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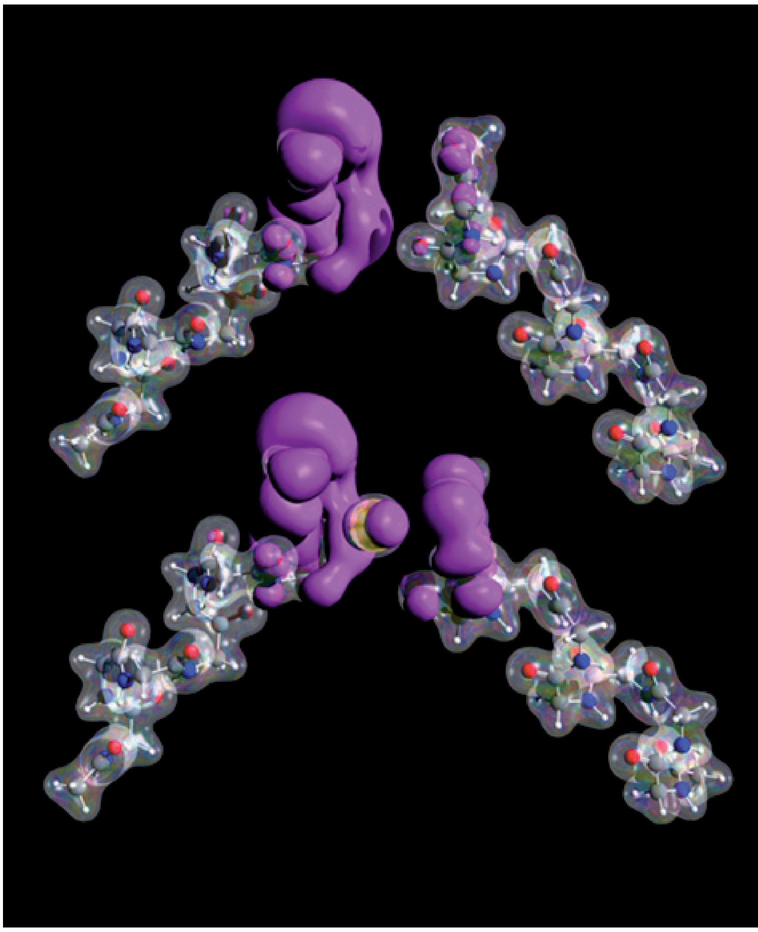
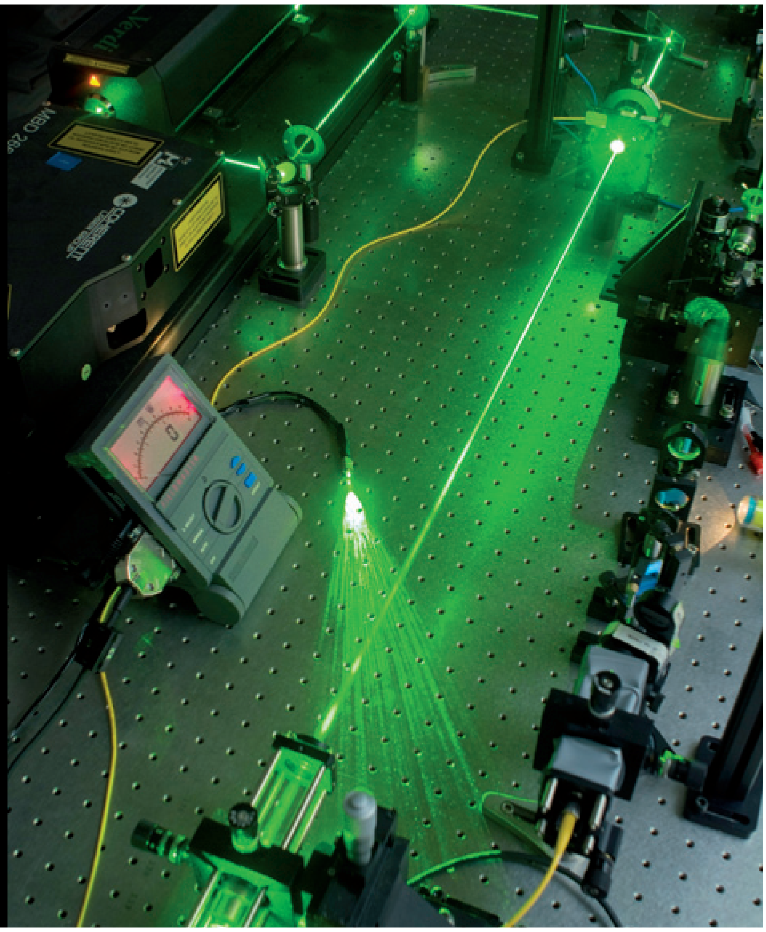
ESF Forward Look

A Foresight Activity on Research in Quantum Biology (FarQBio)





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Foreword

This Forward Look report is the result of a consultation with a community of experts in the field of quantum information who gathered together to identify scenarios of future developments inspired by cross-disciplinary fields. The foresight activity on research and technology in quantum information science and European strategy (FARQUEST), proposed by the Austrian Science Fund and the Austrian Academy of Sciences, originally encompassed several areas of quantum information research: quantum complexity, quantum technology and quantum biology. These all hold great promise for long-term scientific developments and applications.

In this context, quantum biology emerged as a case study of particular interest since it embodies not so much what research currently is, but what it could become. The report therefore focuses on future outlooks in what is a novel, highly cross-disciplinary field which brings together biologists, physicists, chemists, computer scientists, as well as researchers from other disciplines, but which intrinsically requires them to transcend their disciplinary boundaries. We are currently witnessing the birth of a new way of doing science where traditional disciplines converge to find an explanation of phenomena observed in nature and to bring to life new devices and technologies, as has often been the case during the past decades for nano- and biotechnology.

In order for this more integrated approach to science to succeed, quantum biology will require a paradigm shift in the way education, research and interactions between science and society are carried out and delivered. The report that follows provides a set of measures and recommendations in these directions and is therefore addressed to policy makers, research funders, programme managers and educators at the EU and national levels. We hope in particular that it may have an impact on Future and Emerging Technologies and Marie Curie Actions programmes as new collaborative funding initiatives are developed under Horizon2020.

Beyond that, we hope that the elements provided in this report will stimulate further reflection on how to bring long-term visions – such as building quantum machines – closer to reality.

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Executive Summary

Quantum biology has developed over the past decade, within the more general framework of quantum information science, as a result of convergence between quantum mechanics and biology. This emerging field stems from the interrogation of the basic principles that govern interactions at the molecular scale in living organisms. Traditionally, the principles of quantum mechanics have been used to explain a wide range of observed phenomena in physics and chemistry. Experiments that have provided evidence of quantum mechanical behaviour have, in most cases, been performed in highly controlled environments using tools that allow the measurement and manipulation of nanoscale objects such as atoms, single molecules, or ordered solid-state systems. Biological phenomena involve molecules (such as proteins) that are composed of typically hundreds of thousands of atoms and have, therefore, been considered too complex to be tackled by physicists using similar quantum mechanical approaches. However, recent **evidence of quantum phenomena occurring in living organisms** suggests that quantum mechanics does play a role in biological systems:

- Photosynthesis uses quantum transport between chlorophyll molecules
- Olfaction and smell recognition is based on molecular vibrations using the quantum mechanism of electron tunnelling
- Magnetic sensing in birds allowing them to orientate is based on properties of electronic spin in birds' retinas
- The induction of a state of general anaesthesia in the fruit fly is accompanied by changes in electron spin, suggesting that electron current inside neurons may play a role in nervous system function
- All biological electron transfer is based on electron and/or nuclear tunnelling

The research challenges that quantum biology is facing span from fundamental issues related to the interplay between the energy scales of the different phenomena and the thermal noise emanating from the biological environment, to the (theoretical) understanding of the observed phenomena and technological bottlenecks related to measurement techniques. It is difficult to apply currently available (nano)measurement methods to *in vivo* measurements. The development of new techniques to probe and excite quantum phenomena in biomatter reflecting the *in vivo* situation would truly represent a breakthrough. Simulation and modelling tools currently cover different scales and regimes with various degrees of approximation. While entities composed of small atoms or molecules can be described accurately, we do not yet possess simulation tools that would account for quantum behaviour in systems such as proteins. This, however, is likely to be solved in the reasonably near future thanks to algorithmic improvements and the continuing increase in computing performance.

The applications of quantum biology in the longer term are potentially enormous and could impact upon a large number of technologies including sensing, health, environment and information technologies. Model systems will serve as a proof of concept to test the understanding of the physics and chemistry of quantum biological phenomena and lead the way to working devices such as bio-inspired photovoltaic cells, and chemical, magnetic and biological sensors.

The proposed approach to tackle these challenges relies necessarily on the integration of biology, physics and technology with the aim of producing, say twenty years from now, a device that is engineered better than life itself. The starting point is the understanding of underlying quantum biological phenomena occurring at the scale of macromolecules that will allow us to identify (experimental) building blocks ultimately leading to the realisation of a quantum machine. Even today we must recognise that most if not all of the Key Enabling Technologies which are part of the current research funding programme of the European Union (Horizon2020) are based on quantum mechanical phenomena.

Within the European context, the analysis of prospects for the development of quantum biology leads to the conclusion that with the current type and level of efforts, the field of quantum biology could continue to evolve slowly as a basic area of science, while continuing to occasionally deliver interesting insights into biological phenomena which display quantum effects. However, these conditions are unlikely to yield the breakthroughs needed for tapping into the significant potential for technological applications inherent within the field. Therefore in order to fully exploit the potential of quantum biology the following **recommendations** are provided under four key headings.

Human Resources and Education – recognising that expertise in quantum biology and related technologies will not grow in the traditional academic environment due to the continuing existence of wide knowledge gaps and barriers between disciplines, there is need to develop an appropriate skills base early on. This can be achieved by:

- Raising awareness and building competences in quantum science and technology starting with school-age children
- Creating a new doctoral degree of much longer, possibly even double, the normal duration (Dr. Universalis)
- Bridging the 'gap in understanding' by supporting extended cross-disciplinary sabbaticals for junior and senior faculty members.

Funding and Cooperation – recognising that scientists routinely cooperate and efficiently self-organise in collaborations and networks whenever appropriate funding schemes are available, a clear need emerges for:

- A dedicated long-term and large scale collaborative funding scheme at the European level providing support for a small number of research teams working in interdisciplinary emerging fields
- Funding for early stage faculty members for 3–12-month visits to perform collaborative interdisciplinary work
- Marie Curie Innovative Training Networks should enable larger-scale participation and improved success rates with a better focus on innovation.

The general requirements for **any new collaborative funding scheme are that:**

- It allows broad participation at the European level
- There is a centralised source of project review and distribution of funds
- The timeframe is sufficiently long to ensure accomplishment of major scientific endeavours
- It should be flexible with respect to new groups joining a running programme.

In addition, a consultation process should be established between European and non-European science funders in order to develop new mechanisms enabling large-scale international networks where scientists can collaborate across borders and continents.

Research Infrastructures – recognising that quantum biology research needs both experimental facilities (for example sophisticated spectroscopy equipment coupled with biology laboratories) and computational resources, it will be crucial for the progress of this field to bridge the disciplinary divide between biology, chemistry, medicine and (quantum) physics equipment and the way these have traditionally been set up and used. In most cases, the required research facilities are already supported at the national level and efficient networking mechanisms (such as the Laserlab-Europe initiative) would leverage existing resources and provide broader access to the community. A measure that would make a major contribution towards addressing quantum biology challenges would be:

- The establishment and support of interdisciplinary research centres in which complete research groups from biology, chemistry, medicine and physics are hosted in the same building.

