A quantum of natural selection

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The modern evolutionary synthesis, which marries Darwin's theory of natural selection with Mendel's genetics, was developed around the same time as quantum mechanics. Is there any connection between the two?

In the hundred and fifty years since the publication of *On the Origin of Species*[1], much has been made of what Charles Darwin knew and did not know in formulating the theory of natural selection. Perhaps the most surprising aspect of the book is that Darwin was able to construct his theory of how physical traits were handed down and naturally selected, despite operating with a demonstrably incorrect theory of genetics. Although Gregor Mendel's pioneering work on the genetics of pea plants[2] was published in 1866, Darwin never appreciated the significance of this work. He had formulated his theory of natural selection using the pre-Mendelian 'blending' theory of genetics, in which traits of the mother and father were blended together in the offspring. Darwin was aware of the limitations of the blending theory — the offspring of a blue parrot and a yellow parrot are either blue or yellow, not green — but its imperfections were insufficient to undercut his powerful argument for natural selection[3,4].

Darwin was not the only nineteenth-century scientist to under-appreciate Mendel's work. Mendel's laws of genetic inheritance were virtually ignored until 1900, when Hugo de Vries, Carl Correns and Erich von Tschermak rediscovered them and publicized their significance[5]. In the first decades of the twentieth century, geneticists and statisticians began combining Mendelian genetics with Darwin's idea of natural selection to create the 'modern synthesis', the theory of evolution through natural selection of genetic variation[4,5]. But 1900 was also the year that Max Planck discovered the quantum-mechanical nature of light[6]. The same years that saw the creation of the modern evolutionary synthesis also saw the rapid development of quantum-mechanical theories of atoms and molecules, following the mathematical formulation of quantum mechanics by Erwin Schrödinger and Werner Heisenberg. Which brings us to the central question that I wish to consider here: what, if anything, does quantum mechanics have to do with natural selection?

The answer, in short, is: quite a lot. Despite the fact that quantum mechanics rules the world at length scales many orders of magnitude below the size of Darwin's finches or Mendel's pea plants, quantum mechanics has a profound effect on the naturally selected world. In fact, Mendel's work, which demonstrates the 'atomic' or 'unsplittable' nature of inherited traits, already hints at the answer to why quantum mechanics is important to life.

Five digital gifts to nature

Planck discovered that light, which had previously been thought to consist of waves, possessed an intrinsically discrete quality: light came in chunks. Planck called these chunks 'quanta.' Soon, Niels Bohr and others showed that atoms possessed a similarly chunky quality: the electrons in atoms could only take on a discrete set of states. Atoms were also quantum mechanical. This chunky quality implies that nature, at bottom, is not continuous, but discrete instead. Quantum mechanics makes nature digital. It is this digital character of all things at their smallest scale that nature discovered and used to construct the genetic basis for life. Quantum mechanics effectively gives a package of digital 'gifts' to nature, which in turn uses these gifts crucially in the development of life.

The first gift that the digital quality of quantum mechanics gives to nature is the gift of stability: the quantum-mechanical hydrogen atom is stable. If the hydrogen atom obeyed the laws of classical mechanics, by contrast, the electron would spiral into the proton in a tiny fraction of a second, ending the atom's life in a burst of radiation. Radiation is exciting stuff, but not the stuff of which life is made.

The second digital gift is countability: the forms of matter that can exist at a microscopic scale do not vary continuously. There is only a small, countable set of stable elementary particles. These elementary particles can combine into stable atoms in only a countable number of ways. The atoms can combine to form only a countable set of chemical compounds. And so on: at each length scale, the countable set of different entities can combine to form a larger, but still countable, set at the next larger scale.

The third digital gift that quantum mechanics gives nature is information. The fundamental unit of information is the bit; it represents the distinction between two possible states. The word 'bit' is also used to refer to a physical system, such as an electron spin, that can take on one of two distinguishable states. The key feature of information is that a small number of bits can have a large number of possible states: n bits can take on 2^n states. So, for example, 300 bits can take on $2^{300} \approx 10^{90}$ states, where 10^{90} happens to be the number of elementary particles in the Universe (more precisely, the number within the particle horizon of the Universe). The discrete quality of quantum mechanics, together with the ability to string together many atoms in a molecule, implies that physical systems are naturally capable of registering a large number of bits of information. Perhaps the most explicit example of such natural information is DNA. The entire human genome registers around six billion (6×10^9) bits (which in turn contain between 20,000 and 25,000 distinct Mendelian genes). Nowadays, six billion bits doesn't sound like so much — but this number of possible configurations for our DNA is two raised to the six billionth power, $2^{6\times10^9}$, a more than astronomically large number. It is this huge potential variety of genetic combinations that gives natural selection its power.

