What is life? Essentially, we don't know all the elements that make up life, but we have some hints.

Life can only exist because matter remains stable and does not collapse; this stability of matter, whether living or nonliving, arises from the Pauli Exclusion Principle, which avoids collapses.

Life operates like a template, with atoms constantly exchanged at the microscopic* level. This process is based on the quantum principle of indistinguishable particles.

Life appears as a complex, macroscopic* entity that can range from a minimum size of a single cell, a few hundred nanometers across, such as a bacterium from the Mycoplasma group, to a maximum of hundreds of trillions or quadrillions of cells, like a blue whale or the fungus Armillaria. Multicellular organisms are composed of various types of cells, each with distinct interdependencies. The smallest clearly identified forms of life are unicellular organisms. Cells can be viewed as the basic units of life, which can be considered as quanta of life.

In cells, due to their small size, some incipient quantum effects can already be observed or conjectured. Examples of quantum phenomena, which are the focus of current research at the cellular level, include: 1) Quantum coherence explaining the exceptional efficiency of energy transfer in photosynthesis within the chloroplast; 2) Quantum tunneling associated with protons involved in genetic mutations in DNA or particles in general crossing energy barriers; 3) Quantum conical intersection excitation of the retinal molecule in the rhodopsin protein linked to the vision process; 4) Quantum entanglement in magnetoreception, involving a pair of electrons with linked spin states in the cryptochrome photoreceptor protein found in the retina of migratory birds, functioning as a compass.

In general, a cell is small enough to exhibit certain quantum phenomena but still large enough to follow the laws of thermodynamics. However, the smaller the system, the greater the statistical fluctuations around the thermodynamic average values. In short, cells are structures that express life, bridging the realms of quantum mechanics and classical mechanics in a continuous form, while also linking statistical fluctuations and thermodynamic averages.

An essential thermodynamic requirement for the emergence of life is meeting the following criteria: being an open system and remaining far from thermodynamic equilibrium. Under these conditions, for example, embryogenesis and cellular differentiation can occur in multicellular living organisms. And mainly, cells can be built from a blueprint encoded in DNA for any living being. Chemical and thermal gradients maintain systems far from thermodynamic equilibrium conditions, allowing patterns to emerge that can lead to the formation of organelles within cells and organs in multicellular organisms. These macroscopic structures (considering the previously defined scales) reflect, on average, microscopic (molecular) structures, similar to how classical mechanics reflects the underlying quantum mechanics. These gradients discussed above could also be crucial factors in biogenesis.

These open-system conditions, far from thermodynamic equilibrium, enable chemical reactions to remain in oscillating steady states, supporting life. Strong fluctuations allow these systems to violate (deterministic) rules and become stochastic, potentially reaching states that temporarily break thermodynamic laws. The cell is a heterogeneous environment characterized by strong chemical gradients caused by the flux of chemical components. The macroscopic chemical (concentration) gradient is represented at the microscopic molecular level by changes in chemical reaction rates. These rate changes enable chemical reactions to occur, supporting cellular metabolism and, therefore, maintaining life. In particular, a thermal gradient can also occur within the (eukaryotic) cell due to mitochondrial activities during oxidative phosphorylation. These activities generate energy that can keep the cell far from thermodynamic equilibrium due to vibrational motion caused by the dissipation of excess energy in a non-equilibrium way. The macroscopic thermal gradient reflects an average of microscopic variations in vibrational motion. These motions affect chemical reactions at varying rates in different parts of the cells.

Chemical reactions are fundamentally controlled by quantum mechanics. The processes inside cells are described through chemical reactions, making cells an intrinsic example of quantum mechanics at the microscopic edge. Conversely, cells are far from thermodynamic equilibrium at the macroscopic edge, which enables life to emerge. Because cells are situated between micro and macro edges, their typical behavior

exhibits strong statistical fluctuations, making these the smallest units of life a lively quantum environment. Regarding their unique features, cells can be considered the quanta of life.

There are possibly numerous quantum effects at the molecular level, which can be observed in cells as described above. The most evident and common quantum effect is tunneling in chemical reactions, occurring in the presence of strong fluctuations along with chemical and, if possible, thermal gradients in the cellular environment. While tunneling is common, it is less noticeable for larger particles than for electrons and protons. Its probability decreases exponentially as the particle's mass increases. All activation barriers in chemical reactions may involve some tunneling component, which naturally lowers the barrier and influences all reactions.

Our current goal is to immerse ourselves in the vibrant quantum environment of the cell and explore its chemical reactions and organelles to gain insight into what the surroundings are like.

There are two main types of cells: prokaryotic and eukaryotic, which we can invade to experience the admirable quantum world of cells. The structures of prokaryotic cells are simpler than those of eukaryotic cells. Since life can exist within a prokaryotic cell, such as a bacterium, it is more instructive to start our quantum journey of life inside this cell.