Communication – recognising that new directions of research can only flourish if they are supported by the broader public and if they find promoters in the media and in the political sphere, a clear and distinct profile of quantum technologies needs to be established. In addition, the dissemination of convincing "stories" around fascinating instances of either existing natural quantum systems (from biology) or potential future man-made quantum machines will be prerequisites for a successful communication strategy. Some measures to reach and engage a broad public are:

- The use of social media
- Proactive interaction with media and journalists
- Participation in science outreach events and prizes
- Enhancement of communication between scientific disciplines.
- The construction and exhibition of a quantum machine

In conclusion, it is expected that the field of quantum biology is still to produce unforeseeable discoveries that will expose the existence of quantum phenomena in nature ultimately leading to their exploitation in new every-day technologies available to benefit society.

1.
Introduction

A perfect storm of science and technology has been brewing for some years and is about to break. It is likely to last for several decades and will deliver new devices, new therapies, new computing paradigms and, above all, new insights. It is the result of approaches converging from several directions that have long waited to join forces. It deals with systems operating at the nanoscale, but is not confined to what we think of today as nanotechnology. This new paradigm will not be achieved by reducing bulk entities into ever smaller pieces, but by building devices from atoms up, as living organisms do. It will operate at the boundary between quantum and classical physics. Near to its core is very likely to be the new science of quantum biology.

This Forward Look report is about this New Nanoscience: not the science, as is commonly believed, of the very small, but the science of the – so far – intractably big. The scale of nanoscience, i.e. the nanometre, is perhaps the most uncomfortable scale to study in all of physics and chemistry. A sphere 1nm in radius is huge. It can contain a protein that has evolved over billions of years to mysteriously catalyse a reaction that we cannot replicate in a flask in the chemistry laboratory. What is more challenging is that we cannot even fully simulate the dynamics of the protein and its electronic structure at the same time using quantum chemistry.

But a 1nm sphere is also tiny. It is too small for us to handle and assemble. It resists averaging, refuses to behave like a bulk solid and does not let us use the powerful tools of condensed matter physics and thermodynamics that we have developed to study large systems. More challenging still, a nanometre-scale system sits at the boundary between quantum and classical effects, where we can neither calculate exactly nor approximate confidently. Yet the nanoscale territory is not barren and uninhabited. Quite the contrary: life has always been there, operating at the nanoscale for billions of years, endlessly varying and selecting the devices and programs that lead to survival. When we finally succeed in understanding these systems we will be in a position to reverse engineer biological evolution, to use it not just as a technology we embody, but as a technology we control. What is its promise? What stands in the way? This report will list some of the goals, as well as address the obstacles and propose ways to overcome them.

2.
The Science of Quantum Biology

Three Billion Years of R&D

In 1792, when immunisation against smallpox was discovered, it became clear that life harbours technologies so advanced as to be, in Arthur C Clarke's famous phrase, *indistinguishable from magic*. The intervening two hundred years have refined and sharpened this perception. While at the level of organisms adaptations often seem like contraptions, at the molecular level the colossal inventiveness, subtlety and elegance of nature's devices can only inspire awe. Every "molecule of the month" in the Research Collaboratory for Structural Bioinformatics (RSCB) structural database is a humbling reminder of how much we must still learn.

Much of what life does with proteins is beyond our current abilities to understand, and bears an uncanny resemblance to the Key Enabling Technologies (KETs) that the EU is seeking to master in the next decade. Success in any KET would confer enormous first-mover competitive advantage. Here are a few examples of what life can do that we cannot, together with the relevant KET: single-photon detection in a low-voltage electrochemical system [photonics], nitrogen fixation at room temperature and pressure [nanotechnology], chemically powered transport of ions and electrons across nanometre distances with low dissipation [nanoelectronics], formation of hydrogen gas from H^+ without noble metals at zero volts SHE [advanced materials], photobiological charge separation with close to 100% quantum efficiency.

There is, however, one positive caveat. Everything in life's machinery is built under three daunting constraints peculiar to a self-replicating machine:

1. the use of only five elements (not counting a few transition metals) and 20 amino-acid side-chains;
2. the stringing of everything together in polypeptides as if the parts of a machine were strung on a clothesline encoded in DNA;
3. evolution at random. We are free from these constraints: the entire periodic table is available to us; we can assemble objects rather than extrude them, as a ribosome does; understanding how life makes its machinery will help us gain insight so that we can deliberately design mechanisms rather than randomly hunt for improvement.

Learning from life will not just lead to biotechnology, but to new (quantum) physics and chemistry.

Quantum efficiency:
A measure of the probability that a single quantum, such as an individual photon, is transformed into the desired output. This output could be a charge separation event which turns the volatile energy of this quantum into more stable electric form of energy, analogous to the charging of a capacitor, from which it can be made available for future use at a desired moment in time.

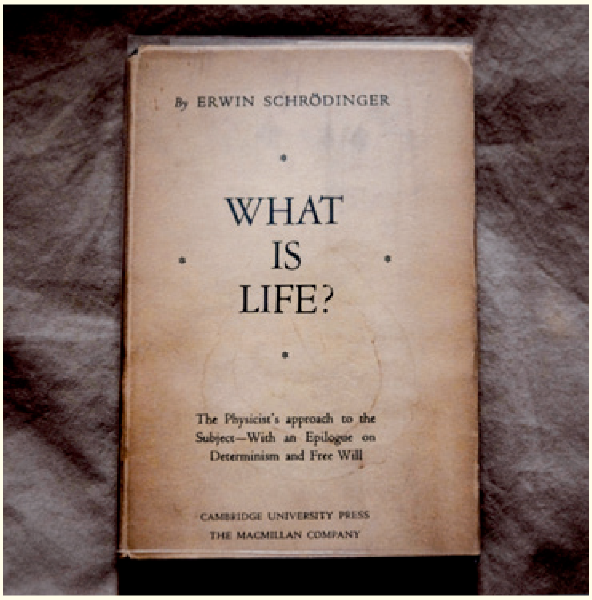
Is Life Quantum or Classical?

While physics and chemistry are now accepted to be governed by the laws of quantum physics, biology appears to remain in the classical domain. Yet we suspect that life must, like everything else, be quantum at the atomic scale. Does this atomic scale matter? The debate goes back a long way. Erwin Schrödinger, a founder of quantum mechanics, in his influential book "What is Life?" said that "quantum indeterminacy plays no biologically relevant role". Pascual Jordan, another albeit less recognised founding father of quantum mechanics, was instead convinced that the "Secret of Organic Life" was to be found in quantum "organising centres" that controlled the classical machinery around them.

This debate has simmered in the intervening decades, with quantum aspects of biology remaining a decidedly minority interest. Perhaps a parallel may be found in the history of foundational questions in quantum mechanics, which was long thought to be a non-experimental field until the theory made quantitative predictions and technologies became sufficiently advanced to make the measurements. We believe that the convergence between molecular biology and nanotechnology will in the near future bring quantum biology into the mainstream. But two questions must be answered before this can happen:

1. How large is the quantum domain?

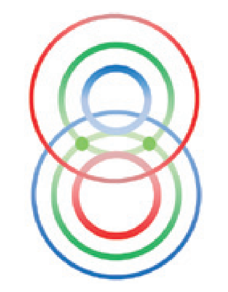
Proteins function at what has been called the mesoscale, roughly 1–10 nm. The number of atoms and electrons in a given volume increases with the cube of its radius, so going from 0.5nm (a small molecule) to 5nm (a typical protein) brings into play a thousand times more atoms. Interestingly, quantum chemistry software runs out of power somewhere between these two scales. Typically, therefore, a small quantum region is calculated exactly by quantum mechanics, surrounded by a much larger system calculated classically. Do such simulations correctly predict the behaviour of enzymes? The answer is a qualified yes, but only in the case of the simplest enzyme reactions, where quantum-level understanding of active site chemistry is sufficient. Supramolecular chemistry, the science of large chemical assemblages involving non-covalent bonds, has shown that this insight can be applied with great success. A clear understanding of the reaction mechanism and the spatial arrangement of the reactive amino acids at the active site can, free from the constraints of biology, be replicated by a much simpler molecule. Apply this to more complex proteins, however, notably those that sense signals or convert one



form of energy into another, and the method fails. Is the unaccounted-for "enzyme magic" quantum or classical? Recent evidence (see 'quantum transport in photosynthesis' below) suggests that mesoscale quantum properties of protein matter are crucial to its function and are optimised by evolution. The conjecture we would like to put up is therefore: ***the quantum domain is large when it needs to be.***

2. How stable is the quantum domain against thermal noise?

Extended quantum systems, in particular those showing "exotic" quantum correlation properties, were thought to be very fragile to thermal and other sources of noise. However, quantum information scientists are developing methods to stabilise entanglement (i.e. quantum correlation) against noise and to even use noise to *create* entanglement. Nevertheless, most experiments showing such effects are conducted in carefully shielded, very dilute phases and at very low temperatures, to reduce the perturbing effects of collisions between atoms. This is all necessary because quantum information needs to preserve coherence and entanglement for long periods because the tasks it is intended to be used for require the execution of many quantum operations that are intrinsically slow. Physicists, faced with the "hot and wet" environment of biology, have often retreated to more temperate climes. There are two reasons for cautious optimism, however. The first is that stability is only a relative term. If our lives lasted a millisecond on average, we would think sturdy a house that lasted half a second. Similarly, the time-scale over which quantum phenomena occur is only significant in the context of the timescale of what the protein is trying to achieve. The second reason is that proteins



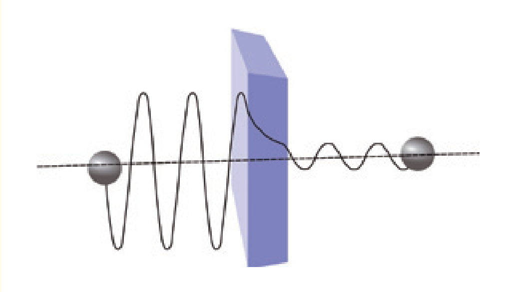


Figure 1. (left)
A symbolic representation of a biphoton (a pair of entangled photons).
© Neolexx/ Wikimedia Commons

Figure 2. (right)
Symbolic representation of electron tunnelling through a potential barrier.
© Yoschi/ Wikimedia Commons

can do a great deal to mitigate the effects of noise and even make use of it. The sometimes long coherence times of protein vibrations can be borrowed by the electronic coherence to make it longer lived too, similar to a music conductor who makes sure that the orchestra remains 'in phase' and does not start to play at random. Proteins, as we shall see below, can thus help to prolong coherence. The conjecture is therefore: ***the quantum domain is stable enough under the right conditions.***

The Return of Quantum Biology

After a long eclipse, Pascual Jordan's view has thus come roaring back with the discovery of four *manifestly* quantum phenomena in biology. The first is the highly efficient energy transfer and charge separation in photosynthesis. The second is phonon-assisted electron tunnelling in olfaction. The third is navigational sensing of the magnetic field by birds. Remarkably, these phenomena were considered together for the first time not in a symposium or a review, but in a February 2009 Discovery Magazine article. In 2010, the US Defense Advanced Research Programs Agency (DARPA) initiated the QuBE program (Quantum effects in Biological Environments) that helped put the field on the scientific map. The fourth phenomenon is anaesthesia. These four manifestly quantum processes are, for now, just four small clouds in the otherwise blue sky of classical biology. But they have been likened to the three small clouds that appeared in the last quarter of the nineteenth century and presaged the storm of quantum mechanics: photoelectric effect, black-body radiation and heat capacity of solids.

