QUANTUM BIOLOGY
Richard Feynman:

“Anyone who claims to understand quantum mechanics is either lying or crazy”

Nevertheless......
The quantum world seems, despite many, many experiments to disprove it, to be the way the universe functions
Features of the Quantum World

- Particles can exist in multiple possible states or locations simultaneously: “superposition”

- Unified particles which become separated remain connected over distance and time: “quantum entanglement”

- Multiple particles can condense into one unified entity: “quantum coherence”

- Precise location AND momentum of quantum particle are indeterminate: “uncertainty”
Reality is described by two distinct sets of laws.

- In our everyday “classical” world, matter and energy follow predictable, behaviors (Newton’s laws of motion, Maxwell’s equations etc.)

- But at small scales (and sometimes at large scales!), the bizarre laws of quantum mechanics reign.
A **femtosecond** is the SI unit of time equal to $10^{-15}$ of a second.

For context, a femtosecond is to a second what a second is to about 31.7 million years.

A femtosecond is equal to 1000 attoseconds, or $1/1000$ picosecond.

Typical time steps for molecular dynamics simulations are on the order of 1 fs.

The waves of visible light oscillate with a period (reciprocal frequency) of about 2 femtoseconds.

The precise period depends on the energy of the photons, which determines their color:

- 1.3 fs – cycle time for 390 nanometer light, at the transition between violet visible light and ultraviolet.
- 2.57 fs – cycle time for 770 nanometer light, at the transition between red visible light and near-infrared.
- 200 fs – the swiftest chemical reactions, such as the reaction of pigments in an eye to light.
Erwin Schrödinger reasoned in 1944 that quantum mechanics was important in the stability of genetic information, and that quantum fluctuations might be the cause of some mutations. He arrived at this conclusion on general energetic grounds.
More than the “trivial” quantum effects of atomic and molecular interactions, but deep involvement of biological processes.
Mutations.

- Ever since Crick and Watson elucidated the structure of DNA the possibility has been seriously entertained that mutations might occur as a result of quantum fluctuations, which would serve as a source of random biological information.
- Proton tunneling can indeed spontaneously alter the structure of nucleotide bases, leading to incorrect pair bonding.
- McFadden and Al-Khalili have suggested that, in some circumstances, the genetic code should be regarded as a quantum code, so that superpositions of coding states might occur, leading to spontaneous errors in base pairing.
Tunneling
Enzyme action.

- Enzymes are proteins.

- They catalyze biochemical reactions.

- But their hugely accelerated reactions rates, are difficult to account for by conventional catalytic mechanisms.

- Evidence that quantum tunneling plays an essential role.
Genetic code.

- It has been argued that the code contains evidence for optimization of a quantum search algorithm.
- The replication of DNA.
- This is accomplished by a DNA polymerase enzyme.
Quantum Nanostructures.

- The living cell is a collection of nanomachines that approach the quantum limit.

Quantum electrodynamical effects become significant.
Another nanostructure of interest is the proton pump.

Although these structures are complex enzymes, it may be possible to model their operation as one-dimensional quantum nanotubes.
Eccles argued that neuron firings are controlled by quantum tunneling processes at the synapses.

Hameroff and Penrose have suggested that microtubules inside cells permit long-range quantum coherence, enabling quantum information processing to take place at the subcellular level.

They use this hypothesis to develop a theory of consciousness.
The Problem of Decoherence

- If quantum mechanics is to play a non-trivial role in bio-systems, then some way to sustain quantum coherence at least for biochemically, if not biologically, significant time scales must be found.

- The situation would be transformed, however, if unexpectedly long decoherence times could be demonstrated experimentally in a biological setting.
Classical World

Quantum State Reduction

Quantum World
(small in size scale but vast in information density)
Water's quantum weirdness makes life possible.

- The hydrogen bonding network that is formed between molecules of liquid water plays an important role in the function of biological molecules.
- The folding and function of the proteins.
Do we live in a Quantum World?

