The quantum life

The idea that quantum mechanics can explain many fundamental aspects of life is resurging, as **Paul Davies** reveals

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To a physicist, life seems little short of miraculous – all those stupid atoms getting together to perform such clever tricks! For centuries, living organisms were regarded as some sort of magic matter. Today, we know that no special "life force" is at work in biology; there is just ordinary matter doing extraordinary things, all the while obeying the familiar laws of physics. What, then, is the secret of life's remarkable properties?

In the late 1940s and 1950s it was fashionable to suppose that quantum mechanics – or perhaps some soon-to-be-formulated "post-quantum mechanics" – held the key to the mystery of life. Flushed with their success in explaining the properties of non-living matter, the founders of quantum mechanics hoped their theory was both weird enough and powerful enough to explain the peculiar living state of matter too. Niels Bohr, Werner Heisenberg and Eugene Wigner all offered speculations, while Erwin Schrödinger's famous book *What is Life?*, published in 1944, paved the way for the birth of molecular biology in the 1950s.

Half a century later, the dream that quantum mechanics would somehow explain life "at a stroke" – as it had explained other states of matter so distinctively and comprehensively – has not been fulfilled. Undoubtedly, quantum mechanics is needed to explain the sizes and shapes of molecules and the details of their chemical bonding, but no clear-cut "life principle" has emerged from the quantum realm that would single out the living state as in any way special. Furthermore, classical ball-and-stick models seem adequate for most explanations in molecular biology.

In spite of this, there have been persistent claims that quantum mechanics can play a fundamental role in biology, for example through coherent superpositions and entanglement. These claims range from plausible ideas, like quantum-assisted protein folding, to more speculative suggestions, such as the one proposed by Roger Penrose of the University of Oxford and Stuart Hameroff of the University of Arizona that quantum mechanics explains consciousness by operating in the brain over macroscopic dimensions. Unfortunately, biological systems are so complex that it is hard to separate "pure" quantum effects from the shifting melee of essentially classical processes that are also present. There is thus plenty of scope for disagreement about the extent to which life utilizes non-trivial quantum processes.

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But why should quantum mechanics be relevant to life, beyond explaining the basic structure and interaction of molecules? One general argument is that quantum effects can serve to facilitate processes that are either slow or impossible according to classical physics. Physicists are familiar with the fact that discreteness, quantum tunnelling, superposition and entanglement produce novel and unexpected phenomena. Life has had three and a half billion years to solve problems and optimize efficiency. If quantum mechanics can enhance its performance, or open up new possibilities, it is likely that life will have discovered the fact and exploited the opportunities. Given that the basic processes of biology take place at a molecular level, harnessing quantum effects does not seem *a priori* implausible.

Even if life does not actively exploit "quantum trickery", we cannot ignore the impact of quantum mechanics on biology. Quantum uncertainty sets a fundamental bound on the fidelity of all molecular processes. A distinctive feature of biology is the exquisite choreography involved in its highly complex molecular self-organization and self-assembly. For the cell to perform properly, it is crucial that the right parts are in the right place at the right time. Quantum mechanics sets fundamental limits to the accuracy with which molecules can cooperate in a collective and organized way. We might expect some of life's processes to evolve at least as far as the "quantum edge", where a compromise is struck between speed and accuracy.

The 19th-century view of life as "magic matter", exemplified by the use of the term "organic chemistry", has been replaced by a model of the cell as a complex system of linked nanomachines operating under the control of digital software encoded in DNA. These Lilliputian components, made mostly from proteins, include pumps, rotors, ratchets, cables, levers, sensors and other mechanisms familiar to the physicist and engineer. Their exquisite design, honed by eons of evolution, exhibits extraordinary efficiency and versatility, and is an inspiration to nanotechnologists. Intuition gained from macroscopic and mesoscopic mechanisms can be misleading on a nano-scale, where quantum phenomena such as the Casimir effect could come into play and dramatically change the nature of the forces involved.