1. Quantum transport in photosynthesis

Sunlight provides the entire energy input available to life on or near the Earth's surface. Peak radiation from the sun lies in the green region of the spectrum at a wavelength of 500nm, corresponding to 2.5eV of energy per photon. This, by the standards of biology, is a large energy, enough to break a chemical bond – hence sunburn – and, just as

Quantum correlation:
Components of a quantum many-body system that are interacting with each other will become correlated whereby the measurement on one component allows for the prediction of the measurement outcome on another component with high probability. Quantum systems exhibit correlations that are stronger than those allowed in classical physics, a fact that can be made use of in applications such as quantum cryptography and quantum teleportation.

Quantum many-body system:
A system that is composed of in-principle identifiable individual components that are quantum objects and are interacting with each other. Electron spins that make up a magnet and which are interacting with each other via their magnetic fields is an example of everyday practical importance. It is a key aim of quantum technologies to create such systems under highly controlled conditions and conditions of low temperature and high insulation for example in ion traps, ultra-cold atomic gases or superconductors.

Coherent superposition:
In classical physics a system takes on one value *or* another – a coin shows either heads or tails. A quantum particle may exist in a coherent superposition of two possibilities – a spin can be in spin-up and spin-down state at the same time, a photon can be both horizontally and vertically polarised at the same time.

Entanglement:
A consequence of the combination of the existence of coherent superposition and of quantum many-body systems. If a single electron spin can be in coherent superposition of two states, then two electron spins can be in a superposition of all possible combinations, i.e. 4 states. N electron spins can be in a superposition of 2^N states at the same time. This forms the basis for applications such as quantum computation as long as the quantum many-body system can be isolated from the environment sufficiently well to protect the quantum nature of the system. Entangled states exhibit quantum correlations.

Electron tunnelling:
In quantum mechanics, the wavelike character of all matter allows for quantum objects such as electrons to traverse a potential barrier even if their energy is lower than that of the barrier. In classical physics this is impossible as a particle will always have to be lifted above the barrier. Electron tunnelling is of fundamental importance in chemistry and physics and has found application for example in technical devices such as the scanning tunneling microscope (Nobel Prize for Physics 1986).

Figure 3. Computer artwork of a molecule of chlorophyll ($C_{55}H_{72}MgN_4O_5$) superimposed on a leaf. The atoms, represented as rods and spheres, are colour-coded; carbon (orange), hydrogen (green), oxygen (red), nitrogen (blue) and magnesium (white). Chlorophyll is a pigment molecule in plants. It absorbs sunlight and uses its energy to synthesise carbohydrates from carbon dioxide and water, a process called photosynthesis. Chlorophyll also gives plants their green colour. The central part of the molecule is the porphyrin ring surrounding the magnesium atom. It is the arrangement of electrons in this ring that allows chlorophyll to absorb solar energy.

importantly, to make one. For comparison, the energy currency of "dark", i.e. animal, biochemistry is ATP [1] hydrolysis, which is roughly four times smaller at 0.6eV. The edifice of photosynthetic machinery in plants is designed to capture photons efficiently and with little collateral chemical damage. The first step is the creation of an excited electron, termed an exciton, in a chlorophyll molecule. Chlorophyll is an eminently quantum object in which a metal atom sits at the centre of a highly delocalised cloud of electrons. The exciton can move around very efficiently in the system of connected chlorophylls if they are sufficiently close and only a small part of the exciton energy is dissipated as heat. The exact energy of an exciton depends not only on the associated chlorophylls which have a constant structure, but on their immediate molecular environment. If an exciton jumps from one set of chlorophylls to another with a smaller exciton energy, the difference must be absorbed or generated by the environment in the form of vibrations. By good fortune, a protein was discovered which embodies all these features, is water soluble and makes good crystals which enable the positions of all its atoms to be known. This is the Fenna–Matthews–Olson (FMO) complex, which has yielded a rich harvest of insights. Since this original breakthrough, the same basic principles have been found to apply to other protein complexes, such as light-harvesting complexes of photosynthetic bacteria, marine algae and plants.

Exciton:
An electronic excitation delocalised over several sites.

Leaving all technical detail aside, the picture that has emerged is remarkable. The job of these proteins is to transport excitons from one end to another via seven chlorophyll molecules embedded in the protein, like currants in a bun. How this is done efficiently is rather counterintuitive.

1. The exciton does not usually reside on a single chlorophyll, but is spread over several;
2. the exciton simultaneously follows different paths which interfere in a wavelike fashion with each other;
3. the vibrational modes of the protein in which the chlorophylls are embedded are matched to the differences in energy between excitons, so can absorb or generate the correct amount of energy and therefore facilitate exciton transport from one end to the other.

Whether it is the protein vibrations that become adapted to the electronic structure or vice versa is not known, but it seems easier, evolutionarily speaking, for the protein to tune the interaction between chromophores and their excitation energies, as their interactions will be more sensitive to local changes in protein structure than the vibrational spectrum of pigments or proteins. For example, substitution of one amino acid for another close to the chlorophyll could change electronic energy levels by 1eV or so, while having almost no effect on the low frequency collective modes of the protein. The light-harvesting complex of higher plants, LHC2, requires tuning of the chromophores to function. In this case, thanks to our extensive knowledge of the genetics of *Arabidopsis* (the fruit fly of the plant world) it will be possible to design both chromophores and protein to study the effect of mutations on efficiency. A key to the survival of quantum coherence in this temperature regime is an interplay between the energies of electronic levels and the energies of long-lived vibrational modes. If electronic levels in different chromophores are separated by an energy which corresponds to the energy of a vibrational mode, we have a resonance that leads to mutual energy exchange, much like that between coupled pendula of similar frequency. If a long-lived vibration is excited then it can drive oscillations between

1. Adenosine triphosphate, a molecule used as carrier of energy in the cells of all known organisms.

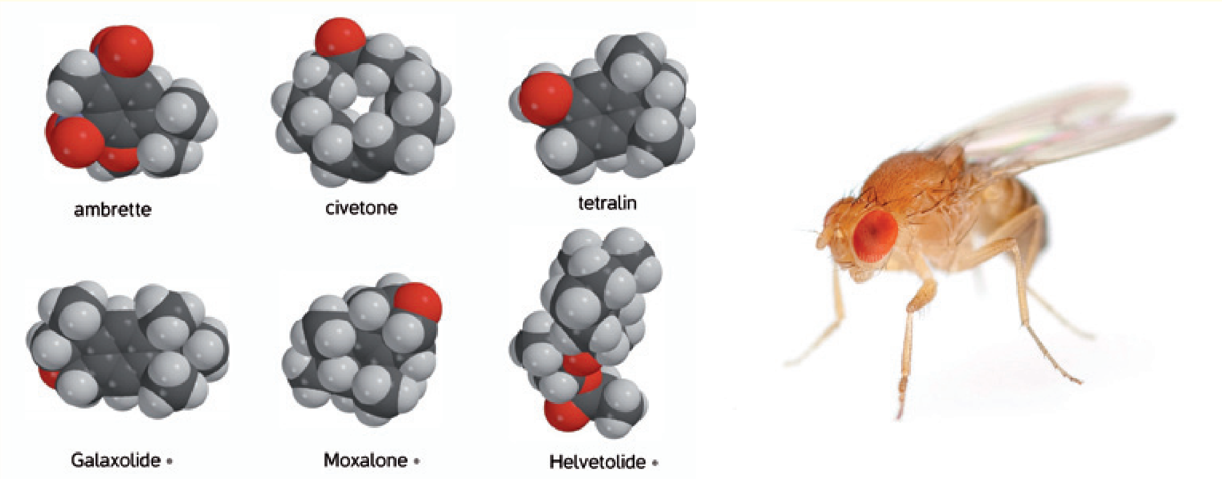


Figure 4. 120 years of synthetic musks with diverse structures and near-identical odors. Deuteration of a macrocyclic musk like civetone completely changes its odor character, suggesting that humans, like flies, can smell molecular vibrations. © Luca Turin (left) – iStock (right)

electronic excitations in a light-harvesting antenna, thus enabling the pigments to share the same coherent modes. This is novel engineering: it is fair to say that no device created by man so far has made use of all these properties at these lengths and time scales at the same time.

2. Phonon-assisted tunnelling in olfaction

Olfaction (the sense of smell) is the ultimate molecular recognition system. Our noses, and those of other animals, unerringly detect and identify thousands of molecules. We now know that there are several hundred receptors in man (several tens in fruit flies) that bind odorant molecules, albeit rather unspecifically. How exactly this binding is translated into a smell sensation has remained a mystery. There are broadly speaking two schools of thought on the matter. One is that the familiar principles of 'lock and key' (same shape results in same odour, different shape results in different odour) apply to olfaction, and that structural features of odorants are recognised by the receptors and translated into a pattern of activation which yields a smell character. The other is that receptors first bind the odorants, then probe their molecular vibrations using a quantum mechanism, inelastic electron tunnelling. An electron could tunnel – a purely quantum process – near or across the odorant from a donor to an acceptor site within the protein *only* if the energy difference between donor and acceptor can be soaked up by a vibration of the odorant. Note of course that these vibrations themselves are quantised. This is reminiscent of phonon-assisted transport of excitons in FMO and once again illustrates the role of vibrational excitations in the quantum biology context. In the vibrational view, olfaction is reminiscent of colour vision where three broadly tuned receptors

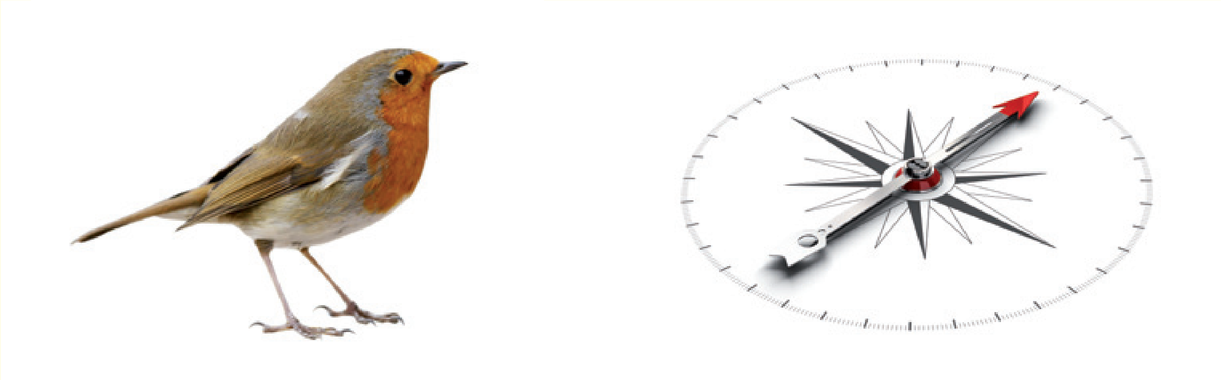
Inelastic electron tunnelling:
An experimental tool for studying vibrations in molecules. Electrons tunnel between source and drain. When electron source and drain have different energies, then energy conservation requires that the difference is taken up or provided by another degree of freedom. Here this is a vibrational mode whose energy per excitation quantum is matched to that of the energy difference between source and drain.

enable the discrimination of tens of thousands of colours.