Quantum mechanics dictates that all matter has an inherent wave property.

On a molecular scale, this property can lead to destructive and constructive interferences that have a pronounced effect on transmission probabilities along reaction coordinates, for example the photo-induced isomerization of the retinal molecule in rhodopsins.
Myoglobin
Myoglobin Secondary Structure
The Environment of Action

- The vibrations of the surrounding protein are important.
- Simulation studies show that the vibrations of carboxy-hemoglobin must take surrounding protein structures into account to get qualitative agreement with experimental results.
Six well-characterized photoreceptor families function in Nature to mediate light-induced signal transduction:

- the rhodopsins,
- phytochromes,
- xanthopsins,
- cryptochromes,
- phototropins, and
- BLUF proteins.
Photosynthesis

- Photosynthetic light-harvesting proceeds by the collection and highly efficient transfer of energy through a network of pigment-protein complexes.
- Interchromophore electronic couplings and interactions between pigments and the surrounding protein determine energy levels of excitonic states, and dictate the mechanism of energy flow.
A quantum machine for efficient light-energy harvesting.
The Fenna-Matthews-Olson (FMO) complex is a water soluble complex and was the first pigment-protein complex (PPC) that has been structure analyzed by x-ray spectroscopy.
Redfield relaxation superoperator

- transfer between populations (blue), transfer between coherences (green), and transfer between a population and a coherence (red).
Direct evidence of quantum transport in photosynthetic light-harvesting complexes.

- Evidence of interaction between the bacteriochlorophyll chromophores and the protein environment surrounding them not only prolongs quantum coherence, but also spawns reversible, oscillatory energy transfer among excited states.

- Resolving design principles evident in this biological antenna could provide inspiration for new solar energy applications.
\[
i \hbar \frac{\partial \Psi}{\partial t} = -\frac{\hbar^2}{2m} \frac{\partial^2 \Psi}{\partial x^2} + V(x) \Psi(x, t)
\]
The avian quantum compass.
Flavin Adenine Dinucleotide (FAD)

- Flavin adenine dinucleotide (FAD) is a redox cofactor involved in several important reactions in metabolism.
- FAD can exist in two different redox states, which it converts between by accepting or donating electrons.
- The molecule consists of a riboflavin moiety (vitamin B2) bound to the phosphate group of an ADP molecule.
- FAD can be reduced to FADH₂, whereby it accepts two hydrogen atoms (a net gain of two electrons):
  \[
  \text{FAD} \rightarrow \text{FADH}_2
  \]
  FAD is an aromatic ring system, whereas FADH₂ is not. This means that FADH₂ is significantly higher in energy, without the stabilization that aromatic structure provides.
- FADH₂ is an energy-carrying molecule, because, if it is oxidized, it will regain aromaticity and release all the energy represented by this stabilization.
Magnetically sensitive light-induced reactions in cryptochrome

- Transient radical pairs (flavin-tryptopan) may be formed by photo-induced electron transfer reactions in cryptochrome proteins.

- Coherent spin dynamics are influenced by the geomagnetic field leading to changes in the quantum yield of the signaling state of the protein.
FAD

Flavin Adenine Dinucleotide
Reduced
Quantum Coherence Beating and Population Oscillation
Could humans recognize odor by phonon assisted tunneling?

- Our sense of smell relies on sensitive, selective atomic-scale processes that occur when a scent molecule meets specific receptors in the nose.

- The physical mechanisms of detection are unclear: odorant shape and size are important, but experiment shows them insufficient.

- One novel proposal suggests receptors are actuated by inelastic electron tunneling from a donor to an acceptor mediated by the odorant, and provides critical discrimination.
The observation of coherent vibrational motion of the photoproduct supports the idea that the primary step in vision is a vibrationally coherent process and that the high quantum yield of the cis→trans isomerization in rhodopsin is a consequence of the extreme speed of the excited-state torsional motion.
Consciousness is a process on the edge between quantum and classical worlds.
.... However it takes time
Brain activity correlating with conscious perception apparently occurs **too late** (150 to 500 msec after impingement on our sense organs) to account for actions initiated or completed within 100 msec!