The fourth digital gift from quantum mechanics is information processing. As noted above, an electron spin can be taken to register a bit of information: for example, spin clockwise along some axis ('spin up') can be taken to represent a logical 0, and spin anticlockwise along that axis ('spin down') can be taken to represent a logical 1. When the spin flips, for example by absorbing a photon, then spin clockwise goes to spin anticlockwise, and vice versa, spin up goes to spin down, and 0 goes to 1.

Flipping the spin flips the bit. It is this ability of nature to process information at the most microscopic scales that we use when constructing quantum computers that store bits on individual atoms[7]. This ability of nature to process information translates to higher levels as well: each time two chemical species react to form a third species, information is being processed. A chemical reaction takes its input molecules, together with the bits of information that they contain, and transforms them into output molecules, which contain a different, related set of bits. The ability of nature to process information at one length scale translates, as before, into an ability to process even more information in a more sophisticated fashion at the next larger length scale. By the time the length scale of DNA is reached, nature is processing information in a highly sophisticated fashion. A sequence of DNA can be thought of as a set of instructions for constructing proteins, or strings of amino acids. The genetic code contains features such as start codons, redundant coding and stop codons. The coding techniques discovered by nature billions of years ago were only incorporated in human codes, such as Morse code, within the past 200 years.

The fifth and last gift that quantum mechanics gives to nature might not always be considered a gift: it is randomness. Unlike classical mechanics, quantum mechanics contains intrinsic uncertainty, which translates, under the proper circumstances, into irreducibly random behaviour. It was this intrinsic randomness to which Albert Einstein was objecting when he declared "God does not play dice". In fact, Einstein was wrong: God does play dice and, luckily, is very good at it. Randomness is indeed the enemy of order — this is the quality to which Einstein objected. But randomness is also the source of variation. And as Darwin taught us, life without variation is not life.

Nature took these quantum gifts of stability, countability, information, information processing and randomness, and ran with them. The Universe began with a bang, and immediately started processing information. The first information processing was relatively simple: thermal excitations of quantum fields led to stable elementary particles, which, as the Universe expanded and cooled, eventually formed atoms and simple molecules. Gravitational clumping added more bits of detail to the almost featureless expanse of hydrogen and helium and a few other light elements. Finally, early stars began to shine, rapidly used up their nuclear fuel and exploded, giving rise to heavier elements which in turn clumped together to form nebulae, then further stars and planets.

Even before the evolution of life, the Universe contained a huge diversity of environments supporting a similarly huge diversity of chemical reactions, together with a vast diversity of types of information processing. Each reaction transformed its input molecules and their attendant bits of information into a particular mix of output molecules and bits, which in turn became the inputs to further chemical reactions and so on. Eventually, in a sequence of events that scientists would desperately like to uncover, the more sophisticated methods of processing information that underlie life came into being. Once proto-life had attained the ability to reproduce with variation, the genie was out of the bottle. Darwinian natural selection kicked in. Bacteria, multicellular organisms, plants, animals, primates and humans all came onto the scene in due course.

Natural selection of quantum weirdness

God playing dice is not the only aspect of quantum mechanics to which Einstein objected: quantum mechanics is full of weird and counterintuitive effects. One such effect is a peculiarly quantum form of correlation known as entanglement[7], which Einstein called 'spooky action at a distance' because it apparently allowed distant particles to influence each other without sending energy from one particle to the other.

Quantum computers are devices, mentioned above, that store and process information at scales where quantum weirdness holds sway[7]. When I give talks about quantum computers, every now and then a member of the audience will object that quantum computers are not possible to build, because if they were, "nature would have already discovered them". This is a silly argument, not least because we can already build simple quantum computers. The same argument could also be made about lasers: natural selection did not cause pre-human life on Earth to evolve the laser, yet we still have lasers. Nor is the laser somehow unnatural. Natural selection evolved human beings, who then, naturally, invented the laser.

