristics of particles, with particular positions in space, and in others to behave like waves, which are spread out through a large region of space. The particles of light, called photons, do this, and so do electrons: that's how electron microscopes work, by making use of their wavelike character. And so do atoms. Below are some pictures of real, individual atoms: each blob is an atom, and each one has been pushed gently into place on the surface of a metal. (Sure, the images have been processed and nicely coloured, but the basic data are real.)



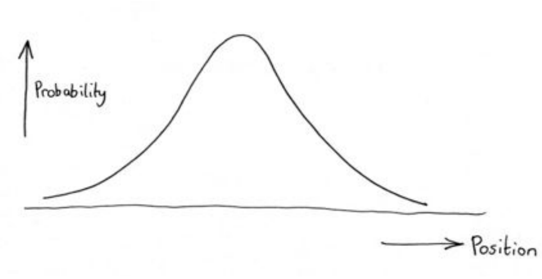
Atoms as particles

And yet consider what happens if you fire atoms through two narrow slits at a screen. At first you see what appear to be random dots where the individual atoms hit the screen. But as more impacts accumulate, what starts to emerge is a superimposed pattern of bright and dark regions. This is caused by interference effects between atoms behaving like waves. This wavelike behaviour has even been seen for quite large molecules containing dozens of atoms, and some researchers are aiming to show it for proteins – to show that whole protein molecules can behave like waves.

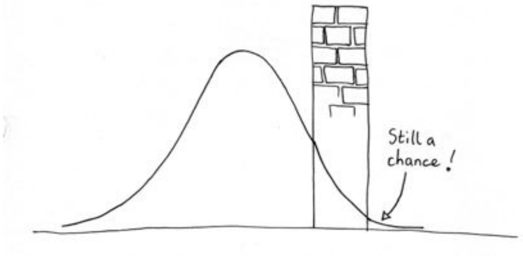


Atoms as waves: the interference bands that emerge for many atom impacts.

There's no indication as yet that such wavelike properties of molecules are relevant to biology, but that's not the point I want to make. This smeared-out character that atoms and subatomic particles can possess has some strange consequences. It means that in quantum theory you can't speak of particles like this as having definite positions in space, but only of the probability that they will be in a particular position. This probability can, depending on the conditions (including the way you look), be quite tightly constrained, as it is in the "atom snapshots" I just showed you, or rather spread out. Even if you put an obstacle in the way of a quantum particle that it should be unable to get over or through, there may remain a small chance that the particle could be found on the other side. In other words, the particle can seem to tunnel through an impenetrable barrier.

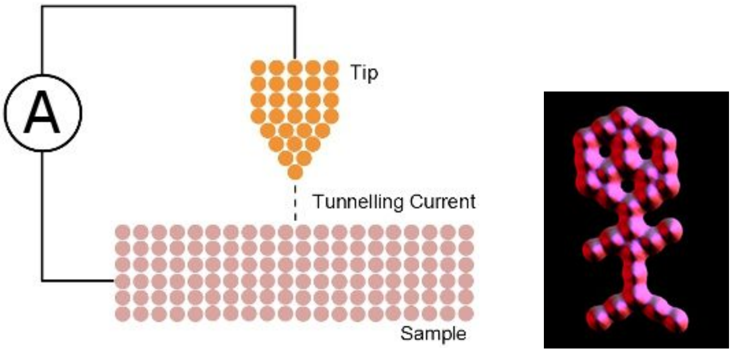


Positions of quantum particles can only be described in terms of probabilities.



…so there remains a finite probability that a particle might appear on the far side of an "impenetrable" barrier.

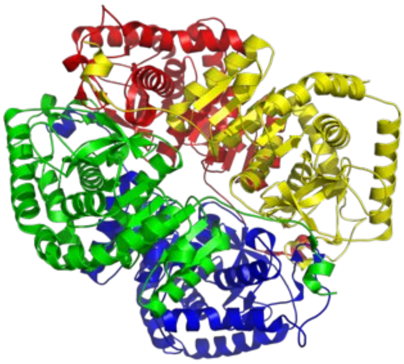
And that, in fact, is exactly how the earlier pictures of atoms were made. They used an instrument called the scanning tunneling microscope, in which a very fine metal tip is brought very close to the surface. If there is an electrical voltage between the tip and the surface, there is a small chance that electrons will tunnel across the gap between them. If the tip and surface are connected in an electrical circuit, this means that a current may flow because of electron tunneling. And because the tunneling current is extremely dependent on the distance between the tip and sample, small changes in that distance, for example because there's a single atom poking up from the surface, may produce a large change in the tunneling current. In this way the current measures the topography of the surface as the tip is scanned over it.



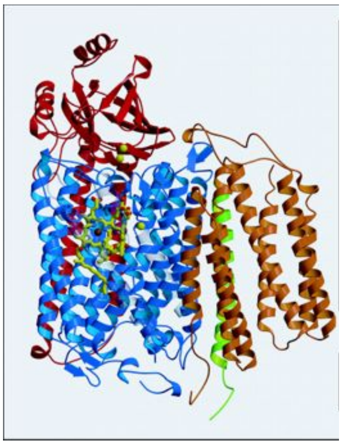
Taking pictures of atoms with the scanning tunneling microscope.

Now, loosely speaking the amount of quantum smeared-out-ness of a particle is greater the smaller the particle is – that's why electrons can tunnel through walls but we can't. Atoms can tunnel in principle, but the probability that they will do so is generally only significant if they are particularly tiny atoms. The smallest, lightest atom is the hydrogen atom, which has only one proton in its nucleus.