Early speculations

An early idea about quantum effects in biology was proposed by Herbert Fröhlich of the University of Liverpool, who in 1968 suggested that the modes of vibration

Quantum of life
Quantum physics might be responsible for photosynthesis.

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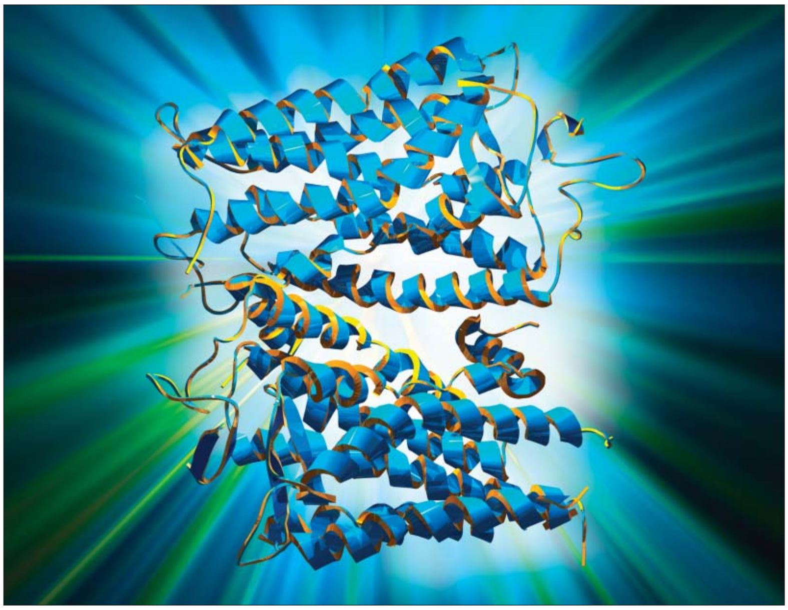

Protein trickery Protein chemistry involves a complicated protein choreography in a complex energy landscape. Physicists have found strong evidence that quantum tunnelling is fundamental to the efficiency of these processes.

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of some membranes in the cell might exhibit the phenomenon of a Bose–Einstein condensate, in which many quanta settle into a single quantum state with long-range coherence. Bose–Einstein condensates are normally associated with very low temperatures, but Fröhlich proposed that non-linear coupling between a collection of dipole oscillators driven by a thermal environment could quite generally channel energy into a single coherent oscillator even at biological temperatures. Quite what advantage an organism would gain from this mode of energy storage is unclear, although it could perhaps be used for controlled chemical reactions.

Another early and recurring speculation is that some biological mutations come about as a result of quantum tunnelling. The genetic basis of life is written in the four-letter alphabet of the nucleotides A, G, C and T that pair up to make the rungs of the twisted-ladder structure of DNA. The normal assignment is that T pairs with A and that G pairs with C, with the pairs being held together by two or three hydrogen bonds, respectively. However, the nucleotide bases can also exist in alternative, chemically related forms, known as tautomers, according to the position of a proton. Quantum mechanics predicts that a proton can tunnel with a finite probability through the potential barrier separating these two states, leading to mispairing, for example, of T with G instead of A. Mutations are the driver of evolution, so in this limited sense, quantum mechanics is certainly a contributory factor to evolutionary change. The physicist Johnjoe McFadden of the University of Surrey has built on this process to suggest a quantum model of adaptive change, in which environmentally stressed bacteria seem able to select favourable mutations that boost their survivability.

Another example of quantum tunnelling with biological relevance concerns the chemistry of proteins – large molecules that fold into complex 3D shapes. Some proteins contain active sites that bond to hydrogen, and to reach the sites, the hydrogen atom has to negotiate an elaborate and shifting potential-energy landscape. Quantum tunnelling can speed up this process. Studying just how important tunnelling might be is highly challenging, because many complicated interactions occur as the protein molecule jiggles around and changes shape as a result of thermal agitation. One approach taken by the chemist Judith Klinman of the University of California, Berkeley, is to work with deuterium instead of hydrogen. As the deuteron is roughly twice as heavy as the proton, using it makes a big difference to the tunnelling rate. Comparing the relative reaction rates of hydrogen and deuterium over a wide temperature range has therefore allowed experimentalists to separate out the relative importance of quantum effects. The results seem to confirm that quantum tunnelling is indeed significant, which raises the fascinating question of whether some proteins have actually evolved to take advantage of this, making them in effect "tunnelling enhancers". In evolution, even a small advantage in speed or accuracy can bootstrap into overwhelming success, because natural selection exponentiates the relative proportion of the winners over many generations.

