What is Life?

What’s in it for me? A fascinating perspective on biology from one of the greatest minds in physics.

If you know only one thing about the Irish-Austrian physicist Erwin Schrödinger, it’s most likely this: Schrödinger’s cat, a famous thought experiment Schrödinger used to illustrate quantum superpositions, a notoriously difficult concept in the equally notoriously difficult field of quantum mechanics. We won’t be getting into the quantum theory weeds, so suffice it to say that, because of his part in developing this new field, Schrödinger was one of the giants of twentieth-century physics. But Schrödinger’s curiosity stretched far beyond physics and into other areas of science and philosophy. In 1943, he delivered a series of lectures at Trinity College in Dublin. The topic was nothing less than the fundamental nature of biological life, or more precisely: How can science account for the complexity of living organisms and the rules that govern them? Roughly a decade later, in 1956, he returned with a series of lectures about the connection between mind, matter, and consciousness. These lectures, which were later turned into a book, would go on to inspire a whole generation of scientists and philosophers. And that’s where these blinks come in. They’ll not only familiarize you with Shcrödinger’s key insights; they’ll also explain

why living organisms are so big; how life is like clockwork; and how consciousness may help humanity continue to evolve.

Living bodies can’t be affected by the activities of single atoms.

Schrödinger started off his lectures by asking his audience a simple question: Why are atoms so small? Or – and this is really the same question but from a different perspective – why are we humans, and all other living organisms, so ridiculously large compared to the tiny atoms we’re made up of? And just to be clear, atoms are really, really, really tiny. The size of a single atom ranges from 1/5000 to 1/2000 of the wavelength of yellow light. This is important because this wavelength is roughly the size of the smallest possible grain you can detect in a regular microscope – well, at least back in 1943, when Schrödinger delivered this lecture. So, even with the most state of the art microscope in 1943, the tiniest thing you could see would still contain thousands of millions of atoms! So, why are atoms so small? Well, for any organism to function properly, it relies on its parts to behave in an orderly way and obey strict physical laws. And this is precisely where things get a bit hairy, because, individually, atoms behave in a pretty disorderly way; they’re constantly vibrating and producing energy. In fact, the behavior of a single atom, or a small number of atoms, doesn’t obey any recognizable physical laws. It’s only when you have a large enough number of them that they start to behave according to statistical laws. There are many examples of this. Magnetism is a good one. If you fill an oblong quartz tube with oxygen gas and put it into a magnetic field, the gas is magnetized and the oxygen molecules orient themselves parallel to the field like the needle of a compass. However – and this is important – not every oxygen atom changes its orientation. The atoms only orient in the direction of the field on average – as a group. Alternatively, consider a light object suspended by a long thin fiber. Physicists often use these in experiments to measure weak forces like electricity and magnetism, which can work to alter the position of the body. As physicists experiment with lighter and lighter bodies, those bodies reveal themselves to be susceptible to weaker and weaker electric or magnetic forces. Eventually, the body performs a constant and irregular dance around its neutral resting, or equilibrium, position. This example is especially helpful because it shows how the human body would cease to function if all the atoms inside it were constantly responding to all the forces operating on them at a given moment. For an organism to benefit from the statistical laws that govern large groups of atoms, its body must be large in comparison to its atoms.

Small groups of atoms contain all the instructions for how a living body will develop.