Moving around hydrogen atoms is immensely important in biochemical reactions. There are several enzymes in our bodies that do this. They are involved in the generation of energy and respiration, for example.

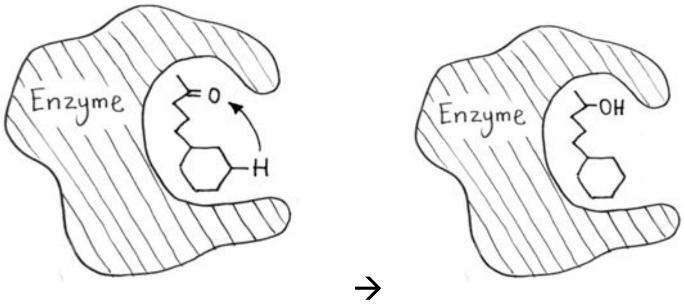


Lactate dehydrogenase



Cytochrome c oxidase

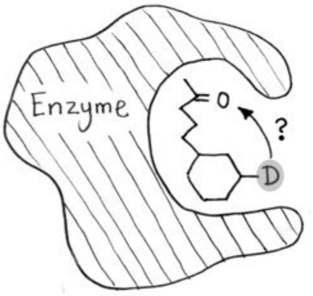
In general, the reactions involve moving a hydrogen atom – in effect, a single proton – from one location, where it is bonded to one atom or molecule, to another. That costs energy, because the proton has to be transported over an energy barrier – it's like plucking an apple off a tree, you have to tug at it.



Proton transfer in enzymes.

But it seems that in some, perhaps most, of these processes of biochemical proton transfer, the process is made easier and faster by tunneling. That's to say, the proton tunnels across the gap, rather as if the apple on the tree just vanished and appeared in our hand.

How do we know this? As I say, the ease of quantum tunneling depends on the mass of the particle: the heavier the particle, the less it tends to tunnel. So if we replace an ordinary hydrogen atom with one of heavy hydrogen – the isotope deuterium, which has about double the mass of ordinary hydrogen because it also has a neutron in its nucleus – we should alter the tunneling rate significantly. At the same time, the *chemical* properties of the hydrogen are virtually unchanged: different isotopes of elements, which differ in their number of neutrons, are chemically identical. So all we'd change here is the mass, and therefore the tunneling rate.



Does substitution of ^1H for ^2H (deuterium; D) change the tunneling rate?

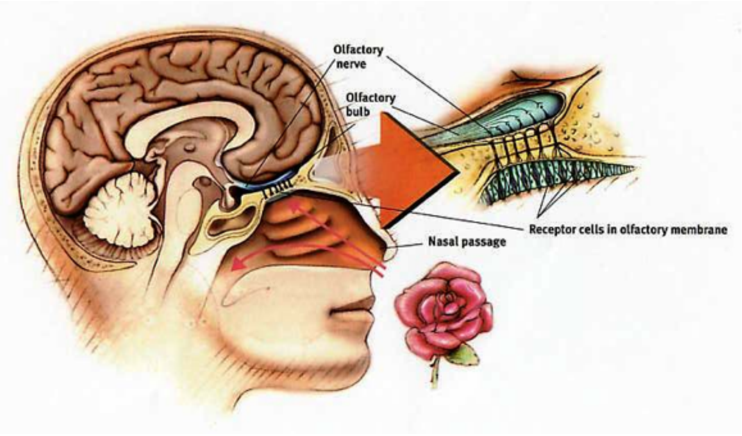
When chemists first did the experiment in 1989 for an enzyme called alcohol dehydrogenase, they found that indeed the rate at which protons are transferred is different for deuterium in a way that fits what we'd expect from a change in tunnelling rate. This has now been confirmed for several other enzymes[4].

Tunneling makes biological proton transfer easier and faster. So does this mean that biology *uses* quantum tunneling? It sounds like that's just what I've said. But in fact tunneling is almost impossible to *avoid* in a situation like this. In fact, even how hydrogen atoms (more strictly hydrogen ions: lone protons) may move between water molecules in ordinary water involves a degree of tunneling. So while you could argue that tunneling is useful for biology, it's not at all clear that enzymes have *evolved* to make use of it – they might just be stuck with it whether they like it or not. Some biochemists, such as the Nobel laureate Ariel Warshel, believe that quantum tunneling is not only of rather minor importance in biology, because it only speeds things up by a factor of 2-10 (which is not a lot for an enzyme), but also that it's just a side-effect, not something exploited by evolution. As one theoretical chemist has put it, "tunneling is a fact of life, but life has no special effect on tunneling"[4].

Protons aren't the only particle to tunnel in enzyme reactions. Some of them involve transferring a lone electron from one molecule to another. This, for example, is a crucial part of photosynthesis, in which an electron kicked out of chlorophyll by sunlight is passed along a chain of molecules in the chloroplast membrane. Electrons tunnel even more readily than protons, and it's been known for years that tunneling is significant in biological electron transfer too.