Though still controversial, vibrational olfaction has received fresh support in recent years from two directions. The first is that it has been shown that fruit flies can 'smell' molecular vibrations. For example, the flies are fond of the odorant acetophenone (hawthorn odour). When the hydrogens in acetophenone are replaced with the heavier isotope deuterium, which leaves its shape unchanged, the flies are repelled instead of attracted. Further, flies trained to avoid deuterated odorants also avoid the chemically unrelated nitriles which vibrate at around the same frequency. The second line of evidence has come from theory, which has shown that a hopping tunnelling mechanism is plausible and efficient. Efforts are now underway in several laboratories to build a room-temperature tunnelling sensor incorporating what has been learned from biology.

3. Magnetic sensing in birds

It has been clear for over forty years that birds possess a magnetic compass that helps them perform extraordinary feats of migration. The molecular mechanism underlying this compass has been controversial for a long time. One thing has however always been clear: the sensor must include either a ferromagnetic solid like magnetite or a paramag-



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netic entity like an electronic spin. The current favourite, at least in birds, is a mechanism involving electron spins, called the radical pair mechanism. It is based on a chemical reaction whose rate is affected by the spin state of electrons which in turn is controlled by the orientation of an external magnetic field relative to molecules that carry the electron spin, and has been demonstrated in vitro in an artificial system. The bio-molecular components that would be required to realise this mechanism are known to be present in birds.

The operating principle is subtle: a photon of visible light excites the electrons in a chemical bond to jump to a higher energy level, in which they no longer form a bond but instead reside on the atoms at either end, turning each into what is termed a radical, hence the name. Each electron has spin, and behaves like a quantum magnet. Initially the spins are opposed (in technical terms the singlet state) and insensitive to the orientation of an external magnetic field, but the combined action of external magnetic fields and local interaction with their environment can let them oscillate between aligned and opposed (in technical terms, the triplet states) configurations.

This process is sensitive to the orientation of the external magnetic field relative to the orientation of the local environment principally made up of nuclear spins in the molecules. Hence it is an interplay between symmetry and asymmetry in the interaction with the outside world that gives rise to magnetic field sensitivity. The trick that makes it work is this: the radical pair state is unstable, and can decay to a more stable state preferentially from the singlet spin state. It does so in a time comparable to a period of the slow oscillation between different spin states. The decay therefore becomes sensitive to the magnetic field that causes the slow oscillation. How this might work in a bird is remarkable: it is likely that this mechanism inhabits the retina of the bird's eye enabling it to *see* the Earth's magnetic field as if it were light.

4. General anaesthesia

The most recent area to enter the quantum biology arena is neuroscience, following a recently published study showing that general anaesthesia in Drosophila is accompanied by large changes in electron spin. These spin changes are sometimes absent in mutant strains of Drosophila that have been selected for their resistance to general anaesthetics. The study also proposes that the effects of general anaesthetics on spin may be related to the conduction of electrons. The nature of the substrate to which the measured spins are bound is unknown, but the signals are consistent with it being neuromelanin. This raises the interesting possibility that electron currents inside neurons, in addition to the well-understood ion currents discovered nearly a century ago, could play a role in nervous system function.

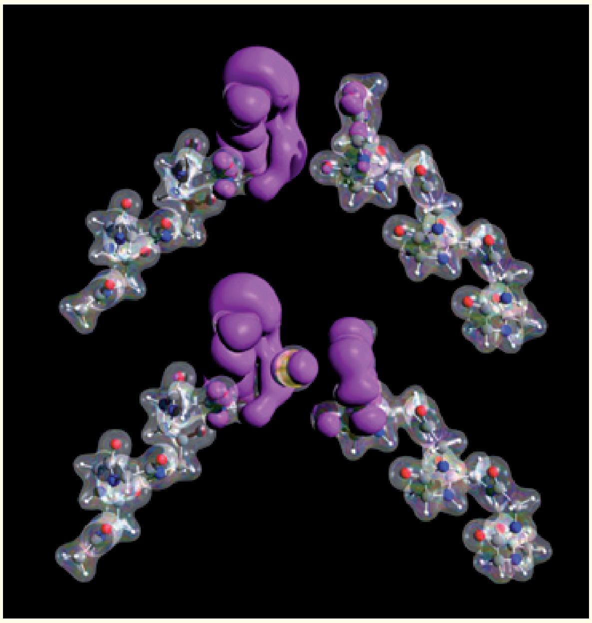

Figure 5. Effect of the anesthetic noble gas Xenon on the electronic structure of two short peptides. Top: the highest occupied molecular orbital [HOMO, purple surface] for two 9-residue helices positioned close to each other. A small fraction of the HOMO extends from one helix to the other. Bottom: when a Xenon atom [gold sphere] is in the gap, the orbital spread increases. Transparent surface is Van der Waals electron density. © Luca Turin

It will not have escaped the reader that all four quantum biology mechanisms discovered so far involve electrons, in one form or another: electron currents in olfaction, unpaired electrons in magnetic navigation and in anaesthesia, and electronic excitons in photosynthesis. In each case, the electrons interact with a fluctuating environment, in which the fluctuations are due to thermal motion, itself quantised into phonons.

Knowns and Unknowns: the Challenges

Table 1 summarises what we know about the four most prominent phenomena in quantum biology so far.

The **energy scale** of quantum biological phenomena falls into two widely separated ranges which determine experimental approaches. All the phenomena involving visible light benefit from the fact that the energies of photons in the visible octave (2–4eV) are far higher than thermal energy at 300K, by a factor of at least 100. In a sense, light is both energy source and also acts as a switch. The subsequent dynamics can take place on rather different time scales. In photosynthesis the dynamics stretch from hundreds of femtoseconds (fs) to picoseconds (ps) which is at least 1 000 time slower than the times given by an energy scale of 1eV.

This means that the relative effect of thermal noise will be generally smaller. Additionally, the medium, water, in which the biological machines are embedded is transparent in this range. For mechanisms in biology not involving visible light, i.e. the majority of animal biochemistry and biophysics, the situation is dauntingly different. Beyond a wavelength of 1.4μm (i.e. below 0.9eV) water becomes opaque to electromagnetic (EM) radiation and remains so all the way down to thermal energies. For comparison, ATP hydrolysis energy, the 'energy currency' of cells, sits at approx 0.6eV. Large scale collectve protein motions are in the THz range. At 1THz (33 cm^{-1}, 4meV) 1 micron of water lets through 10^{-8} incident radiation.

Our **understanding** of these phenomena cannot be deemed satisfactory, except in the case of exciton transfer in photosynthesis, which is reasonably well understood thanks to the availability of incisive experimental tools for its investigtion. In the case of olfaction, clear evidence exists for a contribution from a vibrational mechanism, and so far only a phonon-assisted mechanism seems to be able to account for the effect. There is, however, no "smoking gun" proof of electrons traversing receptors. The field of avian magnetic sensing is still in flux. Experiments had encouragingly shown that low-power radiofrequency (RF) waves at the energy corresponding to the Zeeman splitting (the difference in energy between up-spin and down-spin) of electrons in the Earth's magnetic field disrupt navigation. This was taken as direct evidence for a spin-based mechanism. More recent work has shown that this resonant effect may not be necessary, and that RF at most frequencies is just as disruptive. A theoretical understanding of this effect is still outstanding.

Table 1: Summary of phenomena in quantum biology

Phenomenon	Photosynthesis	Olfaction	Magnetic navigation	Anesthesia	Biological electron transfer
Mechanism	exciton-phonon	electron-phonon	spin-spin interaction	semiconduction	electron-phonon
Energy scale	2 – 3 eV	0.05 – 0.5 eV	2 – 3 eV and 20MHz	≈1 eV	0.01 – eV
Understanding	good	limited	limited	limited	good
Macro measurement	optical	behaviour	behaviour	ESR-EPR	optical/ESR/EPR
Nano measurement	single molecule	NVD	NVD and spin labels	NVD	single molecule
Excitation	light, IR, THz	chemical, IR, THz	light	thermal	light, IR, THz
Calculation	QM, MD	DFT, LSDFT,MD	DFT, QM, semiclassical	DFT	DFT, QM
Application	energy conversion	sensors, drugs	sensors	drugs	energy conversion
Models	supramolecular	tunnel sensors	D-A pair	none so far	partially understood

Glossary of acronyms. NVD: Nitrogen vacancy defects in diamond; ESR: Electron spin resonance; EPR: Electron paramagnetic resonance; IR: Infrared; QM: First principles quantum mechanical calculation; MD: Molecular dynamics simulation; DFT: Density functional theory; LSDFT: Linear scaling density functional theory; D-A: Donor-acceptor pair. Details can be found in the main text.

Our **measurement** methods at the **macroscale** are woefully primitive in the case of olfaction, where only behaviour in the case of fruit flies or sensation reported by humans guide our understanding. No progress will be made until a more direct grip on mechanism is achieved. In magnetic sensing a similar situation prevails, with the added disadvantage that the migrating birds which navigate using a magnetic compass do so only at certain times of the year. This field seems to be in urgent need of an alternative, more amenable preparation. By contrast, exciton transfer on FMO is studied on purified preparations which can be crystallised. Indeed, it was the fact that the crystallographic structure was known that motivated the choice of FMO and later several other photosynthetic complexes in the first place.

Both olfaction and magnetic navigation would greatly benefit from the development of single molecule **nanomeasurement** methods, e.g. isolated, individually addressable spin sensors as exemplified by nitrogen vacancy diamonds (NVDs). These are diamonds in which a very small fraction of carbon atoms forming the lattice have been replaced by nitrogen atoms and a neighbouring carbon atom is missing from its lattice site. These substitutions result in the presence of electrons that are not participating in a chemical bond and exhibit a magnetic moment that may be exploited for the purposes of magnetic field measurements. The spin state can be measured optically. The clear promise of NVDs in the not too distant future is the detection of currents and spins with a time resolution of a few milliseconds, a sensitivity of a single spin or a few pA and a spatial resolution of the order of nanometres. Much of this has already been achieved in the physics laboratories, and now the challenge is to make it work in a biological environment. Processes in photosynthesis, by contrast, appear mostly to be too fast for this approach, although hybrid IR–visible schemes could overcome this. Here the frontier is currently the single-molecule measurement, where no ensemble averaging occurs. Already remarkable phenomena like "blinking", i.e. the switching on and off of a protein photopigment under continuous observation, implying that the protein exists in two states, have been observed, with the promise of much more to come. The existence of this phenomenon implies a means of direct control of photosynthesis by conformational change of the protein, either by on–off switching or by phonon modulation of exciton transfer under control of the environment.

Selective excitation of all these phenomena by an external agency, particularly in vivo, would be of considerable interest but at present remains elusive.