OK, let’s sum up what we’ve learned so far: any living organism, along with every biologically relevant process it undergoes, must be composed of a huge amount of atoms. This is a safeguard against the potential for single atoms, which can behave erratically, to influence the overall behavior of the organism. So far, so good. But now we run into a problem, which is this: tiny groups of atoms – much too small to display exact statistical laws – do, in fact, have an enormous influence over everything that occurs within a living organism! These small groups of atoms dictate all the features the organism acquires as it develops. They also determine how the organism will function. Biologists sometimes refer to organisms as “four-dimensional patterns,” with the fourth dimension signifying time. The pattern includes the organism’s ontogeny – that is, the structure and function it will develop throughout its entire life, from its beginnings as a fertilized egg cell to the state of maturity when it begins to reproduce. The ontogeny is determined by the structure of exactly one cell: the fertilized egg. Actually, it’s determined by just one small part of that cell: the nucleus. When the cell – that is, the fertilized egg – is “resting,” the nucleus is distributed across it. But during cell division, when cells split in two and cause the organism to grow, that changes; during this stage, the nucleus consists of a set of rod-like particles called chromosomes. Inside these chromosomes are genes, which determine properties the organism will have, such as blue or brown eyes. A gene contains no more than a few million atoms at most – far too small a number to operate according to statistical physical laws. Yet these chromosomes contain all the code necessary to determine whether the egg should develop into a chicken, a fly, a corn plant, or a person. How? Well, written into the code-script is the entire pattern of the individual’s future development – that is, how it will develop into its mature state. And every complete set of chromosomes contains the full code. But even this is too narrow a description. Chromosome structures don’t just provide instructions for how the organism will develop – they also work to bring about that development. They’re both blueprint and architect all in one.

The process of evolution mirrors the principles of quantum theory.

So, we just learned that genes contain not only the blueprint for any living organism but also the instructions for how to build it. And we've learned that individual genes are far too small for the atoms they're made up of to obey any statistical laws. Add to this the fact that genes are remarkably stable over time. How do we square these things? To answer this question, let's first clear up a common misconception about evolution. The famous naturalist Charles Darwin famously theorized that natural selection occurs through small, continuous, accidental variations. He was wrong. Consider a crop of pure-strain barley. If you measure every ear in the crop and plot those measurements on a graph, you'll wind up with a standard bell curve. Then, say you take a few outliers with extra-long ears from that crop and plant them in an empty field. If you were Darwin measuring this new set of crops, you'd expect the bell curve to have shifted to the right – in other words, that selection would have produced an increase in the average length of the ears of corn. But that's not the case. The new statistical curve would be exactly the same as the first one because small, continuous variations aren't inherited. Instead, evolution occurs through discontinuous changes called mutations, which are less like Darwin's smooth, small changes than the sudden leaps in another branch of science: quantum theory. One rule in quantum theory states that very small systems can only possess specific amounts of energy. For such a system to increase its level of energy, it must make a "quantum" jump to the next possible level, and it can't pass through any intermediary quantities of energy in between. Similarly, in evolution, there are no intermediate forms between the "unchanged" form of a species and the few "changed" offspring. Instead, changes happen in big leaps – and these leaps are extremely rare. Which brings us back to our main question here: How can genes remain relatively unchanged over time when the small number of atoms they're made up of tend to be disorderly? Quantum theory provides a potential answer. Atoms can bond together to form molecules. When this happens, the atoms are arranged in specific configurations that determine the molecule's stability. For the molecule to enter a different configuration, it must be brought to a different temperature, and even then, there's no guarantee. In fact, it's very possible for it to take thousands of years for any given molecule to make one of these jumps. In other words, a molecule could change its configuration on the same time scale at which evolution occurs. In this sense, a gene is like a huge molecule that can only change through large and infrequent jumps. But this explanation isn't totally satisfying – it solves the problem by just inventing a new, hypothetical molecule! The next blink will tie everything together.

Life is orderly on both a small and large scale.