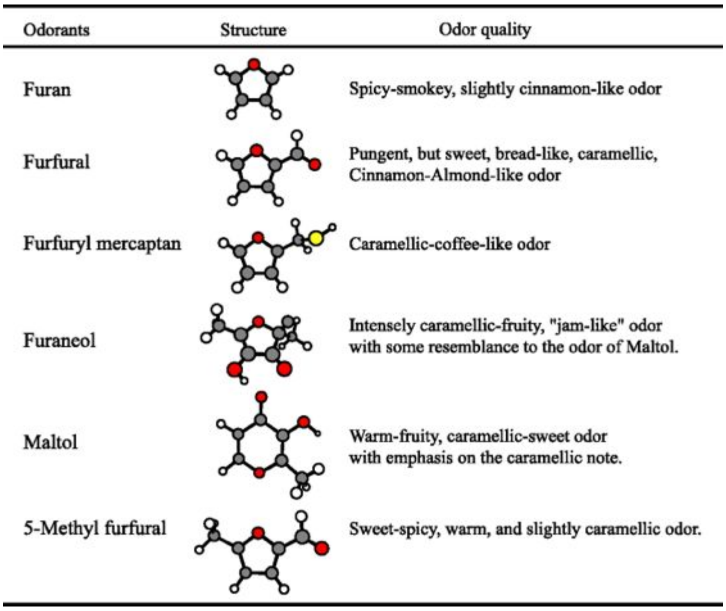
Yet one of the most celebrated candidate systems for quantum biology involves electron tunneling in a much more unexpected manner. The idea here is that tunneling within the receptor proteins involved in our sense of smell enables us to detect and identify molecules from the way they vibrate.

In the olfactory bulb inside our noses, where smell takes place, there are membranes studded with protein molecules that have cavities in which smelly molecules get lodged.



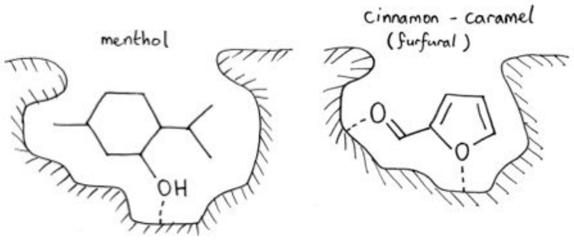
Olfaction.

Of course, these molecules aren't intrinsically smelly: they smell precisely because they can slot into the sites on the receptor proteins and trigger a nerve signal. That signaling process is quite well understood, but what remains unclear is exactly how odorant molecules start the process off. The conventional idea is that the odorant and receptor are like a key and a lock, which have complementary shapes that fit each other.



Odorants	Structure	Odor quality
Furan		Spicy-smokey, slightly cinnamon-like odor
Furfural		Pungent, but sweet, bread-like, caramellic, Cinnamon-Almond-like odor
Furfuryl mercaptan		Caramellic-coffee-like odor
Furaneol		Intensely caramellic-fruity, "jam-like" odor with some resemblance to the odor of Maltol.
Maltol		Warm-fruity, caramellic-sweet odor with emphasis on the caramellic note.
5-Methyl furfural		Sweet-spicy, warm, and slightly caramellic odor.

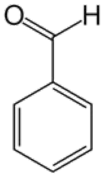
Some odorant molecules.



Is olfaction a matter of a molecular "key" fitting a "lock"?

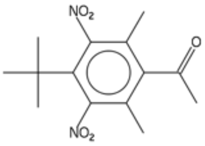
But it can't be quite as simple as that. For one thing, we can smell many more molecules than we have different types of receptor. But also, some molecules with very different shapes can smell very similar, while some molecules with almost identical shapes, like the two forms of the molecule carvone, can smell very different.

Almond smell:

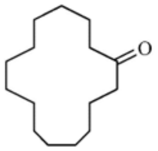


Benzaldehyde $H-C\equiv N$ Hydrogen cyanide

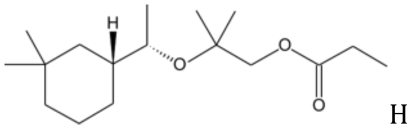
Musk smell:



Musk ketone

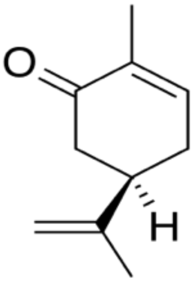


Cyclopentadecanone



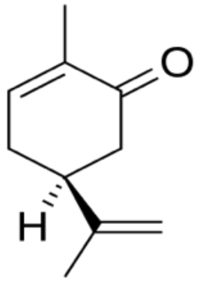
Helvetolide

R-carvone



Spearmint

S-carvone



Caraway

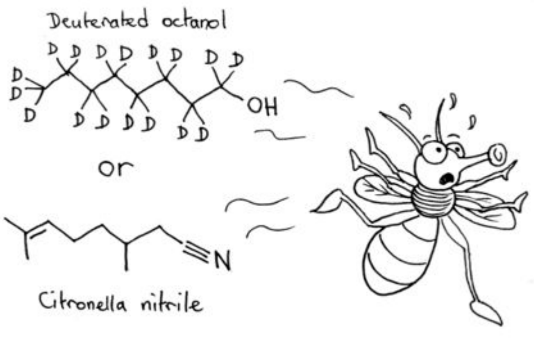
In 1996, the scientist Luca Turin, who is a specialist on perfumes and set up his own company to advise the perfume industry, suggested that smell might not work primarily by the lock-and-key principle. Instead, he thinks that odorant receptors act a bit like vibration sensors: they can sense the way the molecules that they bind are vibrating[5]. Molecules with very similar structures can have quite different vibrations, while differently shaped molecules can have vibrations of the same frequencies, just as a saxophone and a trombone can both play the same note. Turin's idea is that the receptor detects the whole spectrum of molecular vibrations, and he thinks that it does this using electron tunneling. In effect, the vibrations change the distance between the odorant and the walls of the cavity in which it sits, and thereby help electrons to jump the gap. It's this electron current that the receptor then senses to trigger the smell response.