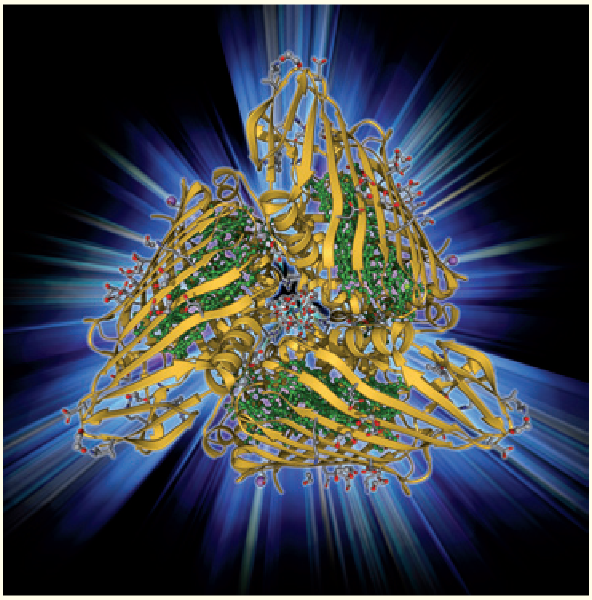

Figure 6. Molecular model of the Fenna-Matthews-Olson (FMO) complex from the green sulphur bacterium *Prosthecochloris aestuarii*.
At the centre of each of the three proteins is a bacteriochlorophyll a molecule. © Laguna Design/Science Photo Library

In the case of photosynthesis, the overlap between absorption spectra of different photopigments precludes this, and information is best obtained at the level of the purified individual system, although better phase and frequency control could achieve this. In olfaction, there is a possibility that direct mid-IR stimulation might interfere with the vibrational sensing. The technology is there, since pulsed lasers continuously tunable in the mid-IR are available, but the perennial problem of intense IR absorption by water still hampers experimental progress. The field awaits a preparation with as little water as possible situated between the light source and target, possibly an insect antenna. Magnetic navigation would probably also benefit from pulse RF methods to disrupt the suspected radical pair mechanism, but when using birds the power requirements would probably have unwanted thermal side effects. Again a smaller, possibly insect, preparation is needed. Magnetic sensitivity has been described in Drosophila and a combination of genetics and behaviour would provide a powerful set of tools to make progress continuously without having to wait for other factors such as migratory bird seasons.

Calculation of these phenomena is where the problems are at the same time most glaring and most likely to be solved in the reasonably near future. Whenever the structure of the protein(s) responsible for the biological effect is known, a sign that we have gained a full understanding will be our ability to simulate the process in its entirety. We are well short of that at the moment. Our computational methods are specialised for different

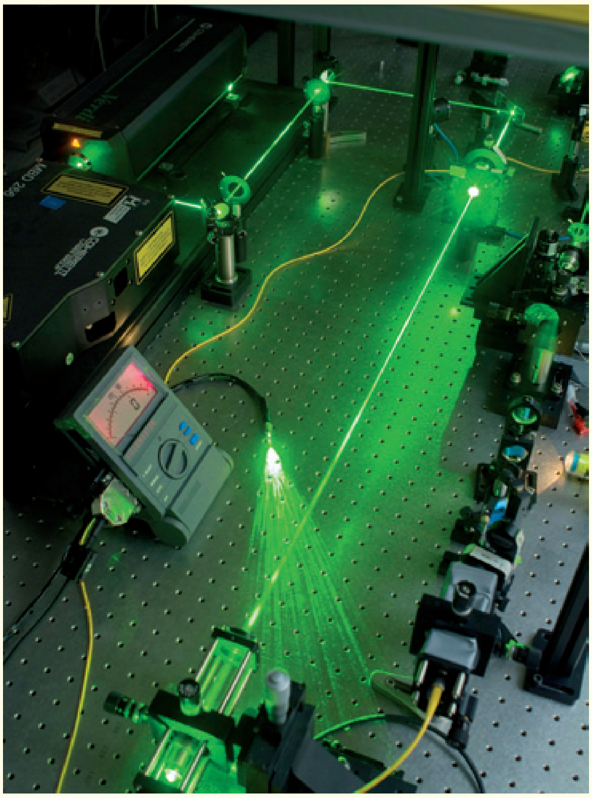

Figure 7. Quantum physics research lasers.
© Sam Ogden/Science Photo Library

scales and different approximations, and each has strengths which recommend it together with weaknesses which limit the insights gained. Molecular mechanics (MM) and molecular dynamics (MD) use entirely classical force fields and do not readily incorporate any quantum component or indeed any electronic excitation or bond breaking, let alone quantum dynamics. In addition, despite the drastic approximations they include, these approaches are currently unable to simulate real time. Complex enzyme mechanisms often operate on the millisecond (10^{-3}s) time scale, an aeon for a code whose unit of time iteration is the femtosecond (10^{-15}s). Semi-empirical quantum chemistry codes are increasingly applicable to large systems and proteins are well within their reach in terms of numbers of atoms. Three problems limit their use: the difficulty of modelling solvents, the problem of finding a global energy minimum for the protein as a preliminary to obtaining its normal modes, and the adequate simulation of hydrogen bonds, all-important in biology. Density functional theory methods can calculate electronic structure with useful precision, are better at hydrogen bonds and give very accurate energies on small systems, but scale unfavourably with size. An emerging area of tremendous promise is linear-scaling density functional theory (LS-DFT) which is on the cusp of becoming a method for non-specialists. A not unrealistic goal would be to be able to calculate the full electronic structure and dynamics of an entire protein in water from first principles over a nanosecond within the next decade.

The **applications** of these fields of quantum biology are potentially enormous and will warrant a large-scale, concerted technological effort as our understanding of the basic science progresses. The potential applications of a better understanding of photosynthesis need hardly to be emphasised. Solar energy is the only direct, inexhasutible power source on Earth. Harnessing the lessons learned by evolution's "3 billion years of R&D" could prove to be crucial. For example, better design of solar cells could follow from a better understanding of the crucial material properties for optimal biological charge separation. Alternatively, new strains of plants could be engineered that make more efficient use of solar radiation. Olfaction *per se* is a field where the applications may perhaps be considered mostly frivolous (relating to fragrance and flavour) and no major unsolved medical problems exist. However, sensors to detect hazardous gases, spoiled food, toxic substances, air contaminants, pollution and diseases could be built on the basis of the mechanisms at work in olfactory receptors (ORs). Further, olfactory receptors are members of the huge G-protein coupled receptor (GPCR) family, which includes receptors for many brain neurotransmitters. If ORs were proven to operate by an electronic mechanism this would likely have consequences for other GPCRs. It seems unlikely that vibrational sensing will turn out to be essential to function in other GPCR systems, but a "probing" of the ligand after binding could be general. If indeed drugs turn out to be molecular electronic devices, then this insight will be be crucial to rational drug design. A better understanding of the connection between spin and general anaesthesia may reveal previously unsuspected electronic intracellular mechanisms in neurons. This in turn could lead to advances in anaesthesia itself, in the closely related field of diving physiology, and in the action of drugs on the central nervous system.

Model Systems will serve as a proof of concept to test our understanding of the physics and chemistry of quantum biological phenomena, and lead the way to working devices: these could include bio-inspired photovoltaic cells, chemical sensors, magnetic field sensors or man-made enzymes. It is likely that they will be at the supramolecular scale, which has in the past been very successful at mimicking biological mechanisms without the constraints of self-replication. Indeed, efforts are already underway to build a molecular tunnelling sensor that mimics olfaction. The applications of such a device to medical diagnostics and environmental monitoring are obvious. In the case of magnetic sensing, a better understanding of the chemical physics involved could lead to highly sensitive sensors at the nanoscale capable of measuring nT magnetic fields with a high spatial resolution. This could lead to applications in the field of materials and spintronics. It could also allow the detection of, for example, neuronal activity by detecting the magnetic fields caused by ion currents, thereby achieving a cell-level optical sensing of current or local spin on length scales that may even exceed those of the currently emerging nanoscale magnetometry based on colour centres in diamond. In photosynthesis a huge effort is already underway to optimise materials and the design of morphology of solar cells to achieve more efficient charge separation than that which is currently attainable in organic solar cells by mimicking nature. Light harvesting is part of the problem, and understanding quantum phenomena will unquestionably contribute to the design of light-gathering antennae, again at the supramolecular scale or higher still, using self-assembly methods such as monolayers and 'DNA origami'.

Quantum Biology Needs Quantum Physics and Vice Versa

Discoveries are seldom plucked from thin air. Chance *only* favours the prepared mind, as a context is built up that leads to the creative insight. In an interdisciplinary field the context is unusually dispersed and the elements necessary for a breakthrough may be very far from one another. The context of FarQBio is, properly speaking, neither biology nor quantum physics nor condensed matter physics but something in between – supramolecular quantum physics – which it is the purpose of FarQBio to develop. There is a need for a collaborative effort bringing together mature fields like condensed matter physics and quantum information science with biology and biophysics.

The four advances into possibly quantum biological phenomena described above would not have been made without prior familiarity with the underlying physics and physical chemistry: the excitonic transfer between chromophore molecules and light-driven charge separation has a long history dating back to the early days of spectroscopy (photosynthesis); the basic mechanism of inelastic electron tunnelling spectroscopy was discovered in 1966 (olfaction); the spin physics of photochemical reactions go back to the immediate post-war years when ESR was developed (magnetic sensing), and the new insights into anaesthesia go back to the pioneering work in physics and chemistry of Freeman Cope and Albert Szent-Györgyi forty years ago.

It would therefore be wrong to expect biology to serve as the only source of inspiration for FarQBio. For a start, a biologist is unlikely to recognise a quantum phenomenon unless primed to do so, and the priming can only come from a physicist who has either seen it before or predicted its existence. Conversely, physicists are often put off by the complexity and uncertainties of biology and need to be introduced to its methods and concepts. Many great advances in biology and biophysics in the past have depended crucially on the choice to become prepared in this way. What may be impossible in a mouse may be doable in a fly, a worm, an alga or a virus, in a controlled sub-cellular preparation or even an isolated protein. **FarQBio** therefore **rests on two pillars** of equal size and strength: **biology and physics**. In our vision only the most vigorous research effort in fundamental quantum physics will make the biology worthwhile and vice versa. The effectiveness of FarQBio will therefore lie in the integration of these two disciplines. In addition, this Forward Look would like to encourage the creation of a forum and a focal point bringing together experimental biophysicists, theoretical physicists and computational chemists. A long-term effort in this direction would have a catalytic effect on the field.

The FarQBio Vision

Quantum effects in biology are surely not limited to the above-mentioned phenomena. Most probably quantum mechanics play crucial role in numerous steps of metabolism. For example, a resting adult human has 100 amperes of electron current flowing through respiring mitochondria to reduce oxygen to water. The mode of electron conduction is unknown but is very unlikely to be accounted for by classical physics. Discoveries in this area are hampered by the lack of measurement techniques. Coherent states of matter (including biological matter) are fragile and are destroyed by the measuring apparatus. Traditional structure-resolving methods (X-ray, transmission electron microscopy and scanning tunnelling microscopy) are strongly invasive. They allow single atoms to be observed, but are unable to detect the non-classical behaviour of biomolecules. Therefore, new approaches enabled by recent developments in quantum sensors, powered by techniques developed in the quantum information community, will be crucial.

The practical exploitation of the ultimate laws of quantum physics is forming the basis for the defining technology of the 21st century. In the last five decades, results from fundamental quantum physics have already revolutionised information and communication technologies (ICT). It is estimated that in advanced economies two-thirds of the gross domestic product is based on technologies related to quantum physics. To illustrate this let us mention those discoveries for which a Nobel Prize was awarded and which have found direct application in industrial production: transistors (Nobel Prizes in 1956 and 2000); lasers (1964, 1971, 1981, 1999, 2005); superconductivity (1913, 1972, 1973, 1987, 2003); giant magnetoresistance, on which hard drives are based, (2007); as well as nuclear magnetic resonance and tomography (1943, 1944, 1952, 1981, 1991, 2002, 2003) with its direct connection to biology and healthcare.