Photosynthesis and ornithology

Although the previous examples have been in the literature for many years, they have not led to a widespread acceptance that quantum physics is important for biology. However, the subject matter is sufficiently rich that I held an entire workshop on quantum biology at the BEYOND Center for Fundamental Concepts in Science at Arizona State University in December 2007, which was followed by another organized by physicists Vlatko Vedral and Elisabeth Rieper at the National University of Singapore in January 2009. This flurry of activity was spurred by two new and rather dramatic experimental developments.

The first involves a study of photosynthesis by Berkeley chemist Graham Fleming and his group. Photosynthesis is a highly complicated and sophisticated mechanism that harvests light energy to split water by using individual photons to create a cascade of reactions. The process is extraordinarily efficient, and represents a classic example of how evolution has fine-tuned the design of a physical system to attain near-optimal performance.

The primary receptor of the light energy is a complex of pigment molecules known as chromophores. These can become excited and pass on the energy of excitation in a multistage process to the final reaction centre where charge separation occurs. Because the wavelength of the photon is much larger than the molecular assemblage, a superposition state of many excited pigment molecules is initially created, and this proceeds to evolve over a timescale of some hundreds of femtoseconds. Fleming and his group used laser excitation and probe pulses to study the relaxation pathways of these light-harvesting complexes, and observed a type of "quantum beating" effect in which the maximum amplitude of the excitation visits and revisits different molecules in the system coherently. Fleming claims that, with appropriate timing, the system can "grab" the coherent excitation (which persists for a few hundred femtoseconds) with greater probability than if it was merely distributed according to classical statistical mechanics. He believes this could lead to a manyfold increase in the speed of the energy transfer.

The results have recently been complemented by the work of Elisabetta Collini and Gregory Scholes at the University of Toronto, who demonstrated room-temperature coherence in electron-excitation transfer along polymer chains. An important feature of photosynthesis is that the molecular architecture involved is structured in a highly unusual and compact manner, which suggests that it has been "customized" to exploit long-range quantum effects. It could be that the particular configuration is efficient at preserving coherence for surprisingly long durations, thereby enabling the system to "explore" many pathways simultaneously and thus speed up a "solution" (i.e. delivering energy to the reaction centre).

The second recent development that suggests that quantum physics is relevant to biology concerns bird navigation. It is well known that some birds perform amazing feats of navigation using a variety of cues that including the local direction of the Earth's magnetic field. The nature of this magnetic sensor has, however, remained something of a mystery and the problem is particularly acute because the magnetic field penetrates the entire organism. How, for example, is the angle of the field relative to the bird translated into neural information? A study by Thorsten Ritz at the University of California, Irvine, Christine Timmel's group at Oxford University and Elisabeth Rieper at the National University of Singapore has made a plausible case, at least for the European robin, that the key lies with a class of proteins found in the bird's retinas.

The mechanism currently under investigation appeals to the photo-activation above the thermal background of a 2D array of aligned proteins, producing radical ion pairs involving singlet two-electron states. The spins of these entangled electrons are linked, and in the presence of a uniform magnetic field they would precess in synchrony, maintaining the singlet configuration. However, if the ejected electron moves away somewhat, the two electrons may experience different magnetic environments. Although both electrons will be subjected to the same ambient field of the Earth, the electron tied to the ion in the protein will also be affected by the ion's nuclear magnetic field, which produces hyperfine splitting. This difference in magnetic fields experienced by the entangled electrons causes the singlet state to oscillate with a triplet state, with a periodicity depending in part on the strength and orientation of the Earth's field relative to the array of proteins. The system may then de-excite in stages and initiate a reaction that in effect acts as a chemical compass, because the relative proportion of the reaction products can depend on the singlet–triplet oscillation frequency.