If Turin is right, then it should be possible to distinguish an odorant molecule containing ordinary hydrogen atoms from one in which they have been replaced by heavy hydrogen or deuterium. That's because the heavier hydrogen isotopes, with twice the mass, vibrate more slowly, even though the molecule's shape is pretty much unchanged.

And there's some evidence that fruitflies can tell the difference. In 2011 a team in Greece, collaborating with Luca Turin, found that flies placed in a T-shaped maze with two attractive odors wafting from each passage, one of them deuterated, preferred the ordinary stuff over the heavy stuff[6]. The researchers could train flies, using mild electric shocks, to actively avoid the deuterated odorant – which is something they could only learn if they could tell them apart.

Can fruitflies smell different isotopes?

What's more, flies trained to avoid one kind of deuterated molecule would also show an aversion to a quite different, undeuterated molecule with a very similar spectrum of vibrations. Another team has since shown that bees can be trained to discriminate between ordinary and deuterated odorants too[7]. There's no reported evidence that humans can tell apart ordinary and deuterated molecules, although I have been told by chemists in Prague that they have been testing this out and can make the distinctions pretty reliably.[*]



Fruitflies trained to avoid a deuterated odorant seem to share an aversion to a different odorant with a similar vibration frequency.

Unfortunately, none of this proves beyond doubt that Turin is right. For one thing, the doubling of the mass for ordinary and heavy hydrogen means that they are not quite as chemically identical as isotopes of other atoms, where the mass ratio is smaller. So it could be that these creatures are actually detecting small differences in chemical bonding, rather than vibrations. Even if they're not, I've

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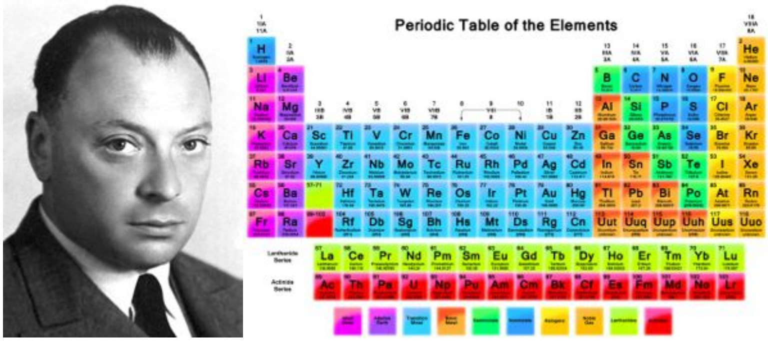
[*] My mistake. I overlooked ref. 8, which reports some evidence of reliable human discrimination of musky cyclopentadecanone.

been told by one of the leading specialists on fruitfly behaviour, Scott Waddell at Oxford, that there could be more conventional explanations of the experiments.

In any event, some heavyweight supporters of the conventional theory of olfaction, including Nobel laureates, are bitterly opposed to the vibrational idea[9], even though physicists and biophysicists have shown that it could work in principle[10,11]. My own opinion, for what it is worth, is that, whether it's right or not, it deserves to be taken seriously as a splendidly inventive and stimulating proposal.

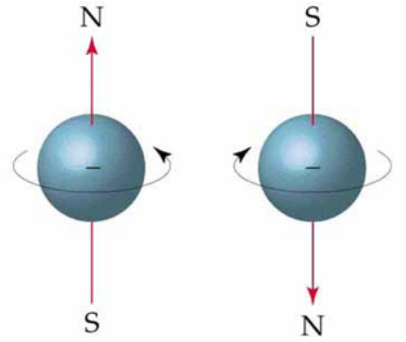
Spin

As well as having an electrical charge – a negative charge, opposite to that of protons – electrons possess another feature, called spin. Whereas electrical charge is a concept familiar from classical physics, spin is a purely quantum property. The name is misleading: it doesn't mean that the electron is literally spinning, although sometimes that analogy is loosely made to convey the idea, because spin is related to the electron's so-called angular momentum, which is classical physics comes from an object's rotation. An electron's spin can take two possible values, which can be imagined as electrons spinning clockwise or anticlockwise. Electron spin was first introduced into quantum theory in the mid-1920s by Wolfgang Pauli, based on the ideas that had just been formulated by Schrödinger and Heisenberg. This led Pauli to propose the so-called exclusion principle, which states that no two electrons can share the same quantum state. It's because two electrons can have opposite spin that they can both share the same orbit in an atom, and this picture of how electrons occupy orbits – or more accurately, smeared-our orbits called orbitals – explains the whole periodic table of elements in terms of the arrangements of their electrons. So spin is central to understanding chemistry.



Wolfgang Pauli (1900-1958). His Exclusion Principle, using the quantum concept of spin, rationalizes the structure of the periodic table of elements.

Because of their spin, electrons are magnetic. You might again crudely think of this as being a little similar to the way the spinning earth has north and south magnetic poles. For this reason, the spin states are called "spin up" and "spin down", though you shouldn't take those labels too literally. One way to flip the spin of an electron, from up to down say, is to put it in a magnetic field, which can realign the poles.

