Schrödinger’s gardenia: Does biology need quantum mechanics?

A review of the processes that might exploit quantum weirdness.

Erwin Schrödinger, who pondered the deep connection between quantum physics and biology. (We're not referring to his famous thought experiment involving cats, or his unconventional living arrangements, either.)

In a real sense, everything is quantum mechanical: matter and interactions are governed by the rules of quantum physics. True, we haven't figured out how gravity fits in yet, but the structure of atoms, nuclei, molecules, and solids—along with the characteristics of light—are best described by quantum mechanics. However, we don't need to take the unique features of quantum mechanics into consideration when modeling many systems, including most in chemistry or biology.
Nevertheless, it is possible life has evolved to exploit some quantum phenomena, including coherence and tunneling. In a new *Nature Physics* review article, Neill Lambert and colleagues examined the evidence in favor of quantum biological phenomena in photosynthesis, photoreception, magnetic sensation, and even our sense of smell. They conclude that the evidence is ambiguous: compared with other biochemical processes, any uniquely quantum influences appear small.

For something to be considered fully quantum, the researchers used the criterion that it could not be fully described using heuristic models. (The authors refer to such heuristic depictions as "classical." Though that's common, it's also misleading: talking about chemical bonds, electron transport, and the like isn't exactly the language of classical, Newtonian physics.) By contrast, quantum mechanics requires the use of the quantum state, the physical and mathematical description of a system that encodes the probability of the outcomes of measurements.

These states may be superpositions: combinations of mutually exclusive measurement outcomes, such as perpendicular polarizations of light, or spin orientations of electrons in atoms. Quantum information and computing are based on the preparation, manipulation, and entanglement of quantum states, but these generally require special conditions, including far lower temperatures than organisms can withstand. The present paper concerned itself with examining if life can get around those problems, exploiting quantum physics for evolutionary gain.

### Photosynthesis

Tracing back along the food web, most of the energy organisms need to survive originates with the Sun. Green plants, cyanobacteria (also known as blue-green algae), and other organisms capture photons and use them to drive the chemical reactions of metabolism. Photosynthesis is incredibly efficient: nearly 100 percent of the energy from the photons absorbed by the photosynthetic machinery is transferred to the chemical reaction center.

A set of chemistry experiments that began in 2007 showed that this efficiency may be due to quantum mechanics. The data demonstrated coherence between the electrons in the various pigment molecules during the transfer process, meaning that the states of the electrons were coordinated and they acted as a single system, even though they resided in different atoms. The clearest results were obtained at 77 Kelvin, but follow-up experiments showed the coherence could also be present at room temperature. Additionally, complicated theoretical models of the energy transport process seem to support the hypothesis that coherence plays a role in photosynthesis.

At the present time, no one has observed quantum coherence in a living organism. Additionally, it's not clear whether the boost that should come from exploiting quantum states would be sufficient to explain the efficiency of photosynthesis. After all, it's one thing to observe this phenomenon under lab conditions, it's another to demonstrate it in a living organism, and yet another to show that quantum coherence is the *reason* for the remarkable efficiency. Finally, as always in evolution, it's important to remember that a particular feature may be adaptive but may
have evolved for other reasons: perhaps efficient photosynthesis was the side effect of some other adaptation.

However, if coherence can be shown to exist in these biological systems at room temperature, then it's worth asking why it's there and how it might provide an evolutionary advantage. One possible explanation is that each pigment molecule experiences a lot of "noise," or random jiggling inside the cell. By exploiting quantum coherence, these random fluctuations can be canceled out during the electron transfer, meaning fewer photons are lost to photosynthesis.

**Magnetic navigation in birds**

Many migratory species use Earth's magnetic field for navigation, including a number of birds. Our understanding of how animals sense magnetic fields—magnetoreception—is still lacking some details, and not all species appear to use the same mechanisms. The authors of the review noted that European robins, along with a handful of other species, seem to navigate using photoreceptors: cells in the retina that measure light intensity. The behavior of these cells can be disrupted using magnetic fields, suggesting there may be a dual dependence on light and magnetism for navigation.

The photoreceptors contain radical pairs: two molecules bound to each other that have single electrons in their outer layers. When they are correlated, the spins of these electrons form a state similar to one used in quantum information theory and computing.

In the radical pair model of magnetic navigation, an incoming photon induces one of the electrons to undergo a transition between quantum states. Since it is correlated with the other electron, this induces a second transition, which sends a signal through the bird's nervous system. Since the spin states are sensitive to external magnetic fields (useful for navigation), they can also be disrupted by laboratory fields.

Even though the radical pair concept would explain all the aspects of navigation in some species, there's a major problem with this model. As the review points out, coherence between the electrons' states would need to be sustained for a relatively long time—longer than any current lab experiments have achieved. The very advantage of the model may end up making it untenable, unless researchers can figure out how the photoreceptor cells stabilize the quantum states for extended periods.

**Tunneling our senses**

A less finicky phenomenon based on quantum states is tunneling, the process by which a particle (or some more abstract quantum system) can pass through a barrier between states—a transition that would be forbidden in classical terms. Tunneling is used in many applications, including some types of diodes, where electrons pass from one side of a junction to another. Certain chemical reactions in biology appear to depend on the tunneling of electrons or protons over distances equivalent to dozens of atoms.
Experiments indicate that tunneling plays a part in photosynthesis and certain enzyme interactions, including possibly the sense of smell. In that case, it's not simply the size and shape of the molecules we perceive as odorants that trigger a smell: it's also the transfer of an electron from the odorant to the receptor in the nose via tunneling.

Finally, the authors discussed the possibility that photoreceptor cells used to sense light could depend on quantum coherence. In this scenario, light triggers a very rapid molecular change in a protein-linked molecule in the retina, which then induces a secondary change in a protein. The speed and efficiency of these processes hints at a possible underlying quantum effect, but experimental evidence to support this has not been obtained yet.

An intriguing aspect of all of these possibilities is that perhaps evolution has figured out a better way of performing tricky quantum manipulations than we have. In a sense, that's not surprising: life has had a long time to evolve photosynthesis, photoreception, and navigation, while our understanding of quantum mechanics just began in the 1920s and '30s.

It may also turn out that the phenomena described above don't really rely heavily on the quantum state after all, since evidence is sketchy at present. Nevertheless, the hints are there: we may be at the point where we can test if life has solved the problem of manipulating quantum states, meaning quantum biology could be a new field of study in this century.