The molecule we're describing here is nothing short of a masterpiece. It's incredibly small, yet remains highly ordered over long periods of time. The classical laws of physics don't seem to apply to it at all! This, however, shouldn't surprise us. In fact, this is always true when it comes to discussions of life. For example, take entropy, the tendency of an isolated, inanimate system to decay into a state of thermodynamic equilibrium – basically, into what we can call disorder. Normally, matter quickly decays into this state. Life, on the other hand, repeatedly feeds upon negative entropy – that is, order – inside of the food it eats. By doing so, it avoids death, the state of maximum entropy, and continuously generates order from order. The classical laws of physics would call that impossible. In physics, there are two different methods by which order can be produced: the "statistical" and the "dynamic." The statistical method was described back in the first blink. It's when atoms behave in a disorderly way individually, but in an orderly, statistically predictable way in large groups. Through it, order is obtained from disorder. This statistical method is primarily found operating in nature. With life, however, it’s a different story. Life is governed by the dynamic principle, where order is obtained from order. A single group of atoms existing in one copy of the genetic code produces something marvelously orderly – a living organism, which continually violates the principle of entropy. That is, it somehow stays alive. In a way, life is pretty similar to the operation of a clock. The constituent parts of a clock operate according to dynamic laws, and so too does the overall mechanism. This is possible because clocks consist of solids bound to their shape by the forces of quantum mechanics. And these forces enable the clock to avoid the forces of entropy. Similarly, living organisms are built from particular types of solids – which Schrödinger calls aperiodic crystals – that allow them to avoid entropy, too. These crystals are like the cogs in the organic machine. But these cogs are more than any ordinary human invention. Instead, they are, in Schrödinger’s concluding words, “the finest masterpiece ever achieved along the lines of the Lord’s quantum mechanics.” OK, that covers the first series of lectures. If you’re thinking to yourself right now, “Hey, I know what this molecule is. It’s DNA!,” it’s worth pointing out that, when Shrödinger delivered these lectures, the structure and role of DNA had not yet been fully worked out. But Schrödinger’s ideas played an important role in its discovery. Francis Crick, who together with James Watson won the Nobel Prize for working out the helical structure of DNA, was influenced by the ideas in these lectures.

Consciousness is associated with active learning processes.

Now let’s turn to the second series of lectures, where Schrödinger starts off by exploring a more philosophical question: What, exactly, is consciousness? You’ve probably heard the classic conundrum, “If a tree falls in the forest and no one is around to hear it, does it still make a sound?” But could we take the metaphor further? In other words, is there a chance it might be true of the entire world – that the world only exists because human consciousness is there to make it manifest in our sensations, perceptions, and memories? To answer that question, we first have to define precisely what consciousness is, from Schrödinger’s perspective. Consciousness is an elegant and elaborate mechanism. In fact, it’s the most ingenious of all survival mechanisms. Why? Because it allows you to respond to a wide variety of different situations by altering your behavior. But Schrödinger argues that not every process in the brain is accompanied by consciousness. Some are like conscious experiences in that they’re biologically significant and involve our minds and bodies reacting to the environment – for instance, things like blinking, breathing, or walking to work in the morning using your usual route. Although these reflexive processes are initiated by the brain, they aren’t conscious. Your awareness is essentially separated from the sensations, perceptions, and even potentially the actions associated with them. From this, it can be said that a behavior only becomes conscious when something forces you to change that behavior. You might normally be able to walk to work practically in your sleep while thinking about something totally different. But if there’s, say, some construction blocking the road and you have to take a different path, your behavior suddenly becomes conscious. In a sense, then, consciousness is like a teacher. It educates you until you can do things without its assistance. From this definition, we can ultimately conclude that consciousness is what allows all life to become aware of itself – but only insofar as it continues to develop and create new forms. An infant only becomes conscious as its senses gradually begin to interact, adapt, and practice within an environment. And just like the tree falling in the forest, the world can only be aware of itself as long as human consciousness continues to learn from and interact with it. But why is this discussion of consciousness important? What bearing does it have on humanity as a whole?

Humanity continues to evolve because of consciousness.