> The aim is for people, twenty years from now, to hold an indispensable device in their hand that is engineered *better than life itself*. The excitement and novelty of this new field come from the fact that it is the *first basic physics/engineering effort in the history of science and technology to originate from within biology*. The challenge for those who embark on this adventure is that they will be asked to go far beyond their mere competences: they must learn from each other all the time.

To be clear: FarQBio is *not* another iteration of biomimicry or biotechnology. It is not concerned with using enzymes or copying system-level features of biological organisms. Biotechnology uses nature without necessarily understanding it, biomimicry imitates its large scale features: what FarQBio wants to do is to improve on nature by understanding it at the quantum level. As Oscar Wilde put it: “talent borrows, genius steals”.

Enabling Key Technologies for Europe

The EU 2020 Strategy towards smart, sustainable and inclusive European growth relies on leadership in enabling and industrial technologies which are now part of the Horizon2020 funding programme. There is an urgent need for reinforcement and development of European industrial capabilities in Key Enabling Technologies (KETs) to ensure that Europe maintains its position among the leading economies under the conditions of fierce global competition. Eventually this will require from European policy makers rebalancing of resources and objectives, which is a non-trivial task at a time when economic turmoil rolls over Europe.

There are two ingredients of utmost importance which are prerequisites to successful development and implementation of KETs – a detailed knowledge about quantum mechanical phenomena at all scales, and a sufficient number of qualified professionals who possess a profound knowledge about these phenomena and are able to transform them into technologies and ultimately into products available on the market.

All Key Enabling Technologies rely on the exploitation of quantum mechanical phenomena to some extent:

- **Nanotechnology** relies on the ability to manipulate matter at the scale of 10^{-9}m. At this scale, matter is governed by quantum mechanics of interacting atoms and molecules. The key instruments of nanotechnology, such as the scanning tunnelling microscope, also rely on the exploitation of pure quantum effects.
- **Microelectronics,** in pursuit of Moore’s law of increasing functionality per unit cost, is inevitably heading towards the nano-scale; even the usual semiconductors are quantum devices. New developments, such as quantum dots, are increasingly coming into play.
- **Biotechnology** is often wrongly misconceived as standing outside the quantum realm. We are now beginning to realise that biology relies on the same quantum phenomena as physics and chemistry do. For example, the process of photosynthesis involves energy transport along a chain of chlorophyll molecules in an essentially coherent quantum process with admirable efficiency. Astonishingly, photosynthesis in nature captures more energy than mankind is currently able to produce and consume. Harnessing this phenomenon for technological use holds the promise of bountiful energy harvesting from the cleanest source in which our planet is literally soaked – sunlight.
- **Photonics** exploits light and its interactions with matter – there is hardly anything more quantum mechanical in nature than this. Basic and ubiquitous devices such as lasers used in everyday life are quantum mechanical devices.
- Development of **advanced materials** is the route for European industries out of the looming shortage of rare earth elements and dependence on East Asia’s ability and willingness to supply them. Understanding and exploiting quantum mechanical principles of how solid-state matter is built is the route towards designing and assembling materials

with customised properties. The solution of this complex task may require the replacement of traditional computational schemes by a conceptually different approach utilising quantum simulators.

Towards Quantum Machines

All technology is constrained by the laws of physics. In the 19^{th} century technological limits were set by thermodynamics and classical mechanics. The physics of the 20^{th} century witnessed dramatic changes that led to discoveries of unimaginable scale and consequence. This paradigmatic shift has been triggered by the formulation of quantum physics. Quantum theory provides the correct description of all physical processes at the microscopic scale, which also serves as a basis for the understanding of the foundations of several scientific fields, e.g. chemistry and biology. Two major ideas of quantum mechanics govern their operation. The first is the quantisation of physical properties such as energy and momentum. The second is the duality of wave and particle which become intertwined properties at the atomic scale. In conjunction they lead to new, stronger-than-classical correlations between constituents of many-body systems. While the first basic idea is being widely used in our everyday technology, for example in electronics, and the second, wavelike properties are used in some applications such as lasers, their combination is not yet widely used in real world devices. Quantum coherence and correlations are not mere curiosities: they enable quantum information processing and communication, providing solutions to problems that either cannot be solved at all in the classical world or cannot be solved efficiently on digital computers. The ultimate information processing machines have to use quantum coherent dynamics to deliver their processing power.

The traditional paradigm for quantum information processing relies on arrays of pure, isolated quantum bits (qubits) and their coherent interactions to manipulate quantum superpositions and entangled states. Progress with this approach has so far proved slower than initially expected. In these early days, progress has been steady but major breakthroughs can only be expected once fault-tolerant operation on a sufficiently large set of individual units has been achieved. Currently, the biggest challenge in this direction remains the detrimental effect of environmental noise, which destroys quantum superposition and entangled states.

For a long time it was believed that moving to a condensed phase while retaining useful quantum behaviour would be difficult if not impossible. This has now been disproved by both synthetic and biological systems. Nitrogen vacancy centres in diamond are a prominent example of such an 'atom like' system in a solid. Another example is superconductive device technology. Photosynthetic pigments have shown how coherence can be maintained over hundreds of atoms in a system with low symmetry.

The role of noise as potential enhancer, rather than destroyer, of quantum information processing, is now being reconsidered in various scenarios, ranging from quantum simulations and complexity theory to the emerging field of quantum biology. We need better theory and experiment on quantum many-body systems to clarify under what conditions quantum coherence coexists with noise. This understanding will allow us to identify (experimental) building blocks exhibiting quantum dynamics on a complexity level comparable to macromolecules and lead to the realisation of what we call the quantum machine.

Quantum machines will rely on non-trivial quantum effects on a hierarchy of length and time scales. A first step is the identification of emergent quantum phenomena in interacting quantum systems far from equilibrium. This might also help in the understanding of biological systems.

We know that the technology of the 18^{th} and 19^{th} centuries was built on the steam engine. Electronics was the technology of the 20^{th} century.

This century may well be the century of 'The Quantum Machine'.

3. Policy Framework and Future Needs

Quantum biology is an emerging and still unexplored field which is only now beginning to be funded significantly in Europe. Currently, the field is supported at the European Union level by one STREP project under FET Open with a total funding of 2M€ and as a part of an ERC Synergy grant accounting perhaps for about 0.5M€ of the total funding. At the national level there are no dedicated programmes or initiatives but only a few isolated small scale research projects. This contrasts with the DARPA QuBE[2] effort in the US which has brought together research on quantum effects in photosynthesis, bird navigation and olfaction as main areas of quantum biology under the umbrella of a concerted programme with significant funding of the order of $75M over 4 years. With the current types and level of efforts, the field of quantum biology could continue to evolve slowly as a basic area of science and deliver regularly interesting insights into quantum phenomena. However, under these conditions it is unlikely to yield the kinds of breakthroughs needed for tapping the significant technology application potential inherent to it. Very serious efforts must be made in order to create the interdisciplinary linkages and the momentum to move from basic science to quantum technology and to realise the vision of the quantum machine. Such achievements will not be made by individual scientific disciplines or institutions alone, but will require strong, sustained and harmonised impulses, guided by a convincing policy approach.

Public funding will be essential for such a sustained endeavour, but there are several additional requirements that need to be met to make quantum technology happen. First, quantum technology research requires a specific mode of undertaking research, and thus specific institutional and funding requirements. Without doubt, it is an area of frontier research, but contrary to the funding model of the ERC, which – aside from the Synergy Grant system[3], which should be expanded – is focused on supporting individual researchers, large parts of quantum research need to be conducted in a collaborative way, connecting knowledge about quantum effects with knowledge from different application domains (such as, in particular, the Key Enabling Technologies). The FET-Open scheme under Horizon 2020 can serve these needs to some extent but the lack of 'memory' in the system, as there is no concept of project renewals, complicates unnecessarily the funding of long-term research efforts that are required in highly interdisciplinary and challenging fields. This leads to short-termism as projects run for merely three years and, even if highly successful, have only a small probability for renewal. The intellectual challenges, especially the need to bridge disciplinary gaps, and the technological complexity of the experiments would require a longer time horizon. An open research model with flexible project length and the possibility for renewal, following stringent review, is most appropriate for this purpose, particularly as long as commercial considerations do not yet play a major role. Most importantly, it should be based on a network of tight and intensive collaboration across Europe and even globally fostered by a programme similar in spirit to

2. See for example http://www.darpa.mil/Our_Work/DSO/Programs/Quantum_Effects_in_Biological_Environments_%28QUBE%29.aspx

3. No ERC Synergy Call is foreseen for 2014. Depending on the Scientific Council's analysis of the pilot phase of the ERC Synergy Grant, there may be a Synergy Grant call for 2015. Link: http://erc.europa.eu/synergy-grants

the ESF Research Networking Programmes whose specific aim was to create pan-European research communities.

Highly interdisciplinary emerging research fields such as quantum biology would greatly benefit from the availability of *flexible bottom-up cross-border collaborative funding schemes*. This would further strengthen the European research base and allow the European research community to quickly react to new topics and not lose the competitive advantage with respect to other countries or regions where such mechanisms are available (namely the US and Asian countries). Developing interfaces and bridges between these bottom-up programmes and more applied or innovation-driven activities would then be possible as a means to provide avenues for the exploitation of research outputs by European companies. The requirement of having a cross-border scheme at the European level is a clear necessity in order to access the best know-how and expertise wherever it is located and therefore to fund the best and most promising research in Europe. Finally, flexibility in forming consortia should be allowed since the optimum configuration of partners within a project should be decided based on the topic and the expertise needed to address it and not vice versa.

Given the magnitude of most research challenges, a sustained effort will be needed, calling for longer-term stability beyond the usual four- to five-year time-horizon that is too common in European research funding. Continuity of funding, rather than sheer size, is likely to be a very important feature in this field where so much is to be learnt by all parties involved. A model at the national level for this kind of funding already exists: the German DFG awards Sonderforschungsbereich (collaborative research centres) grants which are competitively renewed in periods of four years for a maximum of 12 years. A transnational version of this, linking two or three leading laboratories with complementary expertise over a long period, would be likely to deliver remarkable results.

Still, in spite of the importance of collaborative, interdisciplinary research, there are areas of quantum research that aim at extending the frontiers of knowledge in understanding quantum effects (e.g. in relation to the understanding of quantum many body systems), and thus require deep disciplinary research work and funding, which should be continuously sustained by both national and European means.

Secondly, for the field to evolve in a sustained manner, a continuous and structural development of the **skills base** is needed. Quantum technology experts will not grow in a traditional academic environment, but will need to be grown in a highly interdisciplinary working environment, where quantum physicists meet and work, for instance, with biologists or material scientists. Hybrid qualifications are needed, but will only be fostered if recognition and reward is ensured in the academic and scientific career models. The demands on the individual scientists in terms of skills are extreme, because in addition to established S&T knowledge (e.g. in any of the conventional KET areas), they will need to be fully knowledgeable about quantum mechanical and quantum biological effects. Without institutionally supported interfaces between disciplines, new hybrid curricula and mechanisms to ensure an appropriate level of staff, the sustained growth of application-oriented quantum research is at risk.

