Quantum biology can be defined as the study of the application of the laws of quantum physics to those aspects of biology that cannot be fully described by the laws of classical physics. Many known biological processes are based on the transformation of energy to produce chemical reactions and these have been found to be quantum in nature. It is a general belief that the laws of classical physics are the foundation of the description of the macroscopic world in which we live. To give an example, the laws of classical motion are useful for calculating the orbits of planets around the sun or the orbits of satellites that revolve around the earth but they do not work on an atomic scale. At this scale of the infinitely small, the laws of quantum mechanics apply, with all their apparent idiosyncrasies. In general, most researchers believe that quantum effects only occur if the system we are studying operates at atomic scales or at temperatures close to absolute zero. On larger scales and temperatures, the world of our senses, the world that surrounds us, can be described using the laws of classical mechanics. Recent remarkable results in black hole quantum physics have shown that this is not exactly the case, but that quantum corrections to classical general relativity may be necessary not at the infinitesimal Planck scale, as it was commonly believed, but at the horizon scale [1-5], which for most black holes is a macroscopic scale (e.g., kilometers for stellar-mass black holes, even larger for black holes with a larger mass). It would therefore seem that quantum mechanics becomes necessary not only in the world of the infinitely small, but, more generally, at high energies even in the macroscopic world. The quantum world is governed by a series of laws whose consequences contradict our logic, they may seem absurd to us. Einstein himself has constantly had a very critical and even conflictual relationship with the assumptions of quantum mechanics, for example he has never been able to digest entanglement and to understand the reason for such hostility it is useful to describe it. Entanglement is a quantum phenomenon in which two or more particles or energy states can become intrinsically correlated so that the state of one simultaneously influences the state of the other, regardless of the distance at which they are located. All this conflicts with Einstein's theory of special relativity which postulates that nothing can exceed the speed of light and therefore true "instantaneousness" does not exist. To put it simply, two "correlated" particles, one of which is on Earth and the other in the Andromeda Galaxy, can communicate simultaneously thanks to entanglement without waiting the 2.5 million years or so that photons of light, the fastest signal we know, would take to bridge the distance!

Quantum tunneling can be described as the phenomenon whereby a particle, under certain conditions, can overcome a potential barrier even though, according to classical physics, it does not have enough energy to do so. To make an analogy, it is as if it were possible to kick a ball over a wall even though it has not given it enough push to be able to overcome it and therefore fall on the other side. In short, according to quantum physics, the ball can pass through the wall. This behavior is related to the Heisenberg uncertainty principle which states that we cannot simultaneously know precisely the position and momentum (velocity) of a particle. This uncertainty is fundamental and represents an intrinsic limitation to the precision with which we can "measure" the subatomic world. In our case, this principle can lead to the disappearance of a quantum particle at a precise position and its reappearance nearby and allows us to have an explanation for bizarre and counterintuitive phenomena. Quantum tunneling is fundamental in several biological processes, such as genetic mutations, enzymatic reactions and electron transport. In fact, "quantum biology" as a new field of study emerged when the Swedish chemist and physicist Per-Olov Lowdin proposed the idea of the quantum mechanical tunneling effect as an explanatory mechanism for mutations in DNA [6]. Recently, it has been discovered that hydrogen atoms, the glue that holds the two strands of the DNA double helix together, can, because of the famous de Broglie hypothesis [7], behave like waves and therefore exist in more than one position at the same time. This means that these atoms can occasionally find themselves on the wrong side of the DNA strand, leading to the appearance of mutations. Although these tunnel effects are extremely short-lived, it is likely that, during the process of DNA replication, they persist long enough for them to produce genetic alterations. This phenomenon was recently demonstrated in a study by researchers at the Leverhulme Quantum Biology Doctoral Training Centre at the University of Surrey [8]. Since it is an intramolecular transfer process, it therefore takes place on a larger, macroscopic, scale than "traditional" quantum mechanics, which focuses mainly on systems at the atomic and subatomic level. Quantum physics also has a major impact on photosynthesis. The latter is a biological process that allows photosynthetic cells in plants to synthesize organic compounds from inorganic materials using sunlight as an energy source. The most surprising feature of this process is its extreme efficiency. It is known that the quantum effects involved allow the highest efficiency of all known natural or artificial reactions to be achieved: close to 100%.