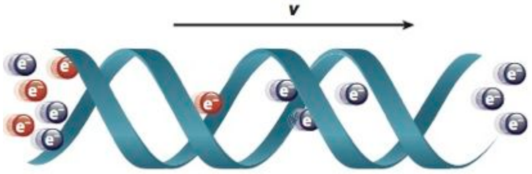


Spin makes electrons magnetic.

In recent years, there's been a lot of interest in constructing a form of electronic technology that makes use of spin. In ordinary electrical currents, the electrons have a mixture of the two spins, and it isn't an important factor at all. But if we could control the spin states of electrons, using magnetic fields for example, then we might be able to use spin to encode binary information, and therefore carry out digital logic, like that used in computer circuits, in a new way. This idea is called spintronics, and it depends on whether we can make electronic devices that can do things like allow electric currents to pass through or not depending on the electrons' spin. It's hard to do, largely because it's hard to stop spins from getting randomized, and so far we have only a few spintronic devices. At least one of these is hugely important, however: magnetic effects on electron spin can create an effect called giant magnetoresistance, where the electrical conductivity of a device becomes highly sensitive to the presence of magnetic fields. Devices using giant magnetoresistance are used in the read-out heads of computer hard drives to read information recorded on magnetic disk.

Spintronics: computer hard drive read-out heads use a spin-related effect called giant magnetoresistance.

But it seems likely that biology already knows how to do spintronics. Ron Naaman at the Weizmann Institute in Israel and his coworkers have found that various biological molecules and systems, such as some of the membranes involved in photosynthesis, or even DNA itself, can conduct electrons selectively depending on their spin[12-14]. It's not completely clear whether this actually happens in real organisms at ordinary temperatures, nor, if it happens, what role if any it serves in biology. But it could in any case be useful for spintronic technology: there are some proposals for using biological molecules, or tricks learnt from them, in these devices.



Bio-spintronics? DNA can distinguish between electrons travelling down the helix with different spins.

What's more, Luca Turin and coworkers have recently presented evidence that anaesthetics, whose molecular mechanism of action has long been mysterious, might act by changing electron spins so as to enable electrical signaling between certain protein molecules[15].

There is, however, an even more striking way in which electron spin might be used in biology. The fact that spin makes electrons magnetic has long been thought to account for how some chemical reactions can be sensitive to magnetic fields. Electrons generally tend to prefer to pair up in orbitals, which lowers their energy – that's why many chemical bonds are formed, by the pairing up of electrons on different atoms. These electron pairs in the same orbital have opposite spins – that's Pauli's exclusion principle – and so the pair has no net magnetism. But certain reactions, including some important ones in biology, involve the splitting apart of chemical bonds to form pairs of atoms or molecules each with a lone, unpaired electron. These molecules are called radicals, and they have a net electron spin, and feel magnetic fields. So magnetic fields can influence reactions involving radicals. These molecules are generally very reactive and so don't last long before they find other atoms or molecules to join with.

For many years it's been suspected that this might explain the magnetic compass that birds seem to possess, which allows them to navigate during migration using the earth's magnetic field. Lots of birds do this, including robins, sparrows and homing pigeons. The idea is that the geomagnetic field, despite being so weak, somehow influences the rate of biochemical processes in the bird's brains so that the neural signaling differs depending on the bird's orientation in the field.

Robin White-crowned sparrow Homing pigeon

Several birds use an internal "magnetic compass" for navigation.

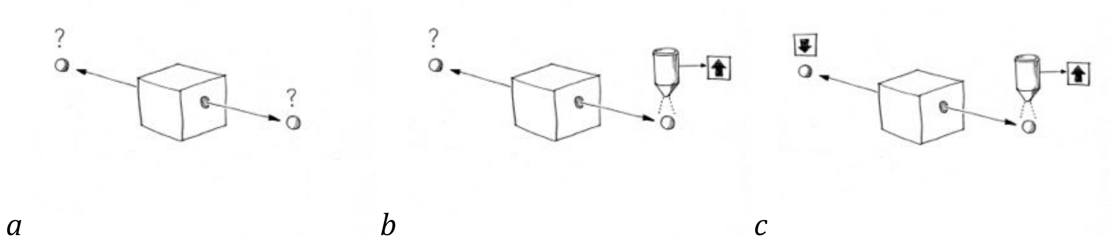
This seems very likely. What's more controversial is a recent idea that this avian magnetic compass uses perhaps the most bizarre effect in quantum physics, which is called entanglement.

Erwin Schrödinger, who gave it this name, proclaimed entanglement to be the central concept of the whole of quantum theory. It's not about quantum jumps, he said, or wave-particle duality or being in many states at once: it's about entanglement. The irony is that the possibility of entanglement was identified by the man who, having more or less started quantum theory in the first place, by the 1930s had become one of its greatest sceptics: Albert Einstein.

Albert Einstein (1879-1955)

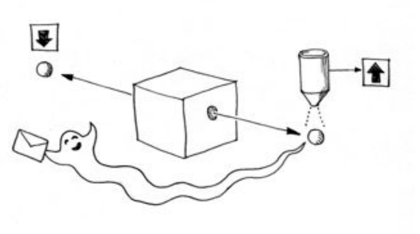
It's not that Einstein thought quantum theory was wrong; he just thought it was incomplete. According to the idea of Niels Bohr, Werner Heisenberg and their colleagues working in Copenhagen in the 1920s, quantum theory imposed fundamental limits on what we can know about the world. In their so-called Copenhagen Interpretation, all you could know was what experiments could tell you. The fact that the experiments seemed to insist on some uncertainty about quantum states, or that different experiments told you apparently different things, wasn't because of limitations in what you could measure, but because there was literally no deeper truth to be found. When quantum mechanics failed to predict whether, say, an electron had one value of spin or the other until you measured it, this wasn't because the theory was incomplete but because there was simply no meaning to that question before you made the measurement.