In a longer term perspective, the foundations for the growth of quantum research and quantum technology applications need to be laid at schooling age. Without denying the importance of classical scientific matters, teaching programmes should incorporate more elements of quantum physics and quantum biology, in order to sensitise the next generation to the possibilities and fascination of the quantum world as early as possible. This may require additional training for physics teachers in biological questions and for biology teachers in quantum phenomena. More emphasis should be given in school teaching to the unity between the sciences, and in particular the deep connections between physics, chemistry and biology. This would also serve to enrol more female students, currently more interested in biology, into the physical sciences.

A third important ingredient consists of the necessary **infrastructures** around which to build quantum research activities. Next to a major leap in computational performance, accessible to a growing quantum research community, the manipulation of quantum objects requires the development of high-performance physical components and devices that are well beyond the current state of the art.

Finally, the quantum research community needs to improve **communication** about its actual and potential achievements to society and stakeholders. Quantum research may be fascinating, but society legitimately asks for a good justification if significant amounts of taxpayers' money are to be spent on quantum research. While this argument applies to all fields of publicly funded research, it is particularly pertinent in a field where the actual benefits to society are likely to accrue in the longer term only. The promises made must be both appealing and credible, and a pro-active approach to making complex research accessible to the public should be followed.

A comprehensive policy approach to foster the sustained development of quantum technology will require all four main elements to be put in place, which are an essential complement to sustained funding. They require a concerted effort of the EU, of Member States and of other countries around the world in order to realise the potential of quantum research.

4. Going Forward – Recommendations and Proposed Measures

Human Resources and Education

A strange and curious fact about university studies is that their duration has not changed much since the Medieval Warming Period when the great European universities were founded (roughly 1088 Bologna, 1288 Coimbra) whereas knowledge has vastly increased. The volume of relevant facts has increased by a factor probably comparable to the increase in scientific publications, i.e. at least 1 000-fold since 1900. The effect of the Web and the globalisation of science is likely to cause even more rapid knowledge growth in the next few decades and makes existing knowledge more readily accessible. Yet we still take three years to get a Bachelor's degree, and a further three or four for a Doctorate. What is one to conclude from this?

Despite a better diet, we are probably not much smarter than our medieval ancestors, and definitely not much smarter than 18th and 19th century scientists. In fact, from a network perspective we know a great deal *less* than they did since we are more specialised. As Mahatma Gandhi put it succinctly: "The expert knows more and more about less and less until he knows everything about nothing." In some fields, especially younger fields in which the body of knowledge does not yet require years of study to be mastered, it is possible to do excellent work after a short learning curve. In other fields, particularly interdisciplinary ones, the amount of knowledge required to make headway can be very large. Upon becoming a professional, a scientist's rate of learning necessarily drops due to competing demands and filling in the gaps can become a – very pleasant – lifetime occupation. Following the dictum of the great mathematician Jacques Hadamard: "It is important for him who wants to discover not to confine himself to one chapter of science but to keep in touch with various others".

In some cases, as with the interface of two large fields such as biology and physics, it is essentially impossible to make up for early ignorance. Very few practising physicists learn biology even to undergraduate level, and even fewer travel in the opposite direction. It is even doubtful whether an interface between physics and biology actually exists, or whether, as in Switzerland and China, they are separated by a long Silk Road travelled only by the brave. Part of the challenge of FarQBio is to create such an interface. Given the decennial scale of the project, it seems appropriate to suggest a bold but permanent remedy: to raise a generation of "Sino-Helvetes" for whom there is only one country. A set of measures addressing the different stages of the educational system to contribute to the development of these cross-disciplinary skills in the next generations of scientists and public is therefore proposed.

School Education – raising awareness and building competences

Attracting and engaging human talent to quantum science and technology (S&T) in general and bio-inspired quantum S&T specifically is a key success factor. An intrinsic motivation to learn is a necessary condition for promoting learning attitudes and high academic achievement lifelong. **Two main goals need to be achieved: raising interest and motivation and building scholastic competence.** A concerted initiative should be started to educate

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schoolteachers in progress in the interdisciplinary sciences of which FarQBio will be an exemplar, and to help them "sell" the idea of scientific research to their students.

Creating awareness is relatively easy to accomplish since most young people like to be challenged; competitions or exciting events are well-known instruments to plant the first seeds of enthusiasm. A Doctor Universalis Olympiad at European level could be set up to promote the notion of interdisciplinary knowledge and to identify and encourage the most gifted. Anchoring quantum science and technology in young people's leisure time is a key factor for emerging intrinsic motivation. 'Infotainment' is key to attract attention – such as recently developed interactive games to attract children to quantum physics[4]. The success of nano-science communication and education is an exemplar for the success of this approach.

However, only if these activities are systematically linked with science education in schools will a cognitive learning effect emerge. Raising interest in this context means to stimulate young people to search for more information on the topic, and thus to take a critical first step towards establishing the aspired open-mindedness towards science and technology. When they encounter quantum physics in everyday life, they engage more personally and – in the best case – they decide to take this discipline as a major later on.

Quantum science or technology topics need to be continuously developed and extended in the classroom. Here the main goal is knowledge development to generate basic understanding of scientific–technical relationships (i.e. systems knowledge) to enhance technological and scientific literacy. Improving technical literacy is also strengthened by acquiring motor skills through the direct handling of technical gadgets and also by theorising about the laws of quantum science and engineering.

Recent changes in teaching and learning in physics education have benefited from new conceptual understanding and cognitive skills required to understand and apply physics concepts, interactive engagement methods, teaching in context as well as use of ICT. A closer connection with the computer games industry is a promising avenue to trigger interest in science. Moreover, the movement towards more interactive learning environments has been successful in raising student achievement – particularly when it comes to complex problem solving and reasoning.

In order to move towards career choice, young people need communication opportunities with peers (same age or same values) and authorities in a given field ('role models'). Extra-curricular learning environments such as internships or face-to-face dialogue with researchers and other experts significantly strengthen motivation and career choice due to the authenticity of the encounter.

Achieving success here requires as an essential ingredient science teachers who are both highly motivated and given the opportunity to stay in touch with recent scientific advances in order to be able to translate them to the classroom effectively. Summer schools for science teachers where they are exposed to recent developments by active researchers and can discuss with them how to best simplify and translate these to the classroom could prove an effective approach. Localised initiatives of this type for specific subjects such as physics exist (e.g. the very successful Summer Schools for Physics Teachers of the German Physical Society) but would need to be expanded to encompass biology, chemistry and physics.

Higher Education – Post-graduate excellence: "Dr. Universalis: the Albertus Magnus programme"

In essence **FarQBio embodies the unity of the sciences** which would have been congenial to Albertus Magnus and Roger Bacon in the thirteenth century, Thomas Young and Hermann von Helmholtz in the nineteenth, practically nobody in the twentieth and, we wish, most of the scientific elite of the twenty-first. **To achieve this we propose to create a new doctoral degree of much longer, possibly even double, the normal duration.** This will be open to graduates in the natural sciences and mathematics. It will involve formal teaching in physics, quantum physics, biology and biochemistry (to mention

4. See for example Quantum Frontiers http://quantumfrontiers.com/2013/10/17/can-a-game-teach-kids-quantum-mechanics/ or Science at home http://www.scienceathome.org/

some of the key areas), each to an advanced undergraduate level. The programme then effectively is a combination of several scaled-down undergraduate degrees and a research thesis. The selection of candidates for this unquestionably challenging task should probably be done at European level, possibly within the well-established Marie Sklodowska Curie Actions framework. It could be modelled on one or more national institutions such as the *Studienstiftung des Deutschen Volkes* which provides support and encouragement to gifted students. Russia and India have long had similar schemes in place from which much could be learned. The higher degree awarded to these exceptional students will be expected to span at least two disciplines. We propose to call this new doctorate **Doctor Universalis**, to connect with an ancient honorific title awarded only to two individuals. One of those was Albertus Magnus (1206–1280), the other his student Roger Bacon (1219–1295) and we propose the programme be named after Albertus Magnus, who had the added merit, as a German-born scholar teaching in Paris, of being international.

It may be objected that these graduates will cost twice as much to produce as is conventionally the case. To this we answer that the network effect of their knowledge will be 2^2, and therefore they are effectively cheap. It will also be objected that this will devalue the normal PhD. We agree, and see nothing wrong with that. Creating a new elite will encourage everyone to raise their game. Doctorates today already span a large range of achievement from three-year literature reviews all the way to six- and seven-year multi-lab doctorates typical of the best schools in the US. The market will know its own. If the letters DU acquire value, it will be because those who style themselves Doctor Universalis are worth the wait.

Steps towards the Doctor Universalis could be achieved by establishing new science degree programmes for the "Quantum (Bio, Info,...) Engineers for the 21st century" that train researchers from an early stage in the skills required to attack the research challenges in relation to quantum machines. The intrinsically interdisciplinary nature of such a degree would present an ideal preparation for the subsequent Doctor Universalis programme.

Cross-disciplinary skills for senior scientists

As outlined above, **the area of science addressed by FarQBio is highly interdisciplinary and therefore very challenging, especially for senior university academics**. The most efficient way **to bridge the 'gap in understanding' is to support short, targeted sabbaticals aimed at both junior and senior faculty** to allow, for example, a biologist to visit a physicist or a physicist to visit with a chemist, and so forth. To fund this efficiently would require a salary top-up for the academic to cover the extra costs of spending time in a different institution and funds to allow the senior academic's home university to pay for a replacement to cover the teaching and administration duties that would have been carried out by the person on sabbatical. This type of scheme would benefit from having a high profile and a prestigious designation, along the lines of a "genius" award such as the MacArthur Fellowship in the US. The ERC with its attendant prestige would seem to be an ideal awarding body for such a fellowship scheme.

Such sabbaticals would be the best and quickest way of transferring amongst the major participants the required interdisciplinary skills needed to underpin the proposed FarQBio concept.

Funding and Cooperation

Scientists routinely cooperate and are efficiently self-organising in collaborative consortia and networks whenever appropriate funding schemes are in place. At the individual and national level the scientific community in the field of quantum science and technology is very successful in competing for grants. However, an overarching support scheme enabling a long-term, large-scale collaboration is urgently needed in order to achieve maximum benefit from investments made in individual projects at the national and European scale.

Cooperation appears to be the most constructive form of competition in science. One of the important key success factors lies in enabling efficient cross-border collaboration between research groups and projects that are funded at the national level. This includes collaborations that go beyond the borders of the EU, the US being the most prominent and sought after non-European collaboration partner.

All European countries fund quantum science and technology, albeit to a varying extent. At the same time, approaches and policies towards funding of science vary strongly across European countries.


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Some countries invest in science a lot, others little. Even within the EU, the percentage of spending on science in national budgets varies by as much as tenfold from country to country. Some countries value highly basic science, while others prefer to invest in applied research. Some countries rely on "blue-sky" bottom-up funding practices, while others are priority driven, and priorities differ in different countries. What is indisputable is the correlation between spending on science with the strength of national economies, in particular the level of development of high-tech industry and of high-value products competing on cutting-edge features rather than price.

Assuming that national policies and practices will not to change significantly during the timeframe of the implementation of the Horizon2020 Programme and given that it will take at least several years to overcome the current recession, it is important to maximise the benefits and added value of the various types of individual projects in the area of quantum science and technology. These include not only the projects funded by national funding agencies in individual European countries, but also a substantial number or ERC grants.