At first, it may seem that by becoming conscious beings we humans have effectively escaped the classic Darwinian survival of the fittest. After all, most people dislike seeing their fellow humans suffering and dying. So societies have developed ethical codes and laws that simply don't allow people to let others die – instead, they help them survive, whatever their physical or mental conditions might be. Darwin's theory doesn't allow for the inheritance of learned traits, either. For instance, a person can't learn how to play the piano and then pass that skill on to his daughter purely through genetics. Together, these facts raise the following question: Given the absence of evolutionary pressure, is humanity doomed not to advance any further biologically? The answer is no. According to Darwinian theory, each mutation that leads to evolution is a single, fortuitous step that has nothing to do with the behavior of individuals throughout their lifetimes. But that comes with a caveat: certain mutations cause further behavior that continues to serve that mutation, effectively furthering evolution. To illustrate this, consider a species of birds whose ability to fly high enables them to build nests high in the treetops, away from enemies that could gobble up their young. That gives these birds an advantage, and in addition, their nesting behavior also selects for the best fliers among their offspring – only young birds who can also fly high will make it back to the nest. In this way, the ability to fly produces a change of behavior related to the environment, leading to an accumulation of an ability. This relates back to the question of humanity's evolution because it shows that behavior has a way of directing the mechanism of evolutionary selection. When organisms make appropriate use of adaptations – when birds which can fly higher use that ability – they aid the process of selection. The ultimate conclusion is this: For humanity, evolution depends on people actively working toward it instead of resigning themselves to a fate determined by the laws of nature. In fact, our biological future is something we can determine by regulating our behavior. But there are obstacles in humanity's way. In Schrödinger's era, factories were encouraging tedious and boring operations on the assembly line. If this continued, he believed selection would favor less intelligent people who'd find it easier to thrive in such an environment. His proposed solution? To replace humans with machines in unintelligent, tedious, mechanical work.

There's a gap between our scientific and sensual understandings of the world.

In this last blink, let's turn to another deeply mysterious question about consciousness – namely, the question of sensual qualities. What, Schrödinger asks, makes yellow yellow? Ask a physicist how she conceives of yellow light and chances are she'll throw a bunch of big and complicated words at you: Yellow light consists of transversal electromagnetic waves of wave-length around 590 millimicrons. But while the physicist is able to describe the objective qualities of light waves in great detail, the sensation or experience of the color itself is totally absent from her description. Likewise, a physiologist could tell you objectively which nerve fibers in the brain and eye are activated when a person sees yellow – without ever mentioning the specific sensation of color. At the same time, of course, your impression of the color yellow can’t tell you the objective properties of light. So sensation isn’t and can’t be contained in scientific description. Instead, it exists only in the mind and the brain of the person doing the experiencing. It’s baffling to contemplate, but everything only has meaning in relation to the consciously contemplating, perceiving, and feeling subject who observes it. But science still hasn’t elaborated on a framework through which we can understand the mind and its role in producing our individual pictures of the world. In fact, science avoids any discussions of meaning at all – and the more attentively it observes and documents the world, the more meaningless everything appears to be. Science tells us that our minds have been produced by the very picture of the world we’re constantly observing – and that it’ll disappear when the sun cools down and the earth ceases to support human life. This is a truly bewildering thing about consciousness. It’s the stage – in fact, the only stage – on which all the world’s events take place. It contains the whole world, and without it, there’s nothing. At the same time, consciousness is just an adaptation evolved to keep its owners alive – owners who grow and live within that same picture of the world. How can we reconcile these facts? The answer is pretty simple – though it’s found primarily in Eastern, rather than Western, thought. And it’s that our minds are identical with the world – in other words, mind and the world are one. Of course, there’s a paradox there, because there appear to be many consciousnesses – individuals with conscious egos – all producing world pictures. The solution is to accept that consciousness is just one thing, consisting of a series of different aspects of that thing. So, when consciousness ceases to exist – when what you think of as you ceases to exist – there’s no real death involved at all.

Final summary

The mystery of life is that living organisms must behave in an orderly fashion and so can’t be impacted by the activity of individual atoms, and yet individual atoms that contain the genetic code determine all the characteristics of the organism. Schrödinger theorized that, as in quantum mechanics, living matter must be composed of molecules that exist in stable permutations and only change form in rare events called mutations. The truly amazing thing about life is that it is order producing order, constantly evading the law of entropy.