These include*:
- Preparation of spoken words responding to heard speech (*Normal conversation!*)
- Analysis of sensory inputs and emotional content
- Choice, planning & execution of voluntary acts
- Hitting a baseball pitched at 90 mph
- etc.

*e.g. M. Velmans, 1991*
The best neurophysiological correlate of consciousness (NCC) comes from EEG, voltage fluctuations recorded from scalp or brain surface.

EEG is divided into frequency bands:

Delta (< 4 Hz)
Theta (4 to 8 Hz)
Alpha (8 to 12 Hz)
Beta (13 to 30 Hz)
Gamma (> 30 Hz)

Coherence in gamma synchrony among different brain regions is the best correlate of consciousness.
Two types of synapses
1) Chemical synapses
2) Electrical (gap junction) synapses
Open gap junctions between dendrites mediate gamma synchrony
Dendritic- Dendritic Gap Junction

Gap junction closed

Dendritic Synchrony

Gap junction open

Collective Integration
Sideways Synchrony

Neuronal network dendrites linked by gap junctions ("dendritic webs") depolarize coherently in gamma synchrony

correlate with consciousness
Conscious feelings of pleasure and reward correlate with gap junction-mediated gamma synchrony in dopaminergic nucleus accumbens.
A closer look at the neural network

Diagram showing chemical synapses, axons, dendritic web, and gap junctions.
Proteins are made up of amino acids.

Some amino acids have ring structures which are hydrophobic.

Within this protein are many locations where such amino acids come together to form hydrophobic domains.

Within such domains electrons can form resonating structures.
Some compounds that have an effect on consciousness
A bit of molecular biology

- Now we have seen microtubules in strategic places in the brain and elsewhere.
- Microtubulin is a protein molecule that can exist in either of two states.
- This is a necessary property for data storage.
- How is the information coded?
- The fundamental energy currency in biology is the high-energy phosphate bond.
Calcium-calmodulin kinase II (CaMKII) holoenzyme.
Learning, memory and long-term potentiation (LTP) are supported by factors including post-synaptic calcium ion flux activating and transforming the hexagonal calcium-calmodulin kinase II (CaMKII) holoenzyme.

Upon calcium-induced activation, up to six kinase domains extend upward, and up to six kinase domains extend downward from the CaMKII association domain, the fully activated holoenzyme resembling a robotic insect 20 nanometers in length.

Each extended kinase domain can be phosphorylated, and able to phosphorylate other proteins, thus potentially further encoding synaptic information at intraneuronal molecular sites for memory storage, processing and distribution.
Activated CaMKII and microtubules - perfect match for information transfer via phosphorylation

CaMKII nanobots each have $2^6$ possible phosphorylation states to convey memory information to microtubules for processing and storage

(Hameroff, Craddock, Tuszyński)
Conclusions

- A better understanding of disease processes is possible.
- The deep problem of biogenesis — the discovery of a pathway from non-life to life — may be advanced by viewing the origin of life not so much as a chemical process, but as the emergence of a specific, coded, information-processing system from an incoherent molecular milieu.
- A full account of biogenesis must address this software aspect.
- Advances in quantum information theory promise to cast this problem in an entirely new light, and could point the way to the decisive breakthrough in explaining one of sciences deepest mysteries.
Thank you for your attention.

Any Questions?

And

Thank you for your attention.
What is Life?   Erwin Schrodinger, 1944
Quantum biology,   Nature Physics 9, 10-18 (2013)   doi:10.1038/nphys2474
Quantum Biology: Current Status and Opportunities
http://www.ias.surrey.ac.uk/workshops/quantumbiology/report.php
Orchestrated Reduction Of Quantum Coherence In Brain Microtubules: A Model For Consciousness?
The Miller Group,   U. of T. Physics Department