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ESSAY REVIEW

What is life?

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A review of **What is Life?** by Erwin Schrödinger, together with **Mind and Matter** and **Autobiographical Sketches** by the same author, Cambridge University Press, Cambridge, 2012, pp. x + 184. Scope: monograph. ISBN 978 1 107 60566 7 (paperback). Level: general reader.

We are all patterns, dynamically evolving ones, but patterns nonetheless. There is nothing special about the individual atoms that constitute our bodies. They could all be replaced by other atoms of the same kinds, and neither we nor anyone else would notice the difference. But what is it about our particular arrangement of atoms that makes us alive and our distinctive selves? Indeed, what is life?

Erwin Schrödinger addressed this later question head-on in the celebrated set of lectures that he delivered at the Dublin Institute for Advanced Studies in 1943. His classic text *What is Life?*, based on the lectures, was published the following year and seems to have been in print in one form or another ever since. The edition to be reviewed, which also includes Schrödinger's *Mind and Matter* and *Autobiographical Sketches*, plus a foreword by Roger Penrose, was first published in 1992 and is now in its 12th reprinting.

As Penrose comments, *What is Life?* must rank among the most influential of scientific writings of the last century. It was written more than a decade before the discovery of the structure of DNA – and both Francis Crick and James Watson, who received the Nobel Prize for the discovery, acknowledged the book as an early source of inspiration. Remarkably, however, many of the ideas, paradoxes and open questions raised by Schrödinger are still as apposite today as they were at the time. The book is wide-ranging and considers, not just the physical/chemical nature of inheritance, but the nature of life and conscious awareness.

Schrödinger opens by introducing the ideas of statistical physics and addresses the question "Why are atoms so small?" which could, of course, equally well be expressed as "Why are we so big?". His answer is that, given the constant thermal jiggling of the atoms and molecules, and quantum indeterminacy, life can only be stable, governed by reliable physical laws, if the statistical averages are good, which in turn requires that the number of atoms be very large. It is one of his penetrating insights which yields a conclusion that, in retrospect, seems absolutely obvious.

Although a lot was already known about heredity, and it was evident that the information to be inherited must be encoded in some way in the genes, it was unclear how that happened. Schrödinger argues cogently that the hereditary information must be carried by a molecule. On the scale of a gene, nothing else would provide the necessary stability. Furthermore, an "aperiodic crystal" as he describes this molecule, would allow for the encoding of a sufficient number of possibilities with relatively few atoms. The stability of the molecule would derive from quantum mechanics, and mutations could be attributed to rare quantum transitions in its structure. He thus shows that the existence of such a molecule could account for the observations. Of course, it

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is now well-known that his arguments were characteristically well-aimed, and that the molecule in question is DNA.

How can one define life? There are many different approaches, none satisfactory, but Schrödinger comments –

> What is the characteristic feature of life? When is a piece of matter said to be alive? When it goes on 'doing something', moving, exchanging matter with its environment, and so forth, and that for a much longer period than one would expect an inanimate piece of matter to 'keep going' under similar circumstances.

An isolated piece of non-living matter soon comes into equilibrium with its environment. Living matter, on the other hand, cannot be isolated, at least not for long. It is a non-equilibrium system that continuously exchanges matter and energy with its environment, which is what gives it the capacity "keep going", i.e. be alive, even when it is in a quasi-steady state.

A difficulty with this definition is that one can easily think of situations where the item under study seems to meet the definition, but is clearly not alive in the normal sense. A well-known counter-example of this kind is a fire, which consumes fuel, excretes waste products, can move, and responds to external stimuli such as wind.

Another definition of life can made be in terms of replication. A piece of living matter, for example a rabbit, is normally able to reproduce further members of the species, either sexually in the case of the rabbit, or asexually for e.g. many single-celled creatures. But here we encounter problems with e.g. mules, worker bees, and post-menopausal women – all unable to reproduce, but nonetheless very much alive. In addition, the fire can in a sense reproduce itself, though one would not usually describe it as being alive.

Returning to Schrödinger's definition which in effect says that the piece of matter is alive if it exhibits metabolism, one encounters difficulties with spores and seeds. One can argue that metabolic processes are still occurring in a seed at room temperature, albeit at an enormously slowed rate, and so it can be considered to be alive. But seeds can be cooled for a while to temperatures close to absolute zero, where all chemical reactions cease, apparently without harm. The same applies to the storage of mammalian sperm, used routinely for artificial insemination. Is one to say that the seeds or sperm cells "died" when cooled, and subsequently sprang to life again when warmed and then planted or implanted?

It is interesting to note that, whether in terms of metabolism or replication, a virus is not alive, because it can only reproduce by taking over the reproductive machinery of a cell. This is a far stronger requirement that just needing a congenial environment and a supply of suitable food, as are sufficient to meet the needs of living matter.

Another requirement that is commonly placed on living systems is that their species must be able to evolve. All living things on Earth, even the simplest single-celled organisms such as bacteria, are vastly too complex to have appeared spontaneously within the ~ 3.5 billion years that have been available. So they must therefore have evolved from something much simpler: otherwise, then they could not be here. It is implausible that the putative organism could have lost its ability to evolve at the very moment we chose to examine it. So, if it is not a member of a species that can evolve, then it is not alive. Note that this argument applies to a species. After being created by their parent(s), individual members of the species grow, reproduce, become geriatric, and then die. The reproductive stage may, very occasionally, produce a mutant that is better fitted for survival, which is of course the process that drives the evolution of the species. It is sometimes argued that e.g. telephones and cars evolve, becoming ever more complex and better fitted to survival in a competitive market as time passes. But nobody would suggest that they are alive. Although it is a pleasing analogy, it is obvious that the evolutionary processes are actually taking place in the minds of the designers and manufacturers rather than in the telephones or cars.