There remain considerable uncertainties both about the mechanism and the precise identities of the molecules involved. Nevertheless, general evidence in favour of a quantum model of some sort comes from experiments conducted by Wolfgang and Roswitha Wiltschko of the University of Frankfurt, who studied the behaviour of robins in the presence of a small, oscillating magnetic field. They found that for frequencies near 1.315 MHz, the birds' vaunted navigational prowess is seriously compromised. A possible interpretation of the experiments is that the perturbing field produces a "resonance" causing singlet–triplet transitions, thereby upsetting the chemical compass.

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Flight path Recent studies indicate that the European robin uses an array of aligned proteins in its retina as a magnetic-field sensor that helps it to navigate.

How to avoid decoherence

Although at least some of these examples add up to a *prima facie* case for quantum mechanics playing a role in biology, they all confront a serious and fundamental problem. Effects like coherence, entanglement and superposition can be maintained only if the quantum system avoids decoherence caused by interactions with its environment. In the presence of environmental noise, the delicate phase relationships that characterize quantum effects get scrambled, turning pure quantum states into mixtures and in effect marking a transition from quantum to classical behaviour. Only so long as decoherence can be kept at bay will explicitly quantum effects persist. The claims of quantum biology therefore stand or fall on the precise decoherence timescale. If a system decoheres too fast, then it will classicalize before anything of biochemical or biological interest happens.

In recent years, much attention has been given to decoherence, and its avoidance, by physicists working in the burgeoning field of quantum computation and quantum-information science. A quantum computer is a way to process information more efficiently than classical physics would allow by using quantum states that are allowed to perform logical operations through the coherent evolution of quantum superpositions. Decoherence represents a source of computational error, so physicists have been busy designing environments that are theoretically free of decoherence, or that minimize its impact. A key parameter is temperature: the higher it is, the stronger the decoherence. For this reason, most attempts at quantum computation employ ultra-low-temperature environments such as superconductors or cold-atom traps.

At first sight, the warm and wet interior of a living cell

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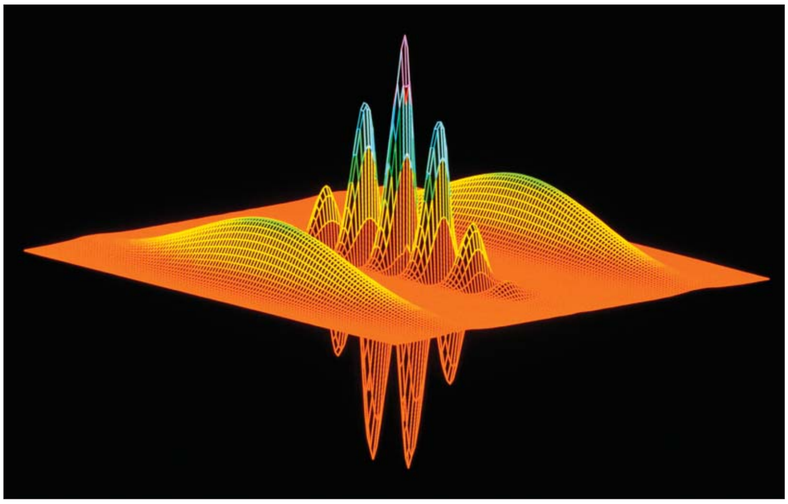

Keeping it coherent Quantum biology is only possible if decoherence is avoided, which might seem implausible in the warm environment of the living cell. However, results in quantum computation indicate that biological systems might be less susceptible to decoherence than simple models predict.