In the history of natural selection, did nature ever come across a way to use quantum weirdness? Do quantum computations occur in bacteria? At first, the presence of coherent quantum information processing in living systems might seem unlikely. The weird correlations that underlie quantum computations are fragile and susceptible to destruction through interaction with the environment, a process known as decoherence. As a result, most human-made quantum computations take place in highly isolated systems, frequently at temperatures only a few thousandths of a degree above absolute zero. The interior of a cell, by contrast, is a hot, wet place, where quantum coherence should survive for only the tiniest fraction of a second.

Remarkably, however, bacteria have apparently evolved to perform simple quantum computations. In 2007, Graham Fleming and his co-workers performed an experiment[8] showing the existence of coherent quantum beating in the Fenna–Matthews–Olson (FMO) complex, a large molecule that makes up the 'antenna' used by green sulphur bacteria during photosynthesis (Fig. 1). The FMO complex collects a photon, turns its energy into an exciton — a bound electron–hole pair — and then funnels that exciton to a reaction centre where its energy can be transformed into chemical energy. The FMO complex is a remarkable system, in that it manages to transfer almost 99% of the energy in the exciton to the reaction centre, implying that relaxation plays at most a minor role in the transfer. Fleming *et al.* were inspired by their discovery of coherent quantum dynamics to speculate that the FMO complex was performing a 'quantum search' algorithm to allow the exciton to find the reaction centre[8].

Quantum search algorithms were invented by Lov Grover[9], who showed that quantum

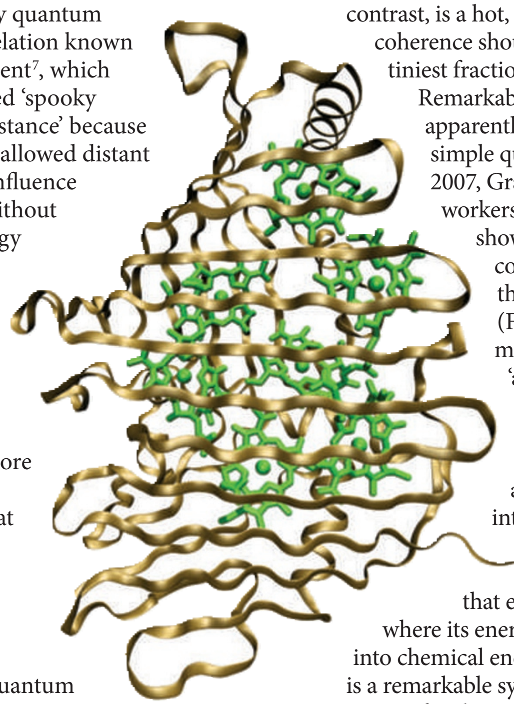

Figure 1 | Real-life quantum mechanics. The Fenna–Matthews–Olson complex helps green sulphur bacteria to perform photosynthesis. A quantum algorithm known as 'quantum walk' might be behind the remarkably efficient energy transfer between the light-collecting antennae and the reaction centre, where, ultimately, the photon energy is transformed into chemical energy. Image courtesy of Graham Fleming and Yuan-Chung Cheng.