Einstein couldn't accept this. He was convinced that there had to be a deeper truth – what became called hidden variables, which assigned everything a definite one-or-the-other value even if we couldn't find out what it was. With two younger colleagues, in 1935 Einstein published a paper showing why the Copenhagen Interpretation had to be wrong. He imagined an experiment in which two particles would be generated with quantum states that had to be related: for example, a pair of electrons in which one has spin up and the other spin down. The electrons are spat out from some device in opposite directions. Now, we don't know which has which spin which until we measure one of them, whereupon we know that the other one must have the opposite spin. Because of this correlation between their spins, this pair of electrons is said to be entangled.



The Einstein-Rosen-Podolsky experiment (1935) on entangled particles.

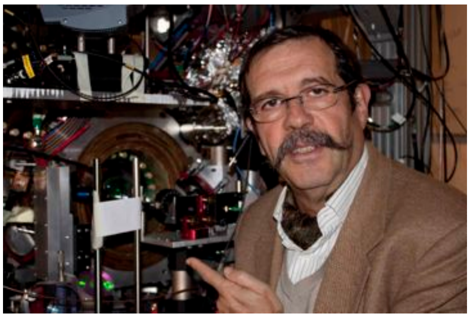
If the Copenhagen Interpretation is right, then it's not just that we don't know which spin is which until we make the measurement. Instead, those spins are literally undecided until then. By making the measurement on one electron we force the choice to be made. Yet that choice would then seem to be communicated instantly to the other one – even if they have become separated by thousands of light years. Einstein called this "spooky action at a distance." How can this information be sent instantly across such a distance? In fact, that idea seemed to violate Einstein's theory of special relativity, which says that no signal can travel faster than light. But in his view there was no need for something so weird, because the spin states had been assigned to the electrons all along: they were just hidden from us.



Spooky action at a distance?

His challenge to the Copenhagen Interpretation stimulated a lot of discussion at the time, but there was no obvious way to test it. It wasn't until the 1960s that the Irish physicist John Bell proposed an experimental way to do that. I don't have time to explain it, but in the 1980s Bell's theory was tested by Alain Aspect in France. Aspect made measurements on entangled pairs of photons from a laser, measuring not spin but states of polarization (horizontal or vertical). These experiments showed that there can be no hidden variables after all: the entangled photons behave exactly as if "spooky action at a distance" is real.

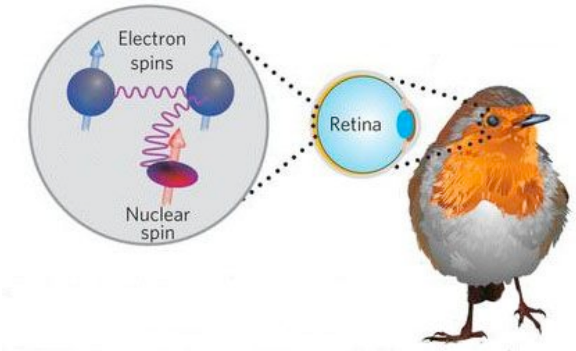
John Bell (1928-1990)



Alain Aspect (b.1947)

I need to qualify that. First, there are various loopholes in the argument that excludes hidden variables, which have only been closed off by very recent experiments. Second, entanglement doesn't actually violate relativity, because it can be shown that although this instant correlation of the particle states is real, we can't actually establish that experimentally faster than light: we can't use the effect to transmit information that fast. And third, this doesn't amount to saying that spooky action at a distance *is* real. It only looks that way if we're thinking in terms of Einstein's idea in which the particles really do have locally self-contained states. What entanglement really shows is that quantum theory involves so-called non-local effects, meaning that in situations like this we can't think of what is happening *here* as being independent of what is happening *here*.

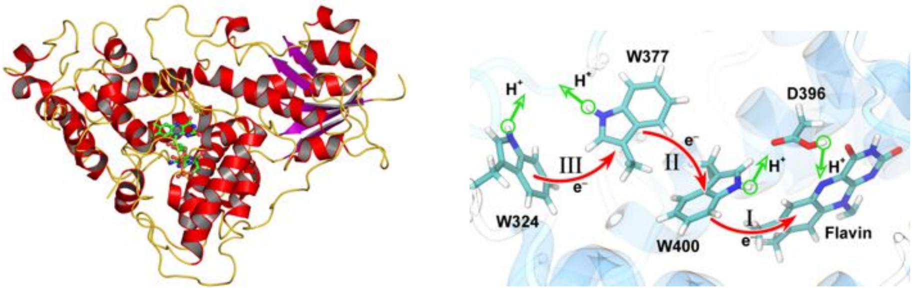
Back to the birds. Their magnetic sensor is activated by light striking the bird's retina. The current best guess at the mechanism for magnetic-field detection seems to be that the energy deposited by each incoming photon creates a pair of radicals, in which the unpaired electrons both have the same spin[16]. As the radicals move apart, they experience different magnetic fields: they both feel the earth's magnetic field, but maybe one of them also feels the effect of some nearby magnetic atom. The difference in the fields shifts the radical pair between two quantum states with differing chemical reactivity. Perhaps some signalling chemical is synthesized in the bird's retinal cells when the system is in one state, but not when it's in the other. And the relative balance of these states would then depend on the orientation of the earth's magnetic field.