It is important to recall that the basis of our current understanding of the interaction between light and matter is the interpretation of the photoelectric effect, due to Albert Einstein in 1905 [9]. The photoelectric effect is a phenomenon in which electrons are emitted from a material when struck by light. Einstein proposed that light was composed of particles of energy called photons, and that each photon could transfer its energy to a single electron. This explanation, based on Max Planck's 1900 idea of energy quanta [10], effectively laid the foundation for quantum dynamics. In fact, Einstein won the Nobel Prize in Physics in 1921 not for his celebrated theory of relativity, but for his interpretation of the photoelectric effect. Before Einstein, classical physics could not indeed explain why the energy of emitted electrons depended on the frequency of light and not on its intensity. Einstein's hypothesis of the photoelectric effect brought a profound understanding of the dual nature of light, which behaves both as a wave and as a particle according to the aforementioned de Broglie hypothesis [7]. Returning to photosynthesis, in the complex chain of events that it is constituted by, there is a quantum element in the stage of reaction to light which turns out to be the very first step. Photosynthesis is in fact fueled by the smallest amount of energy possible: that of the photon, the single quantum of visible light [11]. The individual photons at the basis of the process are captured by photosynthetic pigments and converted into excitons, or energy quanta, which are extremely unstable. It should be recalled that a quantum is the fundamental unit of measurement of some physical quantities, such as energy or spin, in this case an amount of energy. This energy must be transferred to specific molecular structures called reaction centers where actual chemical stacks are created that are much more stable than an exciton. This energy transfer must occur at an extreme speed to prevent it from dissipating. For an exciton, a reaction center can be very distant in molecular terms and therefore it must choose the shortest route through the photosynthetic material to reach it. Even in this case, the process takes place on a larger, macroscopic, scale than "traditional" quantum mechanics. It is known that in nature this transfer occurs extraordinarily efficiently, almost 100%. This is the highest efficiency of all natural or artificial reactions that we know of and it has always been a mystery how this is possible. At this point it is necessary to introduce the concept of quantum superposition which is a principle that describes the possibility that a quantum system can exist simultaneously in multiple distinct states. In other words, while in classical physics an object is in a well-defined state, in quantum physics an object can be in a superposition of states. Recall that in physics the "state" of a particle consists of all the information that can describe it completely at a given moment. In quantum mechanics the state of a particle is described by a wave function that contains information on the probabilities of finding the particle in different positions or with different physical properties. Regarding the exciton, the choice of the most efficient path to reach the reaction center can be made because the energy in the excitons resides in two states at the same time, according to a superposition state and this allows them to simultaneously explore the possible paths to the reaction centers, thus optimizing the overall efficiency of the phenomenon. Then, the aforementioned quantum entanglement (between the two cited states) plays a fundamental role in the transfer of energy in plants during photosynthesis, making the process more efficient. It should be emphasized, however, that, to date, not all researchers support this interpretation of the role of quantum biology in photosynthesis, but the fact remains that in several experiments strong evidence has been observed to support this hypothesis. Quantum biology also helps explain the fascinating effect of robin migration. In general, the system used by birds to orient themselves has been a mystery for a long time. Now we know that they use a fair number of different methods: some use terrestrial landmarks, others the position of the Sun during the day and that of the stars at night, others follow their sense of smell and therefore smell the path they must follow. In some species, orientation can be learned by young individuals by following adults during migrations. This allows the transmission of migratory routes between generations. The robins, however, are a special case, perhaps the most intriguing of all. Robins have indeed the ability to detect the direction and intensity of the Earth's magnetic field and therefore to work out the route to follow using a kind of chemical compass [12]. It should be recalled that the Earth's magnetic field is extremely weak and is therefore very difficult to measure. Robins usually migrate from northern Europe to northern Africa and it has been experimentally demonstrated that they lose their ability to orient themselves if they are blindfolded. Thus, light (photons) plays a fundamental role in this phenomenon. After a long and complex history of research and experimentation, it was discovered that robins use magnetoreception, the ability that several animals have to perceive the Earth's magnetic field, especially to orient themselves. Today, two types of magnetoreception are known: the first is based on the use of a ferrous magnetic mineral, magnetite, which creates a kind of compass that orients itself with respect to the North-South axis exactly like the compasses of our common experience. The second type is not sensitive to the North-South axis and consequently does not discriminate between the two poles but rather is able to measure at a given point the angle between the Earth's magnetic field and the horizontal plane. This angle goes from being 90{^ } at the poles to 0{^ } at the Equator. The mechanism underlying this type of magnetoreception, present in the robin, is very complex and was discovered gradually on the basis of slow experimental progress and intuitions related to quantum physics. This mechanism involves cryptochromes, flavoproteins present in the retina of the eye of numerous animals, and is dependent on light. At the basis of