Two possible grant schemes might be:

- **Albertus Magnus grants:** providing funds for two scientists, A and B, to allow A to stay at B's institution for a period of 3–12 months and then B to stay at A's institution for the same length of time. Conditions would be that: researchers work in different fields; priority is given to young and mid-career scientists; only top quality research should be supported; candidates should have proven ability and interest to look beyond disciplinary boundaries.
- **New Frontiers grants:** providing major funding (similar to the ERC Synergy grants) but with emphasis on: interdisciplinary work (as one of the main criteria to be enforced); a small number of sites (perhaps even two) but where each site can be composed of several researchers. Funding could be provided initially for 4 years with the possibility for an extension by 4–8 years following a competitive review.

Such benefit maximisation could be achieved by a relatively small (compared to the total volume of individual projects) investment to create an overarching funding scheme that would enable cross-border cooperation between scientists carrying out existing research projects or wishing to propose new groundbreaking ideas.

Important requirements towards such a funding schemes are:

1. They should ensure **broad participation.** Experience with previous or currently existing networking schemes, such as ERA-NETs, EUROCORES and RNPs of the European Science Foundation, show that it is important to avoid situations whereby scientific communities from some countries are left ashore because their national agencies do not desire to support an overarching scheme on a certain topic;
2. There should be **one centralised source of project review and distribution of funds**. From the experience of the ERC and Marie Curie Actions, the quality of the projects that are funded and the recognition by the scientific community critically depend on a competitive and solid peer-review selection process which should be run by a specialised agency or a well-recognised organisation;
3. The **timeframe should be sufficiently long** to ensure accomplishment of major scientific endeavours. A good example would be a 12-year scheme with a review after 4 years and a possible extension for another 4–8 years with the possibility, based on a competition, of the continuation of the scheme;
4. The scheme should be **flexible with respect to new groups joining** a running programme. This is particularly important for such emerging fields as quantum biology, which are highly likely to attract the scientific focus of new groups.

A consultation process should be established between EU and non-EU science funders to develop new funding mechanisms enabling large-scale international networks where scientists can collaborate across borders and continents. The statistics show that more than 35 percent of scientific publications are co-authored by scientists from two or more countries, and this number increases from year to year. In part this can be explained by the rapidly increasing speed and ease of information exchange, but equally important is the ever fiercer competition in science. Collaboration is no longer a curiosity or desirable attribute of the research process, rather it is a necessity for those who wish to stay abreast of competitors, especially in the area of quantum information and technologies. Yet existing funding schemes for cooperation build on practices relevant to the 20th century, and they hardly go beyond small bilateral or trilateral schemes between individual countries. Currently there are no mechanisms in place to couple such existing EU schemes as ERA-NETs or Innovative Training Networks with similar initiatives elsewhere, for example the Multidisciplinary Research Program of the University Research Initiative (MURI) of the US Air Force Office of Scientific Research (AFOSR). It is therefore recommended to negotiate potential calls in the Horizon2020 programme jointly with such agencies as the National Science Foundation (NSF) in the US, the Natural Sciences and Engineering Research Council of Canada (NSERC), the Canadian Institute for Advanced Research (CIFAR), the Australian Research Council (ARC), the Japanese Society for the Promotion of Science (JSPS), the National Research Foundation of Korea (KRF) and the Chinese Academy of Sciences and the Russian Academy of Sciences.

Training networks should enable a larger scale and improved success rates with a better focus on innovation. The Marie Curie Innovative Training Networks is a very important instrument for improving the collaborative spirit, culture, and skills for the next generation of scientists. Based on the experiences of scientists during FP7 and the introduced improvements in the ITN scheme under Horizon2020, we would highlight the following important aspects:

1. The limited size of these networks is insufficient to achieve a full impact and provide a sufficiently broad scope of the training environment, especially in the case of interdisciplinary projects. The practice of fitting the consortium size in the Procrustes' bed of guidelines is a clearly inferior approach to assembling a network of best fitting teams with adequate geographical coverage of research hotspots. **Flexibility should be allowed in the formation of training consortia** with a clear focus on scientific excellence and impact of the training programme, rather than the institutional composition of consortia.
2. Success rates have been discouragingly low so far, with ranking and selection of the top proposals becoming akin to a lottery. As a result, an increasing fraction of top scientists shun participation in this programme. **Additional funding should be made available** to account for the high demand from the scientific community and the excellence of the projects applying to this scheme.
3. The requirement for industry participation in a training network has shifted the focus from innovation to development. Instead of facilitating innovation, such a requirement actually hinders it by discouraging truly innovative projects that are not yet close to the technological implementation phase. **Innovative ideas and training approaches should be encouraged with a long-term vision and independently** of the compulsory participation of industrial partners in the consortia.

Research Infrastructures

Research on quantum biology and quantum machines is making use of some highly sophisticated research infrastructures.

Experimental research uses a wide variety of techniques. Ultra-fast laser spectroscopy, for example in photosynthesis, is carried out in university-based laboratories, many of which are networked via Laserlab-Europe which is currently funded by the 7th Framework Programme of the European Union. The continuation of this initiative is highly desirable. It is likely that in future a similar initiative that networks emerging quantum

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technologies, such as quantum sensing by means of colour centres in diamond or sub-wavelength optical imaging, will help to make these sometimes challenging-to-master techniques more readily available to the biology and biophysics community. Structural questions, for example concerning proteins, require the application of NMR, X-ray diffraction and electron microscopy. Some of these are based at user facilities that provide regional or even international access, while others are local university laboratories.

Biological structures are highly complex, a complexity that becomes compounded by the intrinsic computational challenges when quantum physics becomes involved. Theoretical research, especially where it concerns first-principles calculation of electronic structure and dynamics, depends to some extent on the availability of large-scale computing facilities on which to run these very time consuming calculations. These are generally provided by universities or at the national level. Numerical methods deal with a wide variety of scales ranging from the atomic scale of first-principles scale to that of effective models whose input parameters are determined by first principles to allow for long-time simulations of quantum behaviour. An initiative similar to Laserlab-Europe that brings together these often disparate methods to allow for a seamless flow of information and results between them would assist future research.

At present the community is still at an early stage, perhaps comparable to quantum information in the mid-1990s, so that support measures should be aimed at building the research community, the education of young researchers in this field and the provision and networking of research infrastructures. A major effort such as an FET Flagship is not needed in the foreseeable future. Central to progress in the field is the bridging of the disciplinary divide between biology, chemistry, medicine and (quantum) physics. An infrastructure measure that would make a major contribution towards addressing this challenge and thus to the development of quantum biology would be the establishment or support of interdisciplinary research centres in which complete research groups from biology, chemistry, medicine and physics are housed in the same building. These centres should not only provide dedicated research and lab infrastructures but, crucially, also be designed to create and enhance interdisciplinary communication. While the infrastructure investment may have to be shouldered by national funding organisations or universities, the running costs of such centres could be provided through rolling grants by European organisations.

Communication

Financial support for new directions of research will only be forthcoming if these new research domains are supported by the broader public and if they subsequently find promoters in the media and the political sphere. Attracting sufficient attention to quantum technologies is therefore an important horizontal task that should be performed in a professional way. In order to attract the attention of non-experts, decision makers and the public, scientists need to excite journalists who can spread basic information and news about quantum technologies in a sensible, easy to understand, but scientifically correct manner. The broader public, scientists in other disciplines, and policy- and decision-makers, are target groups that each have to be addressed in a specific way. Part of the Doctor Universalis programme would involve intensive teaching in presentation and outreach to ensure that this future scientific elite can communicate well with the public.

One challenge is to give quantum technologies a profile that is distinct from the rather well-established and broadly covered fields of quantum informatics and quantum cryptography. This could, for example, be done by emphasising the fact that quantum technologies mainly deal with "simple" quantum systems and by referring to quantum biological systems. Fascinating instances from nature could help to overcome the difficulties posed by the necessity to explain quantum mechanics in simple words. Another challenge is to present quantum technologies as an intriguing topic, yet to ensure that only realistic expectations are raised.

The primary goal is to create public awareness for the new field of quantum technologies, to attract attention and to spread the message that there is an emerging field of science and technology that is scientifically intriguing, combined with reasonable hopes for important breakthroughs and a potential high practical value.

It is therefore necessary to develop a coherent overarching communication strategy which comprises specific approaches for different kinds of stakeholders – from colleague scientists to schools, from potential funding partners to decision makers in the administration, and, last but not least, from possible media partners to citizens. This communication strategy should answer the question: How do we attract public attention to a new emerging field in competition with other traditional fields of science? The prerequisites for a successful communication strategy in quantum biology are: **a clear and distinct profile of quantum technologies with respect to well-established technologies, and the existence of convincing "stories" around fascinating instances of either existing natural quantum systems (from biology) or potential future man-made quantum machines.**

It is important to set up the right agenda for discussions with the public by giving a clear focus on opportunities, but without neglecting potential risks, e.g. from "dual use" of quantum machines. In general, one could use the following line of reasoning: The Quantum Machine is a concept that contains more general instances but also instances that are easier to realise. Biological systems and small-scale quantum devices such as sensors are already existing instances of quantum machines that serve real, technologically important roles. Hence we believe that also more complex quantum machines can and will be realised. When we understand how these "simple" quantum machines work and can be controlled (like those in biology) we can design new, better, more complex quantum machines which will have key applications important to science and society, such as energy harvesting, sensing, metrology, quantum simulators, and so forth.

Some elements of the communication strategy can be outlined as follows:

- An obvious starting point is the use of social media for communication but also aimed at creating a community around quantum biology technologies.
- Approaching journalists is another obvious point: contact them, invite them, be opinionated but back up quantum technology claims with specific instances and explain possible consequences.
- Foundations and science organisations could be approached to support the external communication and outreach activities of science festivals (such as the annual Cheltenham Science Festival or the European Science Festival ESOF – European Science Open Forum), or competitions among young scientists *for the best new idea for a quantum machine*.
- Constructing and exhibiting a quantum machine (or any quantum-enabled device, such as a new kind of solar cell, sensor or a quantum random number generator) would be a useful and very powerful PR tool.
- A specific point is communication between scientific disciplines for mutual education but also with the aim of attracting promising young researchers to the field.

5. Conclusions

As the research community in quantum biology is being built, there is a number of aspects that the FarQBio exercise and the experts involved in it have tried to address, spanning from basic science discoveries and technological bottlenecks to challenges in education and research funding. Despite the early stage of this field of research, some needs have been clearly identified and possible ways forward have been proposed. While some recommendations may apply exclusively to quantum biology, others may have a general interest to other emerging and interdisciplinary fields of science. Interactions with other interdisciplinary fields of science which face similar issues will be very welcome in the future, and certainly more lessons can be learned.

The outcome of this exercise has been to adopt a long-term strategy and vision for the development of this field, by taking progressive steps towards the better integration and improvement of existing instruments and mechanisms currently available to support research. This has resulted in a proposed set of measures that would be relatively straightforward to implement over the next few years, should this report elicit a positive reaction from research funders and policy- and decision-makers at the national and European level.

Over the long term, it is expected that the field of quantum biology will produce as yet unforeseeable discoveries that will provide further evidence of the existence of quantum phenomena in nature, ultimately leading to their exploitation in new everyday technologies available to society. FarQBio hopes to have provided a first look forward in this direction.

Annex 1: Scientific Committee and Experts

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