The putative mechanism of magnetic-field sensing in birds, involving the photochemical production of radical pairs with the same electron spin.

Simon Benjamin in Oxford and his co-workers have proposed that the two unpaired electrons, being created by the absorption of a single photon, have spins that are in a state of quantum entanglement[17]. Although entanglement is usually quite delicate at ambient temperatures, the researchers calculate that it could be maintained in the avian compass for at least tens of microseconds, which is longer than has proved possible in artificial systems created in the lab. They argue that this entanglement is essential for the extreme sensitivity of the system to very small fields, because magnetic-field effects experienced by one of the radicals can influence the state of the other some distance away.

This is all very interesting, but it won't be proved unless we can identify what are the radical pairs involved. Magnetoreception in birds, and in some other magnetic-field-sensing organisms such as fruit flies, seems to be mediated by light-sensitive proteins called cryptochromes[18]. The idea is that light-activated shifting around of electrons inside cryptochromes will produce the entangled radicals.



A cryptochrome (left), and the proposed mechanism of photochemical radical formation (right).

But no one knows how that works in detail. Recent experiments in flies seem to have pretty much established that the radical pairs shown above, which have been widely thought until now to be the ones involved *can't* be[19]. One of the experts in this field, Steve Reppert at the University of Massachusetts Medical School, tells me that any explanation is probably going to have to come up with different ways to generate radical pairs. So there's a lot still to be understood here.

Coherence

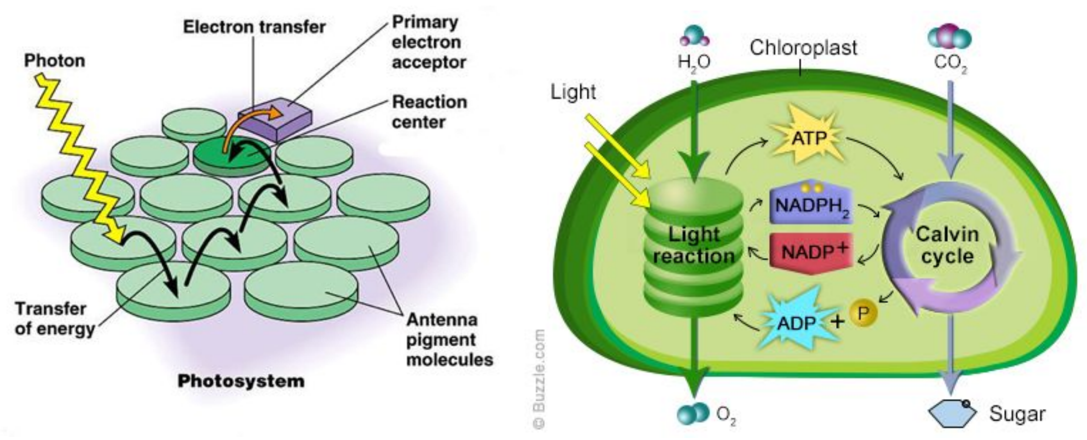
Now, I talked earlier about how quantum effects seem to depend on size: they might appear in very small things, like atoms, but not in big things, like us. No one yet knows if that is a fundamental fact or not. That's to say, the reason footballs can't tunnel might not be because they are big, but rather, because they are so complicated, being made up of so many atoms. Each atom has a wavelike nature, but the waves are all jumbled and out of step, so that these wave properties get averaged away, like soldiers marching out of step. The technical term for this jumbling is decoherence. According to one view, the reason why quantum behaviour at small scales becomes classical behaviour at big scales is because of decoherence. This is a relative thing: decoherence gets worse the more atoms an object contains. That's why it's still possible to see quantum interference effects between big molecules, but not between grains of sand fired from a sandblaster.

If we want to make use of certain quantum effects, we therefore need to control and suppress decoherence. One way to do that is to isolate the system from its environment: the jostling of a quantum system by all the atoms around it can cause decoherence. An area where this is important is quantum computing. Here the aim is to encode information in quantum states, just as we currently encode it in, say, the orientation of magnetic domains on a magnetic disk, or in arrays of light-scattering dimples in CDs and DVDs. The advantage of a quantum computer is that a single bit can be placed in several states simultaneously – a so-called superposition state. This means that quantum bits can in effect perform many calculations at once. Or at least, that's the simplistic explanation: the real reason why a quantum computer can be faster than a classical computer is still being debated, and in fact there may be no single explanation for this.

But it's really hard, because these coherent states of quantum bits are really delicate and easily disturbed: they are very vulnerable to decoherence. That's why so far we have quantum computers with only a handful of bits, and why they generally need to be cooled to very low temperatures. Even the one quantum computer currently available commercially – this one here, made by the Canadian company D-Wave – is the size of the old mainframe computers, because of all the cryogenics. (I should say that not everyone is convinced that the D-Wave device is a real quantum computer anyway.)

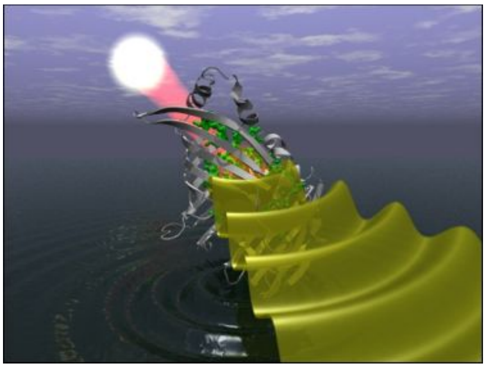
The first commercial quantum computer? If D-Wave truly is that (see http://philipball.blogspot.co.uk/2014/05/quantum-or-not.html), its bulk is due to the extensive cryogenics it needs.