The first step in this journey involves crossing the cell wall, which is made of peptidoglycan and provides bacteria with their shape and protection. After passing through the cell wall, the next step is the plasma membrane, which surrounds the cytoplasm and controls what enters and exits the cell. Inside the cytoplasm, where cellular components are located, we can examine the ribosomes, responsible for protein synthesis, as well as the plasmids–small circular DNA molecules that carry accessory genes, providing traits like antibiotic resistance. The final step is to reach the nucleoid, the area where the circular DNA is stored. Circular DNA in prokaryotic cells is packaged differently from eukaryotic DNA; however, the replication and transcription processes are basically the same in both types of cells.

Now, we can describe the detailed quantum journey of life within a prokaryotic cell. Let us, as much as possible, explore this journey by examining interactions at a microscopic level to reveal quantum effects.

When approaching the cell wall, one can observe a chemical armor composed of peptidoglycan structures, which are sequences of two alternating disaccharides linked by amino acids. These amino acids connect to those in other peptidoglycan structures through chemical bonds. The structures move due to collisions between molecular components; this movement is driven by what is commonly referred to as thermal agitation, or the kinetic energy distributed throughout the system. This agitation encourages the continued growth of these structures, facilitating cell division, remodeling, and rebuilding through the action of enzymes, especially during degradation and antibiotic attacks, which break chemical bonds. All these processes are governed by quantum mechanics, which involves proton tunneling in proton transfer processes and the formation and breaking of chemical bonds. The attack by specific molecules on this structure, changing the chemical bonds, depends on the speed and angle of penetration. During collisions, the atoms involved come into close contact, weakening or strengthening chemical bonds through electron sharing near the collision site. In this quantum interaction, where the principle of indistinguishability allows for the exchange of electrons, protons, and possibly atoms, the strength of the cell wall is maintained by its shape, which keeps the atoms close together, facilitating their reconstruction and expansion through chemical bonds assisted by tunneling effects.

As the interface between the external environment and the cytoplasm, adjacent to the cell wall, the plasma membrane acts as a phospholipid bilayer structured by covalent bonds, allowing for lateral mobility. At the boundaries of this bilayer are the hydrophilic phosphate groups and glycerol. The microscopic structure of this boundary reveals charged regions with excess electrons in the phosphate groups, balanced by cations, mainly from groups IA and IIA of the periodic table. These unneutralized charges at close distances produce electromagnetic fields that enable the exchange of electrons and protons, facilitating interactions with systems also containing unneutralized charges, such as polar molecules, primarily water. Inside, the bilayers contain hydrophobic regions formed by fatty acids. In this region, the charges are microscopically closer together, preventing the emergence of electromagnetic fields at short distances and hindering the movement of polar molecules through electron induction. The combination of these two parts of the plasma membrane generally

blocks the passage of molecules, making it microscopically impassable.

The plasma membrane contains protein channels with selective permeability, carbohydrates attached to proteins and lipids, and a variety of protein structures within the bilayer. These components are essential for molecular recognition, signaling, and maintaining membrane stability. Passage through the membrane occurs via channels formed by amino acids, which regulate which atoms, such as calcium cations, and which small molecules can pass through. Microscopically, these amino acids affect the channels through their chemical groups, changing the charge, size, and shape of the pore, which enables specific interactions and helps transport, such as from the external environment into the cytoplasm. The chemical gradient between these two environments favors this passage when it is greater outside, driven spontaneously by increased disorder, despite fluctuations in the environment. When the gradient is slight or opposite, this process requires chemical energy to overcome the increasing rates of direct collision; this can be achieved by adjusting the interactions between amino acids and substances transported through the channel.

Once the plasma membrane is crossed, one reaches the cytoplasm, a chemical solution composed of water, ions, and molecules that surrounds internal components such as ribosomes, plasmids, and nucleoids. The cytoplasm has an amorphous structure because it is a liquid, making it chemically simple to access cellular components through molecular agitation and van der Waals interactions. Part of life's magic happens at the ribosome, where essential proteins are produced by linking amino acids according to the information encoded by RNA through codons. Codons are triplets of purine and pyrimidine nitrogenous bases that bind, non-univocally, to specific amino acids. The RNA strand consists of a sequence of these bases, allowing pairing between messenger RNA with codons and transfer RNA with anticodons through hydrogen bonds between their nitrogenous bases, similar to the pairing in DNA. During this pairing, the amino acids attached to transfer RNAs in the acceptor stem region are kept close together and then covalently bonded, guided by electron density and atomic geometry, forming a peptide chain quantum mechanically. Specifically, an ester bond covalently links the amino acid to the acceptor stem of the transfer RNA, catalyzed by a specific synthetase. This enzyme brings the two molecular systems together, weakens certain chemical bonds through changes in electron density, and facilitates the formation of the ester. Some errors in the synthesized protein may occur due to problems in base pairing caused by proton tunneling issues involved in hydrogen bonds, which are intensified by inherent fluctuations.