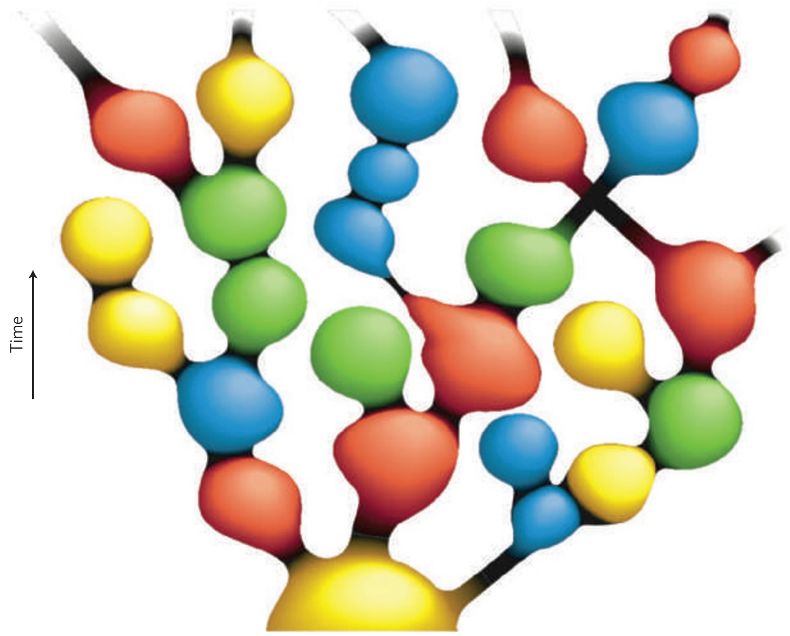

Figure 2 | A branching multiverse. In a self-reproducing cosmos, each 'baby universe' (represented as a bubble) may have physical laws slightly different from its parents. 'Mutations' are shown as a change in colour. Image courtesy of Andrei Linde; reproduced with permission from ref. 17.

computers could search databases more rapidly than classical computers. When my quantum-computing colleagues and I investigated this claim of green sulphur bacteria performing quantum algorithms, we were at first disappointed: we were able to show that the anomalous efficiency of energy transfer in the FMO complex could not arise from quantum search. We quickly discovered, however, that the exciton was indeed performing a different quantum algorithm called a 'quantum walk'. Quantum walks are algorithms in which a quantum particle 'walks' through some complex structure, and uses long-range quantum coherence to find its way to places in the structure that remain hidden to a classical particle[10]. A classical particle can occupy only one point of the structure at a time. If the structure is large enough, the classical particle blunders around and gets lost. A quantum particle, by contrast, can effectively occupy many points of the structure simultaneously — quantum weirdness in action. This ability to 'feel' the whole structure at once allows the quantum particle to walk coherently towards its destination.

The efficiency of photosynthetic antennae is mysterious: if one thinks of the exciton as a classical particle that exists at a single spot in a huge molecule, then as it hops around that molecule, its chances of making its way to the reaction centre are virtually nil. Our quantum-mechanical models of the exciton coherently walking through the FMO complex showed, however, that the quantum exciton spreads rapidly throughout the complex, exerts its quantum right to occupy all possible points simultaneously, and zeroes in on its destination in a tiny fraction of a second[11].

This robustness of this quantum walk is even more remarkable in the face of noise and decoherence. As mentioned above, in the hot, wet environment of a cell, one would expect the coherence that drives a quantum computation to disappear almost immediately[7]. Here, however, the non-local state of the exciton created when a photon is absorbed turns out to be highly resistant to decoherence. Moreover, the small decoherence induced by the thermal jiggling of the molecule seems actually to help the quantum walk along[11,12]. The efficiency of the energy transfer in photosynthesis can be characterized by the probability that the exciton finds the reaction centre, and by the length of time it takes to get there. When we calculated the efficiency of the quantum walk as a function of temperature, we found that it was maximized at 290 K, from which we conclude that, on the one hand, nature is an excellent quantum mechanic, and, on the other hand, trillions of bacteria did not give their lives in vain.

The natural selection of physical laws

Life is a speculative business: nature rolls the quantum dice and generates variety; some of the resulting forms survive to reproduce with variation again. In the spirit of Darwin, let's close with some speculation.

The power of natural selection extends beyond mere biological systems. The laws of physics as we know them may themselves have been the outcome of a process of natural selection. Lee Smolin has suggested that the Universe is constantly sprouting baby universes, whose physical laws are similar to, but not quite the same as their mother's[13]. As they mature, these baby universes in turn sprout further universes, and so on (see Fig. 2). Our Universe could be 'naturally selected', in the sense that its physical laws support life, where the laws of its cousins do not. A similar notion arises in Leonard Susskind's string theory 'landscape' in which some 10^{500} different sets of physical laws, each equally likely *a priori*, vie to construct the Universe we see today[14]. Finally, Max Tegmark[15] and I (ref. 16) have speculated that the Universe is generating all possible self-consistent information-processing structures. If this is so, quantum mechanics itself, with all its weirdness, might have been naturally selected out of other potential bases for physical law for the simple reason that, as we have seen, quantum mechanics has much to offer to life. ❒

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