Dear My Younger Self,

Don't fall for the hype of quantum biology. In this letter I hope to convince you that the physics of biology is itself not understood by humanity, and that focusing time on quantum advantages in biological systems may steer you off course, in our goal of understanding and navigating life. I hope to show you that we have started to do experiments to quantify life, and are only now able to study biological systems with the complexities they deserve.

Why Quantum Mechanics in Life?

100 years ago, in a small city in Germany called Gottingen, the theory of quantum mechanics was born. The theory, developed by famous names such as Heisenberg, Born, and Schrodinger, aimed to describe the nature of matter and energy at the small scale, which was found to fundamentally disagree with the works of Newton which had revolutionized society. Erwin Schrodinger developed an equation to describe particles as waves which lead the way for developing the quantum picture of chemistry, in which electrons form orbitals around the nucleus. These orbitals describe the wide variety of chemistry we utilize today. Near the end of his career, Schrodinger published a work titled *"What is life"*. Unlike his previous work on quantum mechanics, this was arguably the first ever discussion of biophysics.

Our scientific understanding of life started with Charles Darwin who described biology as evolution by natural selection. This birthed the field of biology which studies life, its units such as cells or species, and its dynamics like evolution. Although the fields of physics, chemistry, and biology can often feel orthogonal, they are the same scientific method applied to different scales and systems of interest. Biophysics challenges this paradigm as it transcends the scales of life.

Physics aims to quantify nature and develop theories, normally in the form of equations. As of now the language of biology has still been descriptive, as compared to physics which relies on mathematics. The idea of biophysics is then to somehow come up with an equation that describes how biological systems change over time. As an example, we know all living systems change based on Darwinian evolution over time, but we cannot write that in an equation. We do not yet have the mathematical objects that describe these systems, nor the understanding of how to classify these sorts of dynamics.

However, biophysics has a strong foundation from which we can start looking for theories of life. Thermodynamics developed as the study of energy transfer in systems, and physics found statistical mechanics to quantify these processes. This directly led to the industrial revolution which once again perturbed humanity's trajectory as part of life on Earth. Statistical and theoretical biophysics developed thanks to advancements in our understanding of molecular biology, at least on the cellular level. That is to say, we have just started to quantify how a mix of molecules, like soup, is different from a living mix of molecules, like a cell. The main finding is that living systems are outside of, and actively resist, thermodynamic equilibrium.

We will discuss and question the overlap of quantum mechanics and the physics of living systems. Specifically, we will look at the questions of quantum advantage in biology, and try to understand what role, if any, quantum mechanics has to a theory of biology. We will show that the hunt is not really for quantum life but for a framework that explains how life resists equilibrium. ### ### The Myth of Quantum Advantage as Biological Advantage

An advantage to an organism in biology provides the creature with a benefit to its fitness. In this light, we say an organism exists in some fitness landscape and in one scale larger, we say a species occupies a niche. We can think of evolution by natural selection as the dynamics of species in a fitness landscape which is defined by the environment. If an organism is able to find an advantage, for example via random genetic mutations, then this will help said organism outcompete others. If a species has an advantage it can outcompete other species and ensure its own survival, given that a niche exists for it in the environment. And on a smaller scale, molecules which interacted with others to form patterns, form separate phases, or lead to replicating reactions have an increased chance of existing over other molecules.

Quantum Advantage is described as an advantage based on the quantum nature of phenomena, as opposed to its classical analog. The most common example of this is classic and quantum computing. Classically, the bit has two values, 0 or 1, and this in the framework of Boolean algebras can be used to do calculations and perform computing. More generally, computers are able to do all the incredible things we know them to do, by just answering a series of binary yes or no questions. Oppositely quantum computers use the quantum nature of particles to do computation with all the combinations of the binary states. Specifically quantum computers use qubits which exist in a Bloch sphere between 0 and 1 states, and this is fed into an operator which is analogous to the logic gates in classical computing. This offers an advantage, bit for (qu)bit, in some problems (for example factoring large numbers). We then say there is a quantum advantage in factoring large numbers, and that means quantum computers will beat classic computers at this task.

So, with the tools to discuss the problems at hand, we can address the idea that there are systems or objects which have a quantum advantage which leads to a biological advantage. Two proposed examples are avian magnetoreception, [1] and coherent states in photosystem II. [2] Here we will discuss both these examples, provide counter examples, and argue that while these systems do use quantum phenomena, their quantum nature does not directly lead to biological advantage.

Birds use information about the magnetic field on Earth as an advantage in this competition to survive. This should come as no surprise. Birds who fly in three dimensions and across large distances would benefit from knowing north like a compass needle, and also use changes in the magnetic field to guide them. From this it would be easy to see why this magnetoreception would be an advantage to an organism, and thus be a biological advantage. What is not clear is why the quantum nature of the mechanism, via radical pair formation, would be more advantageous than any other mechanism.