Plasmids and, more importantly, the nucleoid contain DNA that carries the most fundamental information of the cell and life. DNA is a double helix formed by the pairing of two sequences of nitrogenous bases connected by hydrogen bonds between specific pairs. These bonds are relatively weak, allowing them to form and break during the reconstruction of the DNA double helix in both replication and transcription. There are two types of hydrogen bonds between the bases: one formed by a triple hydrogen bond (CG pair), which is stronger, and the other by a double bond (AT pair), which is weaker and more prone to errors and, consequently, mutations.

The pinnacle of life at the microscopic level is the quantum process of DNA replication and transcription. Let us first look at the process of replication, without going into molecular details, as we begin this final journey into the quantum world of life. The process roughly proceeds as follows: The initiator protein (DnaA) recognizes the origin and opens the DNA double helix by breaking a few hydrogen bonds. Helicase (DnaB) then separates the strands by breaking hydrogen bonds. The DnaC protein facilitates the loading of the helicase onto the origin. Single-stranded binding proteins (SSBs) stabilize single strands, preventing them from re-pairing. Gyrase (topoisomerase II) removes supercoiling, relieving strand tension in the process. At this stage, two replication forks form to begin bidirectional replication. Primase (DnaG) produces RNA primers to initiate the replication process. DNA polymerase III elongates the strand and adds nucleotides always in the 5' to 3' direction. Thus, one strand (leading) undergoes continuous synthesis toward the opening, while the other strand (lagging) undergoes discontinuous synthesis in Okazaki fragments. DNA polymerase I removes RNA primers and replaces them with DNA, while DNA ligase joins Okazaki fragments into a continuous strand. At termination, the forks meet opposite the origin (ter region), blocked by the Tus protein. The final separation (decatenation) is carried out by Topoisomerase IV, which cuts and rejoins the circular molecules, splitting the two DNA strands.

We selected the actions of the following main enzymes to describe the DNA replication process with some

molecular detail, based on quantum mechanics: 1) Helicase breaks the hydrogen bonds holding the DNA double helix together through a conformational change. Between the DNA strands, helicase uses energy from ATP molecules to reach a higher energy state, which changes the electron distribution of specific chemical bonds and alters their conformation. This geometric change increases the distance between the DNA strands, weakening the hydrogen bonds and effectively separating the strands; 2) SSBs temporarily bind to the regions of broken hydrogen bonds so they cannot form new hydrogen bonds nearby or reconnect with the other strand; 3) With the strands relatively separated, primase can also incorporate nitrogenous RNA bases through hydrogen bonds; 4) This RNA fragment is recognized by DNA polymerase III, which triggers the specific addition of complementary bases through the formation of new hydrogen bonds, creating double (AT) and triple (CG) hydrogen bonds. These bases, added to form the only possible AT and CG pairs, are equivalent to those to which the strand was attached before DNA replication; 5) DNA polymerase I detects and removes RNA fragments, replacing them with DNA through hydrogen bonds, thereby completing the replication process.

Upon simple consideration, it is evident that hydrogen bonding is essential to the entire replication process. Typically, these hydrogen bonds form through the following quantum steps: a hydrogen atom covalently bonds to a highly electronegative atom, such as nitrogen, oxygen, or fluorine. Under these conditions, the hydrogen atom shows a significant electron deficiency because the electronegative atom captures nearly all of the hydrogen's electron density. This occurs because the covalent bond is formed by a bonding (sigma) orbital with an energy very close to the 2p atomic orbital of the electronegative atom. Specifically, in nitrogenous bases, the electronegative atoms involved are nitrogen and oxygen. The H atoms, which have a strong electron deficiency, interact strongly with atoms that have high electron density, such as the N and O atoms of other molecules. The covalent bond remains, but a second, roughly ten times weaker, (hydrogen) bond forms between the strongly electron-deficient hydrogen and a high-electron-density N or O atom of another molecule because of this interaction. This interaction is known as a hydrogen bond, and it can only occur due to quantum mechanical effects.

The high reliability of DNA polymerase pairing is attributed to the properties of hydrogen bonding. However, a few errors may occur due to proton tunneling, which is related to statistical fluctuations. The reliability of DNA polymerase III is crucial for DNA replication and the maintenance of genetic information in living organisms. If reliability were lower, DNA-based life could become unstable, and other mechanisms might develop due to the potential pressure from the emergence of life, or even worse, life might never have arisen. Conversely, if reliability were higher than usual, variation between specimens would likely be minimal, and the emergence of new species could be much slower than observed, or even nonexistent, which would prevent the emergence of new species and inhibit evolution.

Finally, the process by which nature creates these DNA and RNA structures, which store information about living organisms, remains a mystery. Overall, we still lack a comprehensive understanding of the origin of life, particularly the early stages of biogenesis; however, it certainly began with the principles of quantum mechanics, as outlined by the uncertainty principle. Faced with significant doubts, we could conclude that the cell is a quantum of life.

- The term macroscopic here refers to the physical sense, where direct quantum effects would be very tenuous or barely observable, meaning anything larger than fractions of a micrometer. We will use the term "microscopic" to describe the subnanometer scale of atoms and molecules, rather than the micrometer scale commonly used in biology.