this "sensor-compass" there are quantum phenomena that allow it to perceive variations in the Earth's magnetic field whose intensity, one recalls, is very low. At the origin of everything there is a chemical reaction that produces pairs of free radicals. Free radicals are highly reactive chemical species that contain at least one unpaired electron in the external orbitals. Electrons are normally found in pairs, but free radicals have a lone electron, which makes them unstable and ready to react with other chemical substances. These electrons are subject to quantum superposition and therefore their state is very unstable and, above all, they are sensitive to an external magnetic field. The stimulation of this compass occurs through photons of light which trigger the subsequent processes necessary for its functioning and this explains its location in the robin's eye. The interesting thing about this mechanism is that it is sensitive to specific oscillation frequencies of the magnetic field, which makes it selective and not influenced by other magnetic fields, however intense. Note that, since free radicals are molecules, also this process occurs on a larger distance scale than "traditional" quantum mechanics which operates on atomic and subatomic scales. More generally, a large number of fundamental biological processes are influenced by weak magnetic fields. The development and maturation of stem cells, cell proliferation rates, and the repair of genetic material are examples of phenomena influenced by this interaction. To delve deeper into this discussion, it is necessary to introduce the concept of spin. The spin of a particle, first hypothesized by Wolfgang Pauli in 1925 and then generalized by Pauli himself in 1940 with the spin-statistics theorem [13], is a quantum property of particles. In the case of electrons it is added to their two other main properties: relatively small mass and negative electric charge. Just as electric charge defines how electrons interact with an electric field, so spin defines their interaction with a magnetic field. Nuclear Magnetic Resonance (NMR) is an imaging technique of fundamental importance in medicine. NMR exploits the fact that the application of an external magnetic field to our body causes the spins of the atomic nuclei to orient themselves parallel or antiparallel to it and the difference between these two energy states (parallel or not) is quantized and this is the basis of the images one sees. Some of the quantum experiments currently underway aim to apply weak magnetic fields to change the spins of particular electrons. The responses to magnetic fields observed in physiology are produced by chemical reactions that, in turn, depend on the spins of specific electrons within molecules. Applying a weak magnetic field to change the spins of electrons can therefore effectively control the end products of a chemical reaction, with important physiological consequences. Applying a weak magnetic field capable of changing the spins of electrons can therefore effectively control the end products of a chemical reaction, with important biological consequences. At the current state of research, it is not known exactly how these processes work and therefore it is not possible to determine exactly how to correlate the variations of magnetic fields with specific chemical reactions in cells, but when a mathematical model will be created that will allow us to correlate quantum causes to their respective physiological results, we will have a quantum biology tool whose uses are practically infinite. In the future, these technologies will allow us to develop non-invasive and remotely controlled medical therapeutic devices, even via a smartphone or perhaps a smartwatch. These devices could potentially be used to prevent and treat a wide range of pathologies, including neoplasms. It is safe to say that quantum biology is one of the most interdisciplinary fields ever to emerge. At Oak Ridge National Laboratory (ORNL) [14], researchers are using quantum biology, artificial intelligence and bio-engineering to improve the performance of CRISPR/Cas9, a tool used to modify the genetic code of an organism. CRISPR/Cas9 is based on the use of the Cas9 protein which is similar to a molecular scissors capable of cutting a target DNA thus obtaining specific modifications to the genome of a cell. These studies are aimed at the production of microorganisms capable of producing renewable fuels. ORNL researchers have used quantum biology to better understand the biophysical dynamics that occur at the elementary level in the nuclei of cells, where the genetic material is stored. This is an innovative approach to understanding the effects that the electronic structure can have on the chemical properties and interactions of the nucleotides of DNA and RNA. The unique computing power needed to run AI models related to quantum biology will soon be offered by quantum computers. This type of computer, currently still experimental, is characterized by the fact that information is encoded inside them using quantum objects. We will have quantum computing, no longer based on bits, elementary units of information that can only assume two values (0 or 1) but on quantum bits (qubits). Qubits are carried by subatomic particles (photons, electrons, etc.) that can represent the value 0, 1 or a combination of both, in a state called superposition. As if that were not enough, the state of qbits can be represented by other quantum properties such as interference and entanglement. It is interesting to note that, in order to exploit these properties, the quantum chip must be able to operate at temperatures very close to absolute 0 (0 degrees Kelvin corresponds to -273.15,C{ˆ}). In fact, these processors operate at temperatures lower than those found in outer space, which is approximately 3K (-270.15,C{ˆ}). So, what are the major insights and ideas that emerge from what has been discussed in this Essay? Quantum biology studies the application of quantum mechanics to biological systems at the macroscopic level, that is, at dimensions that are not typically associated with traditional quantum phenomena, which are typical of the atomic or subatomic scale. In practice, one seeks to understand whether and how the principles of quantum mechanics, which normally manifest themselves in the world of the infinitely small, can influence or be relevant to biological processes on a larger scale. It would seem, therefore, that the yardstick for measuring the applicability of quantum theory should not be based on a length scale that leads us to believe that the quantum world is exclusively the world of the infinitely small, but, rather, should be based on an energy scale for which quantum corrections to classical theory are required in the presence of high energies. This new interpretation of the limits of applicability of classical theory and the consequent need for quantum corrections at high energies could lead to an extraordinary paradigm shift in theoretical physics. An indication that this might indeed be the right path comes from some recent remarkable results in black hole physics. Here we will consider two cases:

1. The fuzzball hypothesis was originally proposed by Indian physicist S. Mathur in 2009 [2], with the intent to provide a fully quantum description of the black holes. According to the fuzzball paradigm, the entire region inside the event horizon of the black hole would actually be an extended object: a ball of strings. This is in full agreement with String Theory which considers strings to be the fundamental building blocks of matter and light. It is hypothesized that fuzzballs should be the terminal phase of degenerate matter. The physical surfaces of fuzzballs should have radii equal to that of the event horizon of classic black holes. In this way, fuzzballs would solve the famous problem of the singularity present in the core of the black hole as well as the famous paradox of the information lost by the black hole made famous by S. Hawking [15]. The fuzzball hypothesis therefore predicts that black holes are extended spherical objects with a defined volume and composed of strings. In this it differs from the classical view of black holes due to general relativity, in which at the center there is a singularity surrounded at a certain distance (connected to the mass of the hole) by an event horizon below which even light cannot escape. At distances greater than the radius of the fuzzball, the classical theory and the fuzzball paradigm are thought to coincide. The two theories diverge only at the horizon scale. Classical black holes and fuzzballs differ only in their internal composition and in the way they affect virtual particles that form near the horizon. For his achievements on fuzzballs, Mathur has received several awards from the Gravity Research Foundation, including a First Prize in 2021 [3].

2. Following an original idea by Hawking [16], the Spanish researcher C. Vaz has analyzed with quantum theory the inhomogeneous LeMaitre-Tolman-Bondi gravitational collapse of dust. This allowed him to win Second Prize at the 2014 Gravity Research Foundation Competition [1] as he found that quantum collapse does not lead to the formation of a real horizon and a singularity, but to an apparent horizon onto which all the collapsing matter condenses to form a thin, very dense spherical shell. This second approach would also solve both the problem of the singularity present in the core of the black hole as well as the black hole information lost paradox. Remarkably, Vaz's result was consistent with Einstein's original idea from way back in 1939, of the localization of the collapsing particles within a thin spherical shell [17]. Later, the Italian physicist C. Corda took up Vaz's approach again, showing that a similar result could be obtained starting from the historic and very famous Oppenheimer and Snyder gravitational collapse [4] and furthermore that these spherical shells found by Einstein and Vaz are highly excited quantum states that obey the Schrodinger equation in the non-relativistic regime [4, 18] and the Klein-Gordon equation in the relativistic regime [18]. These highly excited quantum states representing the quantum black hole have a mathematical structure analogous to the s-states of the hydrogen atom [4, 18]. Here again one can invoke the de Broglie hypothesis to interpret these thin and very dense spherical shells subject to quantum oscillations in terms of a particle "rotating" around a central field like the electron "rotating" around the hydrogen atom. The verb rotate is put in

quotation marks here because it is necessary to remember what is the meaning of the word “particle” in quantum theory. In a quantum framework, within the tiny confines of this “gravitational atom”, the “electron” cannot really be regarded as a “point-like particle” having a definite energy and location. So the “oscillating shell-particle” should not be interpreted as if it were a planet orbiting the sun, but rather as a sort of standing wave representing a large and often oddly shaped “atmosphere” (the black hole “electron”), which results distributed around a central field (the black hole “nucleus”).

Both approaches show how quantum corrections to classical general relativity become important not, as is generally believed, at the infinitesimal Planck scale, i.e. at lengths of the order of 10^{-35} meters, but, rather, at the horizon scale, which, as previously emphasized for most black holes is a macroscopic scale (e.g., kilometers for stellar-mass black holes, even larger for black holes with a larger mass). The two scales, the Planck scale and the horizon scale, coincide only for black holes with masses of the order of the Planck mass. The importance of quantum black holes is due to the fact that they are considered “theoretical laboratories” where to test the various models of quantum gravity. They are considered the “atoms of the 21st century” as they should be the founding bricks of quantum gravity similarly to how, in the 20s of the 20th century, atoms were the fundamental constituents of quantum mechanics. The main message here is, therefore, that, as it is shown both by important results in quantum biology and in quantum gravity, the domain of quantum theory is not actually limited to the world of the infinitely small, that is, to the atomic and subatomic scales, but seems to extend also to the macroscopic scales where high energies come into play. Clearly, we are just beginning to understand this important issue, which, if corrected, could have a fundamental importance both in the physics of the present and in that of the future, eventually leading to a paradigm shift and, perhaps even to that unification of physics, the final dream of all scientists since Einstein.