So are we getting any closer to knowing what is life? The broad outline of the sequence of events giving rise to complex life like ourselves seems to be generally agreed. On the young Earth, by chance, a relatively simple self-replicating molecule formed and started evolving. Before long, it had reached a state similar to a modern bacterium. Just possibly, the replicator or bacterium came to Earth from elsewhere, rather than evolving here, but it hardly matters. Either way, the fossil record shows clear evidence for the existence of bacteria (prokariotic cells) since very early in the Earth's history, from almost as soon as it was cool enough to sustain carbon-based life. For æons, the bacteria just reproduced and diversified. Then, about 2 billion years ago the first eukariotic cell appeared, with a nucleus, much larger and hugely more complex than a bacterium. Eukariotic cells provided the basis for all of the multi-cellular organisms and plants that subsequently evolved. On this scenario, once the first self-replicator appears, evolution through mutation and survival of the fittest will inevitably bring us to where we are (or something like it). However, given that it took so long for the eukariotic cell to appear, it may well be the case that this is the rate-limiting step in the evolutionary chain – which may well bear on the likelihood of finding complex life elsewhere in the Universe.

In fact, all life that we know of takes the form of cells. So a good working definition of living matter might be "matter consisting of cells". If the cells are metabolising, actively maintaining their membrane potentials between inside and outside, then the matter is alive. Otherwise it is dead, albeit previously alive to have been created in cellular form in the first place. Of course, we still have problems with seeds and spores, but this definition still seems satisfactory provided that we accept the possibility of suspended animation. We must, however, bear in mind that non-cellular life might occur in other places, e.g. exoplanets, and question whether we would be able to recognise it as being alive. If it seemed to have the other characteristics of life – was able to reproduce itself, was an open system in a quasi-stationary state exchanging matter and energy with its environment, and indulging in purposeful behaviour e.g. by moving towards a food source or away from danger – then, despite being non-cellular, we would probably regard it as living.

Schrödinger concludes that life is based on the laws of physics but that, nonetheless, there may be some additional law at work that we have not yet annunciated. He is not suggesting a "new force" or anything like that, but a new principle not yet conceived. He points out that the construction of living matter is quite different to anything tested in the laboratory, and pictures a steam engine designer's bafflement when inspecting an electric motor for the first time: he is comfortably familiar with copper, iron and electricity, but he has no idea how the device works. Schrödinger discussion points towards the elusive new principle being somehow connected to entropy, non-equilibrium thermodynamics, and "...and an organism's astonishing gift of concentrating a 'stream of order' on itself and thus escaping the decay into atomic chaos – of 'drinking orderliness from a suitable environment...". A human lifetime has passed since he wrote those words but, notwithstanding staggering advances in laboratory experiments on life and quasi-life, that additional principle still eludes us.

What is Life? closes with a discussion of free will and determinism and the central paradox, which he presents as –

(i) My body functions as a pure mechanism according to the Laws of Nature.
(ii) Yet I know, by incontrovertible direct experience, that I am directing its motions, of which I forsee the effects, that may be fateful and all-important, in which case I feel and take full responsibility for them.

He does not of course resolve the paradox, but the discussion is stimulating. The ideas are developed further in *Mind and Matter*.

Mind and Matter is based on Schrödinger's Terner Lectures, which he delivered at Trinity College, Cambridge, in October 1956. He considers the connection between consciousness and physical events occurring in the brain, reminding us that the world is our own construct, based on sensations, perceptions and memories. Its manifestation results from brain processes, and he wonders what is special about them but, not surprisingly, fails to find a satisfactory answer.

Schrödinger goes on to consider "the apparent gloom of Darwinism", sadly accepts the need to abandon Lamarkism (i.e. the inheritance of acquired characteristics – which, actually, has recently returned in attenuated form as epigenetics), oneness of mind in terms of ideas from the Hindu Upanishads and a 13th century Persian mystic Aziz Nasafi, and the relationship between science and religion.

He comments in particular on the "mystery of the sensual qualities", i.e. the disconnection between conscious experience and the physical description of what is observed –

> The sensation of colour cannot be accounted for by the physicist's objective picture of light-waves. Could the physiologist account for it, if he had fuller knowledge than he has of the processes in the retina and the nervous processes set up by them in the optical nerve bundles and in the brain? I do not think so.

He is right, for despite immense progress in the elucidation of the mechanisms of vision and brain function over the last half-century, there is still no direct connection between the conscious experiences of redness or blueness and their physical and physiological descriptions. The physicist can describe the wavelength, intensity and polarisation of the light entering the eye; the physiologist can discuss in extraordinary detail how the rods and cones in the retina generate nerve impulses, and how these travel in a complex fashion to the visual cortex at the back of the brain to produce patterns of excitation there; but we are still as far as ever from connecting the latter to the conscious perception of colour.

The book ends with Schrödinger's *Autobiographical Sketches*, which are exactly that: somewhat episodic; in seemingly random order; and quite brief (18 pages). They were completed in 1960, the year before he died. As an illumination of some of the non-science background to the life of one of the greatest physicists of the last century, I found it fascinating. He describes his family life in Vienna, his awe for Boltzmann (whose suicide occurred the year before Schrödinger entered university), the First World War and how it impinged, the Nazis, and his times in Graz, Dublin, Oxford, and many other places including his "late Viennese period" from 1956 until his death. I was intrigued by his seemingly paradoxical remark at the beginning that his student friend Fränzel was "...the only close friend I ever had", given his lengthy marriage and close relationships with other women.

It is truly remarkable how little *What is Life?* has become irrelevant or dated. Of course, in some parts, the author is "pushing at an open door" in the sense that subsequent research confirmed his arguments and speculations. But most of the book is as fresh and vital now as it was when he wrote it.