So you can imagine, perhaps, why people were so astounded by the claim made in 2007 that coherent quantum superpositions of energy states are created and sustained in bacteria, algae and perhaps all green plants, and that this is perhaps what makes photosynthesis – the font of nearly all life on earth – possible. Photosynthesis starts when a chlorophyll pigment molecule absorbs sunlight. That energy is then transmitted through the forest of pigment molecules embedded in the organism's membrane until it reaches the so-called photosynthetic reaction centre. Here it causes an electron to be spat out and sent down a molecular relay of the sort I mentioned earlier, eventually to be used in the reactions that split water and produce the energy-storing molecules of the cell. The standard view was that the energy, bundled into wavelike packets called excitons that are spread out over several pigment molecules, hops at random from one place in this array to another, as I've shown here. As you can imagine, finding a path by random hopping is pretty inefficient and time-consuming, during which some of the captured energy may be wasted as heat.



Movement of energy packets (excitons) from the point of absorption to the photosynthetic reaction centre (left) is the initial stage of the process of photosynthesis, in which carbon dioxide and water are converted by the energy of sunlight into sugar and oxygen (right).

But researchers in America reported experimental evidence from photosynthetic bacteria and algae that in fact these excitons move not in random hops but as coherent waves of quantum superposition states[20,21] – even at room temperature[22]. If the excitons are in this coherent superposition, they can explore many paths at once, allowing them to find the best route much more efficiently and quickly. This, it was suggested, is much the same as a quantum computer performing many calculations at once: in effect, photosynthesis is a kind of quantum computation.



Does photosynthesis involve energy transport as a coherent quantum superposition of exciton states?

Which sounds amazing, right? But is that really how things are? Since these experiments were conducted, that point has been argued extensively, and now some researchers think that the results interpreted originally as evidence of quantum coherence might have other explanations – in particular, that they might instead be caused by a more conventional interaction between the excitons and the molecular vibrations in the array. While we need some quantum theory to understand the process, it's not clear if what researchers are calling coherence here is necessarily the same as the quantum coherence sought after in quantum computing: the system is far more complicated and subtle[23]. So in fact we don't yet know if photosynthesis is truly a manifestation of quantum biology.

And even if it is, we again have to ask the question: has biology adapted to make use of this effect, or is it inevitable? It's all too tempting to attribute it to the wonderful power of natural selection to find good solutions to problems, but we can't simply assume that this is so. It might be that, if you need to pack the pigment molecules densely to get the best light absorption, something like this coherence of exciton states is unavoidable – that it's just a byproduct, not an adaptation. After all, most photosynthetic organisms are spoilt for light: they don't need to worry about conserving every last bit of photon energy, so there's not obviously any selective pressure to use quantum tricks.

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I hope you can see that there are some extraordinary possibilities in quantum biology, but also many uncertainties about how far it reaches. Nearly all of the prize candidates still have questions to answer.

Yet some speculations about quantum effects in life go much further, and I want to end by just mentioning two of them. One of the biggest questions facing the life sciences today is how the brain works, and in particular the origin of human consciousness. In his 1989 book *The Emperor's New Mind*, Roger Penrose suggested that the choice that seems to happen when we make a measurement, called wavefunction collapse, might underlie processes that are non-computable: ones that a computer can't calculate or simulate. He suggested that the human mind is capable of dealing with processes like this, and that wavefunction collapse might therefore be important for thinking, and for consciousness. In conjunction with the physician Stuart Hameroff, he later suggested [see Penrose's 1994 book *Shadows of the Mind*] that entanglement between electrons on protein structures called microtubules in the brain could be at the root of the process. Like most of Penrose's wilder ideas it is tremendously inventive. And like at least some of them, there's currently not a shred of real evidence to support it.

But some interpretations of quantum theory imply far, far more profound and bizarre consequences for biology than any of this. The collapse of the wavefunction is in fact a very puzzling thing, because there's nothing in conventional quantum theory that predicts or explains it: it has to be put into the maths by hand. Some physicists are very dissatisfied by that, and think that it is much more parsimonious to assume that in fact there *is* no wavefunction collapse. Instead, they say, all the possibilities contained in the equations of quantum theory correspond to real situations. None goes away when we make a measurement; instead, the world – meaning the entire universe – splits into alternative worlds when this happens. They are all real, but our individual consciousness can be present in only one of them. In one of them Schrödinger's famous cat survived; in another, it was killed.

This is the so-called Many Worlds Interpretation, first proposed in the 1950s and now advocated by some of the most influential physicists in the world, including Stephen Hawking and Frank Wilczek, as well as popularizers like Brian Cox, Max Tegmark and Brian Greene. In this view, quantum physics offers you another way to replicate. It's a whole lot less fun than the conventional one, but you can't avoid doing more times a second than you can possibly imagine. Every time a quantum event occurs anywhere in the vicinity, perhaps anywhere in the universe, you split into multiple selves.

Have you replicated recently? The Many Worlds Interpretation of quantum theory.

Well, I felt obliged to mention it. My own view – and I've not time to justify it – is that the idea richly merits Wolfgang Pauli's famous put-down: it isn't even wrong.

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