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Living and non-living in the Quantum world

Life, with all its most fundamental attributes, begins at the most fundamental level itself — at the level of the elementary particles governed by the probabilistic laws of Quantum Field Theory.

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Abstract:

In a classical deterministic, Newtonian, world one needs to define "what is life" as separate from the emergence of other forms of in-animate matter. We argue that life can emerge, in principle, organically in a world governed by the laws of Quantum Mechanics.

Introduction:

There is no unique definition of life except for various descriptions arising from the observations of living entities. Apparently more than 123 possible definitions have been compiled according to Wikipedia. Many of these definitions have their origin in the legal definitions of life and death for purposes other than purely scientific or philosophical. Broadly speaking, living beings have the capacity to grow, respond to stimuli and decay. A central feature of these descriptions is the capacity to reproduce, however imperfect, and pass on the information as encoded in the DNA. In physical terms, animate matter also has the capacity to maintain a steady temperature to be in a state of thermodynamic equilibrium for a length of time.

These descriptive definitions tend to acquire more and more attributes as one move from the simplest (single cell) to the most complex living organisms. The number of functions is increasing with complexity. This mode of descriptive definition requires a reference state which is the so called “non-living” state or “inanimate” matter. Most of the matter in the universe is of course non-living.

At the present state of our knowledge we do not know if life exists outside of our planet Earth [Except when we send some one out into moon or a space station; perhaps Mars in future]. Even within our planet, the inanimate matter overwhelms the animate matter – the biomass of all living organisms on earth is estimated to be about 550 billion tonnes of carbon which amounts to one part in 10 billion when compared with the total mass of the earth.

The purpose of this article is to propose an alternative narrative to the question “what is life?” This question acquires meaning in a classical Newtonian world where there is a chasm between living and non-living although they are made up of the same basic constituents. However, once we accept the foundational principle that all laws of nature are Quantum Mechanical, then it is possible to argue that the origins of both living and non-living matter from a unified perspective. We elaborate on this theme in the following sections.

The Classical world view:

The definition/s of life as outlined earlier has/have its/their origin and reference to what life is not. The classical post-Newtonian view of the world was completely deterministic. The success of classical mechanics [This should also include the success of classical Electrodynamics as formulated by Faraday and Maxwell] after Newton was enormously impressive. So much so, Laplace wrote in his *Philosophical Essay on Probabilities (1812):*

“We ought then to consider the present state of the universe as the effect of its previous state and the cause of that which is to follow … nothing would be uncertain, and the future like the past, would be open to its eyes.”

It is a strong statement of the deterministic view of the material world where the present determines the past as well as the future precisely for all times. Laplace posits that, in theory, we should be able to predict the future and reconstruct the past with complete certainty, embodying the principle of "*causal determinism*".

This defined the physical world almost entirely as opposed to the biological world where nothing is certain as in the classical realm. The evolution ensures that things are changing dynamically in unpredictable ways. Thus, the physical world of non-living is separate from the biological world of living with different fundamental principles. A chemical process may change the character of the material by rearranging the constituents, but the constituents remain the same no matter what the rearrangement is. *Thus, it was not possible to countenance the emergence of the biological world, life for that matter, from a purely deterministic framework of fundamental laws.*

This Laplacian deterministic world view was to change fundamentally soon- first by Poincare who showed that even while the laws are deterministic, the system can be unpredictable (as in transition to chaos). Furthermore, the discovery of radioactivity brought to bear the transient nature of the material world itself- the decay (death of the old) and birth (of the new) which could not be easily accommodated in the classical description. Many other discoveries and new ideas emerging in the first quarter of the 20th century leading to the birth of Quantum Mechanics showed the limitations of classical deterministic world view. This is not to assert that it was wrong; we now know that the classical Newtonian framework can emerge as an approximation in the limit where all the quantum correlations are wiped out.

The Quantum world view:

This is not the place to describe quantum mechanics in detail. Important point to make is that it put an end to the Laplacian deterministic world view. The mathematical foundations of quantum mechanics is one of certainty- that is the dynamical equation of a given state is obtained as a solution of an ordinary differential equation with unique solution. However, unlike in classical mechanics, the solution itself does not represent an observable but provides a probabilistic prediction for the evolution of the experimental observable/s. When combined with the special theory of relativity of Einstein, we get the formulation of the Quantum Field Theory (QFT). This provides the mathematical and physical framework in which all phenomena involving the elementary particles are understood. Within the framework of QFT, we have a mechanism by which particles are "created and/or destroyed" under certain conditions. The concept of "vacuum", which contains everything that can be created by energy transfer, takes root. This is the basis for a fundamental, in principle, understanding of our world and is usually called the Standard Model (SM) of Particle Physics. The standard model is hugely successful as its observations and predictions are consistent with experiments at the smallest scale that we can explore at present. There are, however, clear indications that it is still incomplete. For one, gravity is yet to be integrated into a quantum theoretical framework.

The shift from classical world view to quantum world view is paradigm shift from a deterministic to the rather uncertain probabilistic world view. The quantum field theory description of the underlying microscopic world allows for the creation and destruction, birth and death, of elementary particles which constitute all visible world including the material basis of biological world. In fact, we not only understand the interactions between particles, but also their decay or slow death in mathematical and physical terms. It is this paradigm shift that should make us review our way of thinking about living matters.