Magnetotactic bacteria [3] also use the information of Earth's magnetic field to their benefit. Our understanding so far is that the bacteria which prefer to live in dark and low oxygen conditions use the Earth's magnetic field to find their preferred vertical positions in lakes. Furthermore, we know they use cellular organelles called magnetosomes to perceive and act on this magnetic field information. The current literature does not focus on the quantum nature of interactions required for the mechanism, and rather the focus is on finding all the advantage this information could bring.

So now we can compare the advantages of magnetoreception in birds and bacteria. In both cases the ability to detect magnetic fields is a clear biological advantage to both organisms. Since the pattern of magnetic fields on Earth is position dependent, this information can be used by the organism to determine its own position, which can be the difference between life and death. However, the question of quantum advantage in this biological advantage goes unanswered. Firstly, the quantum nature of of the avian mechanism doesn't clearly provide greater benefit than the mechanism used by bacteria. It could be argued that the birds are able to measure much more sensitive changes, but this does not quantify the added advantage. Secondly, and more broadly, it is not clear how to describe the benefit of a quantum system as compared to a classical system, in terms of biological fitness. To answer this question with the rigor needed to satisfy physicists requires a description of biophysics that we do not currently have.

Another system that has been discussed in the context of quantum advantage is the molecules in plants that do photosynthesis called photosystem II. It has been shown that the collection of molecules uses coherent quantum states in the process of absorbing light and producing energy needed to keep the cells alive. However there is an issue with the idea that quantum coherence is a biological advantage. It is of no doubt that the function that photosystem II is performing is an advantage. Even more, photosynthesis is an essential function, not only for the life of the organism, but for all life on Earth. The quantum advantage of the mechanism is also a biological advantage, as it may be more efficient than other mechanisms that do not use coherent quantum states. This efficiency, even if its small, would be a huge biological advantage in the competitive environment of photosynthetic life forms. What is still unclear, even with such a detailed quantum understanding of the phenomena, is how we could measure or quantify this advantage.

In general, the quantum nature of the molecules that make up living things, can lead to biological systems utilizing them. This is still true for when there is no quantum advantage. Quantum mechanics is needed to describe, study, and understand molecules like DNA and proteins. Quantum descriptions of these biological molecules are sufficient, but not needed to describe the biology of these systems. Chemistry is also a sufficient description. However biophysics is not interested in any one scale, but rather in how information passes through scales.

Do We Need Quantum Mechanics to Describe Biology?

Let me answer that question with a question. Do we need general relativity to describe biology? Is it not strange that a theory on the nature of particles would have more importance in understanding life than a theory on the of nature mass and energy? I believe the apparent need for quantum mechanics, as opposed to any other theory of physics, in describing biology is because we do not have a general theory of biophysics. To drive this point home we will show some systems from biophysics that mimic life, and show that quantum mechanics is not needed to describe their behavior. What biology needs most is a general theory of out-of-equilibrium dynamics.

Let us consider the examples from before, plant cells and birds. If we start from the quantum description of particles as wave functions, we will very soon be outside of what humans or computers could calculate. In photosystem II, there are a handful of molecules which interact, but we cannot study this whole system with a quantum description. Rather in biophysics, we work with toy models in which we coarse grain away the real physical details into a simple physical model, with greatly reduced degrees of freedom. Two classic examples would be modeling molecular motors with a few state model, and modeling the flocking of birds with simple rules. We will try to imagine how the quantum advantages proposed would affect the biophysics picture, and show that what is of interest is not quantum in nature.

Molecular motors, and the cellular skeleton called the cytoskeleton, give the cell shape, allow it to move, and is analogous to our musculoskeletal system. It is composed of filament forming proteins, motors, and connectors which move along the filaments and connect filaments to each other. These things are made and also driven by chemical reactions. Things that are often of interest are the forces the cytoskeleton can generate, and what kinds of shapes and structures can be made in the cell. Imagine a cell with a cytoskeleton that uses fuel to do something of biological advantage for that organism. Now imagine two cells with cytoskeletons, both having mechanisms to generate fuel from sunlight. However, one has a quantum advantage in efficiency from coherent quantum states while the other does not. So the energy efficiency could directly be of biological advantage, however the main process describing the advantage does not care if the description is of a quantum nature or not. The added complexity of the multicomponent cytoskeleton systems obscures the quantifiable energy advantage from the quantum mechanism. It is often the case that in biological systems noise plays a crucial role driving the dynamics. One way to understand this relationship between dissipation through noise and the precision of random processes, is the thermodynamic uncertainty relation. [7] The thermodynamic uncertainty relation says the uncertainty of a thermodynamic process is limited by the rate of energy dissipation. This limits how precisely biological systems can perform the functions required for life. [See technical note 1 for more rigorous details]