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seems a very unpromising environment for low decoherence. Back-of-the-envelope calculations suggest decoherence times of less than 10^{-13} s for most biochemical processes at blood temperature. However, there are reasons why real biological systems might be less susceptible to decoherence than simplistic models predict. One is that biological organisms are highly non-linear, open, driven systems that operate away from thermodynamic equilibrium. The physics of such systems is not well understood and could conceal novel quantum properties that life has discovered before we have. Indeed, sophisticated calculations indicate that simple models generally greatly overestimate decoherence rates. For example, Jianming Cai Hans Briegel of the University of Innsbruck and Sandu Popescu of the University of Bristol have found that a two-spin quantum system dynamically driven away from equilibrium can exhibit ongoing coherence even when coupled to a hot and noisy environment that would rapidly decohere a static system. A calculation based on the so-called spin-boson model by Anthony Leggett of the University of Illinois at Urbana-Champaign also suggests dramatically extended decoherence times for low-frequency phonons. Leggett also points out that because the dominant mode of decoherence is via phonon coupling to the environment, an acoustical mismatch between the immediate and wider environment of the quantum system could prolong coherence at low frequencies. Furthermore, it is not necessary for all degrees of freedom to enjoy subdued decoherence: significant quantum biological effects might require only a small subset to be protected.

The origin of life

A century and a half after Charles Darwin published *On The Origin of Species*, the origin of life itself remains a stubborn mystery, and is deeply problematic. The simplest known living organism is already stupendously complex, and it is inconceivable that such an entity would arise spontaneously by chance self-assembly. Most researchers suppose that life began either with a set of self-replicating, digital-information-carrying molecules much simpler than DNA, or with a self-catalyzing chemical cycle that stored no precise genetic information but was capable of producing additional quantities of the same chemical mixture. Both these approaches focus on the reproduction of material substances, which is only natural because, after all, known life reproduces by copying genetic material. However, the key properties of life – replication with variation, and natural selection – does not logically require material structures themselves to be replicated. It is sufficient that *information* is replicated. This opens up the possibility that life may have started with some form of quantum replicator: Q-life, if you like.

It is well known that wavefunctions as such cannot be cloned, but discrete quantum information, for example spin direction or energy-well occupation, can be copied. The advantage of simply copying information at the quantum level, over building duplicate molecular structures, is speed. A copying event might proceed on a chemical or tunnelling timescale of femtoseconds. This should be compared with the 10 ms that it takes to replicate a DNA base pair. Q-life can therefore evolve many orders of magnitude faster than chemical life. Moreover, quantum fluctuations provide a natural mechanism for variation, while coherent superpositions enable Q-life to evolve rapidly by exploring an entire landscape of adaptive possibilities simultaneously. Of course, the environment of this hypothetical Q-life is unknown, but the surface of an interstellar grain or the interior of a comet in the Oort cloud offer low-temperature environments with rich physical and chemical potential.

How would Q-life evolve into familiar chemical life? A possible scenario is that organic molecules were commandeered by Q-life as more robust back-up information storage. A good analogy is a computer. The processor is incredibly small and fast, but delicate: switch off the computer and the data are lost. Hence computers use hard disks to back up and store the digital information. Hard disks are relatively enormous and extremely slow, but they are robust and reliable, and they retain their information under a wide range of environmental insults. Organic life could have started as the slow-but-reliable "hard-disk" of Q-life. Because of its greater versatility and toughness, it was eventually able to literally "take on a life of its own", disconnect from its Q-life progenitor and spread to less-specialized and restrictive environments – such as Earth. Our planet accretes a continual rain of interstellar grains and cometary dust, so delivery is no problem. As to the fate of Q-life, it would unfortunately be completely destroyed by entry into the Earth's atmosphere.

There is accumulating and tantalizing evidence that quantum mechanics plays a key role here and there in biology. What is lacking is any clear case for a general "quantum life principle" that might offer a new conceptual framework in which the remarkable properties of living systems can be understood, as Schrödinger and others hoped. However, the physics of complex far-from-equilibrium quantum systems with non-linear couplings is in its infancy, and further surprises undoubtedly lie in store. Meanwhile, researchers in quantum-information science intent on reducing decoherence might find the study of biological nanomachines surprisingly rewarding. ■