For example, consider the simple and ubiquitous elementary particle, the electron. The experimental bound on the lifetime of the electron is greater than 10^{29} years. Perhaps it will live forever! An electron can reproduce while interacting with an electromagnetic field. That is apart from itself it can create another pair of electron and positron. The photon is even better- it can lose energy by reproducing itself many times. A photon may also give birth to a pair of electron and positron. In fact, there are many options here- the photon can create any pair of particle and antiparticle pairs under suitable conditions. The basic conditions that are satisfied in all these cases are related to symmetries and conservation laws which govern their interactions. We should emphasize here that there is no classical analogue for particle creation, destruction or decay.

There is another aspect of the behavior of electrons and photons which comes from the laws of quantum statistics- an electron "knows or is conscious" of the nature of the particle it is interacting. For example, it can make a distinction between another electron (identical to itself) or some other particle that is not identical. Its interaction is based on this distinction. This is popularly known as the *Pauli Exclusion Principle*. This principle arises from the Fermi-Dirac statistics obeyed by the electrons. An electron experiences a statistical repulsion if it encounters another identical electron. The photon has no such inhibition. It obeys a different principle arising from the Bose-Einstein statistics. It can co-exist with any number of other photons. The attraction is more towards those which are identical and indistinguishable. Once again, the rules of quantum statistics govern how elementary particles behave towards each other. There is no classical analogue for such properties derived from quantum statistics.

Even the dynamical evolution of the states of these particles is not certain. In principle a given state, prepared carefully for the particle; after evolving for some time according to the laws of quantum evolution is a superposition of many possible states each of which has a well-defined probability. A measurement of the state after some time may show that it is a superposition of many possible states. The actual probabilities are determined by making repeated measurements on an ensemble of identically prepared initial state. The best example of this is quantum interference. We may send identical electrons one by one towards the double slit. As long as we do not know through which slit the electron has passed, an interference pattern develops after a statistically significant number of identical electrons are sent. The electron decides what to do in this case, but only in a probabilistic framework. Any observer interference with the process only results in the collapse of the electron in to one of the states allowed by the superposition.

Therefore, it suffices to say that there is a probability framework for the behavior of elementary particles. Their interactions depend on many intrinsic properties of each of them and an "awareness" of the intrinsic properties of each other. This is different from the classical uncertainty that we are familiar with. One can go on citing many examples. Notice that the operative words used in the context of elementary particles above are simply those that are also used while referring to living systems with almost the same meaning. All the processes cited above, and many more, are no different from the life process at the most elementary level. If any, the complexity increases with scale as these elementary constituents combine to form atoms, molecules, DNA, cells all the way to the most complex biological systems that we know.

Conclusions:

We may therefore conclude that Life, with all its most fundamental attributes, begins at the most fundamental level itself. That is at the level of the fundamental constituents. Life as a process that is dictated by the fundamental laws of nature, as enunciated by Quantum Field Theory, that governs the interactions between elementary particles which are the *basic living constituents*. This may appear as a sweeping statement which needs some more explanation.

This then raises the question of difference between the inanimate and animate objects in the universe. The emergence of macroscopic objects is a matter of degree of coherence that remains when the fundamental constituents start to combine. All matters are made up of fundamental particles which, in a highly reductionist sense, already have many of the features needed for the emergence of life as we understand. The so-called inanimate matter is one where the decoherence sets in, at scales, which wipes out the memory or signature of quantum processes and the probabilistic laws underlying their formation. We then reach the classical limit where we can start using the deterministic laws of classical mechanics. This is the macroscopic limit. There is a caveat here: The Sun for example is a huge macroscopic object whose motion in the gravitational field of other stars in the galaxy is entirely classical. However, the Sun sustains itself for a very long time (9.5 billion years) shining brightly using the nuclear fuel at the core where every process is described using the framework of quantum mechanics. There is no classical analogue for fusion. This is true of all stars in quasi-static equilibrium until they "die". Then there are black holes, the inside of which still remains an enigma- we do not yet know what fundamental laws operate there. Much of the physical world or inanimate world, however, becomes classical, wiping out any trace of quantum correlations. This is how it should be since the tendency of any large system is to maximize entropy which leads to decoherence thus increasing disorder or what we have referred to earlier as decoherence. The systems with increasing coherence and complexity are rather rare and exceptional and that is where the animate world comes in. As far as we know, it forms a minuscule part of the total amount of matter in the universe. This is natural, since it requires a continuous symphony of various processes to be in sync to keep the memory of certain features of the elementary constituents. The complexity increases with scale, size and the huge number of elementary components. It is an entropically much less probable state- the more complex it is the less probable it becomes. It is also in an unstable equilibrium unlike the inanimate matter [One should introduce a caveat here: Most of the matter as we know is never in a stable equilibrium over long time scales. Take for example a star. A star is "born" in some high density regions in a galaxy. It remains in quasi-static equilibrium for a few million years to a few billion years balancing the gravitational collapse against the pressure created by nuclear fusion. Once it runs out of nuclear fuel, it "dies"]. It requires a lot more energy per unit mass to have sustained coherence where many subsystems act together to create an understanding of life as we have now.

In summary, the shift in paradigm from Classical deterministic view to the Quantum probabilistic view is what allows us to think of life as an emergent phenomenon like any other physical phenomena. This is akin to Super-conductivity, Bose-Einstein condensation or such other phenomena being an emergent phenomenon where coherence and order are retained even at scales much larger than that of the microscopic world. This paradigm shift provides space for "chance and necessity" to operate in nature. It also brings all sciences including biology together, at least in principle, in one unified framework where the laws of quantum world operate. Therefore, it is probably futile to search for a more "complete" theory to replace Quantum mechanics! Einstein is believed to have said that "God does not play dice"; it is "probable that She does"!

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