Similarly, consider a model for bird migration across a large distance, of a flocking bird species. These birds should fly south in winter to help their chances of survival, but since it is very far it would be of biological advantage to stay on track. Let's say there are two mechanisms for navigation, one which use magnetoreception to detect north and south, and another that makes birds fly together. We can use a biophysical model like boids to study such a system in which the rules for how a bird flies is quite simple and depends on limited information about other birds, and the previous state. In such a model we can describe the mechanism of magnetoreception as some strength to which the bird aligns to the north-south axis. In that way, we can quantify the quantum advantage of the avian mechanism as compared to another mechanism like magnetosomes and compare the two in terms of biological advantage. One could say that a more sensitive quantum mechanism might help keep more birds on track, but the role of birds guiding other birds would also have the same effect. Disentangling the quantum advantage in the overall biological advantage is not easy. To understand the advantage of the avian mechanism, we needed a quantum description of the system. But in terms of biology there is no inherent quantum advantage. *[See technical note 1 for more rigorous details]*

The point of these two examples is to show that biophysics is not concerned about the rules at each scale, but rather how complex systems reach across scales to be alive. Sometimes a quantum description is needed for the fine details, but in general we do not need quantum mechanics for a complete description of biology. ### ### A New Physics of Life

Initially I warned about the hype of quantum biology. What I meant is that we should not look for the fine connections between quantum mechanics and biology, when there is still so much work to be done in understanding how matter becomes life. We don't even know what a general theory of biophysics would look like. But I am sure there is a description of the special phenomena we call life. I am so certain, that I would go as far as to say that such a theory would help create a more complete picture of quantum mechanics.

We may not have a form, but we know the rules of thumb for a theory of biophysics. The goal of such a theory would be start from physical principles we know to be true, and build up to explain the dynamics of biological systems such as reproduction and evolution. As stated before, the language of this physics is statistical mechanics, in which we have concepts like entropy, free energy, and the second law of thermodynamics, which says entropy always increases. The entropy is always increasing or at a maximum, and once the system is at this entropy maximum, it is said to be at equilibrium. One defining feature of living systems is that they are not at equilibrium. Equilibrium is death. Not only do living things stay away from equilibrium, they actively fight the rate of entropy increase.

Only today are we starting to measure life in such a way. [4] Specifically, by using single particle tracking experiments and calculating the mean back relaxation of said particle, we are able to quantify how far the system is from equilibrium. A nonzero mean back relaxation indicates broken detailed balance. By looking at the diffusion of molecules in living and non living systems, we can try to quantify how far life is from equilibrium. We expect molecules to diffuse freely, since diffusion is such a fundamental process. Biological systems surprise us as individual molecules do not freely diffuse in living systems. They often self organize and perform functions that give rise to life. Consider a bowl of soup made from a plant, and the cells of that plant itself. Somehow they contain the same molecules, but the soup is clearly not alive. We know that the plant has life in the sense that it will age, and one day it will die when it reaches equilibrium. *[See technical note 2 for more rigorous details]*

This breaks an important rule in physics: Most of our theories possess time reversal symmetry. That is to say, since energy is conserved in physics, we expect there to be no given direction of forward or backward time. This is hard for us to understand, because as biological things, we intake energy to avoid equilibrium, to stay alive. This gives us a very mortal direction of forward time. What we seek as biophysicists is a theory that describes the physical nature of life as an out of equilibrium system.

Slowly but surely, we are advancing towards our goal. First by quantifying and defining life, [5] then by modeling it across scales to root out the essence of the laws of biology. As opposed to quantum mechanics being needed for such a theory, said theory could help us better understand quantum mechanics. For example the work done with the eigenstate thermalization hypothesis [6] describes how a quantum many body system can reach equilibrium. If biological systems do break time reversal symmetry, could we study living systems with the idea that they do not follow the eigenstate thermalization hypothesis? *[See technical note 3 for more rigorous details]*

So my younger self. I did not wish to dissuade you from perusing your dream of better understanding living systems. Physics, even quantum mechanics, will be needed in order to give you the tools necessary to rigorously study life. But still, do not forget the bigger picture, the anthropic principle, that we are emergent groups of particles that try to understand how everything works. There might not be an clear quantum advantage leading to biological advantage. A general theory of out of equilibrium dynamics may not be possible. However biophysics is the frontier of the natural sciences. The frontier is not asking how quantum is life but rather what new physics emerges when matter persistently resists equilibrium? Life may not be quantum in essence, but in chasing it, physics itself evolves.

Sincerely, Future you.