

Foreword

When the remarkable book *What is Life?* was published in 1944, written by the great quantum physicist Erwin Schrödinger and based on lectures that he had given at Trinity College Dublin in February 1943, it had a very considerable influence on several key figures in the development of molecular biology. In particular, J. B. S. Haldane, James Watson, Francis Crick, and Maurice Wilkins, have each expressed indebtedness to the penetrating ideas that Schrödinger put forward. One of the basic questions that Schrödinger raised was whether the ideas of classical physics, as normally employed by biologists in their understanding of the behaviour of the physical world, can be sufficient for explaining the basic features of life. He allowed that a case could certainly be put forward that biological systems, being large as compared with the atomic scale and containing vast numbers of constituent atoms, would consequently have macroscopic actions determined essentially by the statistical laws of large numbers. Together with some general over-reaching principles of Newtonian mechanics such as conservation of energy, he accepted that this could lead to an overall behaviour consistent with classical Newtonian laws. However, he pointed out that a key feature of the Darwinian/Mendelian nature of inheritance is its basis in discreteness, which could only be explained through a quantum discreteness and stability, in the basic carriers of genetic information. He argued that these carriers had to be molecules of some nature—the molecules that we now know as DNA.

Molecules, and their chemistry, are certainly governed by quantum laws, according to our present understanding; nevertheless, chemists and biologists may not think of chemistry as very “quantum mechanical,” perhaps because of the many ball-and-stick (or computer) models that they have

built their experience upon, and such a “hands-on” familiarity is not suggestive of the strange non-intuitive nature of quantum systems. In accordance with such images, we may think of chemistry as being only rather “weakly” quantum mechanical, where the more puzzling features of quantum mechanics in which distant entanglements and globally coherent behaviour do not seem to feature significantly. Such coherent behaviour is witnessed in the phenomena of superfluidity and superconductivity, and in the mysterious entanglements that one can find between the distantly separated quantum particles of EPR (Einstein-Podolsky-Rosen) situations, where the overall behaviour of the combined system cannot be understood simply in terms of the individual nature of its constituent components.

A question of great interest, therefore, is whether or not such “strongly” quantum-mechanical features of Nature might be playing significant roles in the essential processes of life. An area where such a non-local role has been argued for is in the operation of the brain, where the “binding problem”, according to which widely separated areas of the brain, with very little in the way of direct neuronal connection, are responsible for the processing of different types of perception (such as colour, shape, and movement, in visual processing); nevertheless all come together in the formation of a single conscious image. On the other side of the argument is the seemingly inhospitable environment that the warm and apparently “messy” living brain provides for such delicate and subtle non-local quantum processes. Indeed, there is no question that if the brain does make use of such “strongly” quantum-mechanical phenomena, it must do so through the agency of some very sophisticated organization. But the situation is certainly far from hopeless as, on the one hand, there is indeed great subtlety in cell structure and, on the other, the very existence of high-temperature superconductors demonstrates that collective quantum phenomena can take place with a relatively small amount of sophistication and without the necessity of extreme cold.

There is a further question that Schrödinger touched upon towards the end of his book, in which he raised the more speculative issue of whether it need actually be the case that even the physical laws provided by standard 20th century quantum mechanics are sufficient for a physical explanation of life. He imagined the situation of an engineer, familiar only with Newtonian mechanics and general statistical principles, being presented with an electric motor. Without any familiarity with the laws of electromagnetism that Faraday and Maxwell have now presented us with, the engineer would have no explanation for the motor’s behaviour, which might seem almost

like magic. But the Faraday-Maxwell laws are still mathematical laws of physics, going beyond (but still consistent with) the overall scheme of things laid down by the general framework of Newtonian mechanics and statistical physics. Likewise, Schrödinger argues, it is certainly possible that new physical ingredients, going beyond those of 20th century physics, might be needed for a full understanding of the physical underpinnings of life.

There are probably not many biologists today who would argue for the necessity of such new physical ingredients in order to explain life. Yet, in an Epilogue (On Determinism and Free Will) to his book, Schrödinger raises the further conundrum of how the conscious mind, with its apparent free will, can be accommodated within the “statistico-deterministic” framework of our current quantum/classical pictures. The possible physical need for going beyond this framework had already been raised by Schrödinger himself some eight years before his Dublin lectures, when he introduced his famous “cat paradox”. Although he did not refer to this paradox explicitly in *What is Life?* (presumably because he had no desire to confuse his lay audience by introducing such unsettling issues into his descriptions of quantum mechanics), this unsatisfactory state of affairs in the foundations of quantum theory no doubt led him to be sceptical of the current dogma that the rules of quantum mechanics must hold true at all levels of physical description. (It may be pointed out that three others of the key figures in the development of quantum mechanics, namely Einstein, de Broglie, and Dirac, have also expressed the opinion that existing quantum mechanics must be a provisional theory.) There is, indeed, a distinct possibility that the broadening of our picture of physical reality that may well be demanded by these considerations is something that will play a central role in any successful theory of the physics underlying the phenomenon of consciousness.

These deep matters are still subject to much controversy, and the present volume provides a multitude of closely argued opinions on the issues that Schrödinger raised concerning the relation of biology to quantum physics. Is it merely the complexity of biology that gives living systems their special qualities and, if so, how does this complexity come about? Or are the special features of strongly quantum-mechanical systems in some way essential? If the latter, then how is the necessary isolation achieved, so that some modes of large-scale quantum coherence can be maintained without their being fatally corrupted by environmental decoherence? Does life in some way make use of the potentiality for vast quantum superpositions, as would be required for serious quantum computation? How important are the

quantum aspects of DNA molecules? Are cellular microtubules performing some essential quantum roles? Are the subtleties of quantum field theory important to biology? Shall we gain needed insights from the study of quantum toy models? Do we really need to move forward to radical new theories of physical reality, as I myself believe, before the more subtle issues of biology—most importantly conscious mentality—can be understood in physical terms? How relevant, indeed, is our present lack of understanding of physics at the quantum/classical boundary? Or is consciousness really “no big deal,” as has sometimes been expressed?

It would be too optimistic to expect to find definitive answers to all these questions, at our present state of knowledge, but there is much scope for healthy debate, and this book provides a profound and very representative measure of it.

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About the author

Sir Roger Penrose, OM, FRS was born on 8 August 1931 in Colchester, Essex, England. He is a mathematical physicist and Emeritus Rouse Ball Professor of Mathematics at the Mathematical Institute, University of Oxford and Emeritus Fellow of Wadham College. Penrose is concurrently the Francis and Helen Pentz Distinguished Visiting Professor of Physics and Mathematics at Penn State University. Penrose graduated with a first class degree in mathematics from University College London. He obtained his PhD at Cambridge (St John’s College) in 1958, writing a thesis on tensor methods in algebraic geometry under John Arthur Todd. In 1965 at Cambridge, Penrose proved that black hole singularities could be formed from the gravitational collapse of large dying stars. In 1967, Penrose invented twistor theory and in 1969 he conjectured the cosmic censorship hypothesis—this form is now known as the weak censorship hypothesis. In 1979, Penrose formulated a stronger version called the strong censorship hypothesis. He is also well-known for his 1974 discovery of Penrose tilings, which are formed from two tiles that can surprisingly tile an infinite plane aperiodically. Another noteworthy contribution is his 1971 invention of spin

networks, which later came to form the geometry of spacetime in loop quantum gravity. He was influential in popularizing what are commonly known as Penrose diagrams. He has written 8 books, including *The Emperor's New Mind* (1989) and *Shadows of the Mind* (1994) that explore the lacunae between human consciousness and the known laws of physics. In 2004, Penrose released his magnum opus *The Road to Reality: A Complete Guide to the Laws of the Universe*. In 1975, Stephen Hawking and Roger Penrose were jointly awarded the Eddington Medal of the Royal Astronomical Society. In 1985, Penrose was awarded the Royal Society Royal Medal. Together with Stephen Hawking, he was awarded the Wolf Foundation Prize for Physics in 1988. In 1989, Penrose was awarded the Dirac Medal and Prize of the British Institute of Physics. In 1990, he was awarded the Albert Einstein Medal and, in 1991, he was awarded the Naylor Prize of the London Mathematical Society. In 1998, he was elected Foreign Associate of the United States National Academy of Sciences and, in 2004, he was awarded the De Morgan Medal.

