FROM STRINGS TO LOOPS: A JOURNEY THROUGH MODERN PHYSICS'S BIGGEST QUESTIONS

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Abstract: This article introduces post-quantum models–advanced theories that aim to bridge the gap between quantum mechanics and general relativity, two of physics' most groundbreaking yet unaligned frameworks. It explores key theories like string theory, which suggests that the universe's fundamental building blocks are vibrating strings, and loop quantum gravity, proposing that spacetime itself is made up of tiny, discrete loops. Additionally, non-linear quantum mechanics and the holographic principle are discussed, providing insights into the nature of black holes, dark matter, and the structure of spacetime at the quantum level. These theories not only offer potential solutions to the mysteries of the cosmos but also hold practical applications in fields like quantum computing and information theory. This article is an attempt to provide an accessible yet intellectually stimulating journey through some of the most cutting–edge ideas in modern physics, challenging readers to expand their understanding of the universe's fundamental nature.

Keywords: Post–quantum models; Quantum mechanics; String theory; Black holes

1. Introduction

In the attempt to explain how our universe operates at the most basic level, modern physics has given us quantum mechanics and general relativity as only two tools. These two pillars have changed our approach to studying nature, but they still do not work together well, especially in conditions as extreme as that found inside a black hole or during the Big Bang. Quantum mechanics controls the workings of particles too small to reveal. At the same time, general relativity determines the behavior of the expansive universe, but the two theories have not been put together yet. This quest for a theory of everything has led to the advancement of models beyond quantum mechanics models, and models beyond quantum mechanics are known as post-quantum models.

Metaphysical theories in post-quantum science seek to go beyond the frameworks of current theories, addressing unsolved problems and working beyond the surface layers of the universe. Susumu Okubo, a scientist at the Perimeter Institute for Theoretical Physics,

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said one of the leading contenders is named string theory, which is based on the idea that the building blocks of the universe are small and vibrating strings rather than points. This model's purpose is to explain all elemental forces right from gravity in one conceptual structure. In the same way, loop quantum gravity (LQG) suggests that spacetime is not smooth proceeding from a continuous, but is made up of discrete 'loops'. These two theories represent different approaches to solving the same fundamental issue: the theory referred to as the quantum theory of gravity or joining quantum mechanics and general relativity. Other methods include non–linear quantum mechanics, which introduces non–linear dynamics into what is an otherwise a linear quantum math equation, as well as the Deformed Heisenberg Uncertainties, which provide an amendment to the uncertainties principles with respect to extreme situations or maybe brand new types of quantum mechanics altogether [1-5].

They have been built with the goal to answer fundamental questions, a number of them: What is dark matter? How do black holes behave? What do the tiniest spaces and time look like? These theories also offer new approaches to the long-standing problems of quantum gravity, the integration of forces in nature, and that of other dimensions in space. They extend their possibilities beyond theory, as the application of quantum mechanics might radically change very practical spheres of life, including, for instance, quantum computing or quantum information theory.

In the post-quantum world, we also get a host of new possibilities for new forms of qubits that operate in higher dimensional realms, better and more efficient quantum entanglement, and concepts of atomic stability and nuclear decay can be viewed in an entirely new light. These breakthroughs could offer things like ultra-secure means of quantum communication and an unprecedented level of computational capability in quantum systems. In addition to the technological advantages, post-quantum models might classify some of the most challenging phenomena in the universe – from dark matter to black hole formation and behavior.

When new physics is discovered, post-quantum theories are the next possibility to revolutionize physics, redefine the fundamental laws of the universe, and innovate with technologies to revolutionize society. These theories have the potential to fill the gap between quantum mechanics and general relativity as the theory's questions increase the horizon of current knowledge.

This manuscript is an attempt to write an overview for a general reader of post-quantum theories aimed at reconciling quantum mechanics with general relativity, a central challenge in theoretical physics. Being intended as a popular science writeup, complex mathematics is avoided. It explores various advanced models, including string theory, LQG, and non–linear quantum mechanics, to address fundamental questions such as the nature of dark matter, black holes, and the structure of spacetime at quantum levels. The discussion

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on emergent phenomena and holography adds a critical dimension by linking quantum gravity theories to broader implications for cosmology and particle physics. This work highlights both the theoretical foundations and potential practical applications in quantum computing, information theory, and high–energy physics, contributing to an evolving narrative in the search for a unified framework of physical laws.

2. Theoretical foundations for post-quantum models quantum gravity theories

2.1. String theory

String theory proposes that the universe's fundamental components are not particles like electrons but tiny, vibrating strings akin to microscopic wiggling rubber bands. It serves as a leading candidate for a theory of quantum gravity, seeking to reconcile gravity with quantum mechanics–two fundamental theories in physics that have remained difficult to unify. Additionally, string theory concepts have been used to address problems in mathematics and other areas of theoretical physics [1].

String theory emerged by accident in 1969 when physicist Gabriele Veneziano (Figure 1) formulated the Veneziano amplitude to describe the scattering of particles like protons and neutrons.[2] This work unexpectedly laid the foundation for string theory. Over the next few decades, researchers expanded on Veneziano's initial work, gradually constructing the theory's whole framework. Despite these efforts, no experiment has conclusively established string theory as the definitive theory of nature, though it has passed many theoretical and mathematical tests over the last fifty years.

Figure 1. Gabriele Veneziano, pioneer of string theory and developer of the veneziano amplitude, a foundational element in theoretical physics[1]

The progress in fundamental physics often unfolds over long periods. For example, gravitational waves predicted by Einstein in 1915 were only confirmed in 2015 by the LIGO experiment. Similarly, future experiments in particle physics, gravitational wave observations, or cosmological measurements may offer conclusive evidence for or against string theory. The theory suggests that space-time consists of ten dimensions, while our observable universe has four (three spatial dimensions and one–time dimension). To reconcile this, string theory proposes that six additional dimensions are compactified or curled up, making them detectable only through extremely high–precision experiments, such as those at the Large Hadron Collider.

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[1] Picture from Wikipedia, the free encyclopedia https://en.wikipedia.org/wiki/Gabriele_Veneziano

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String theory describes how forces typically observed on large scales, like gravity, might interact with tiny objects, such as electrons and protons. In Einstein's general relativity, gravity is a force that curves space-time around massive objects and is one of the four fundamental forces, alongside electromagnetism, the strong force, and the weak force. However, gravity is extremely weak at the particle level, noticeable only at much larger scales like those of planets and stars. Furthermore, gravity does not appear to exist as a particle, and attempts to calculate the effects of gravitational particles (gravitons) result in infinities, suggesting a mathematical inconsistency.

To address these issues, theorists in the 1970s adopted ideas from nuclear physics, proposing that strings, rather than point-like gravitons, could resolve the infinities and provide a consistent framework. Marika Taylor, a physicist, noted that "a–one-dimensional object – that's the thing that really tames the infinities that come up in the calculations".

String theory replaces all matter and force particles with tiny vibrating strings, which appear as different particles depending on their vibrational patterns. For example, a string vibrating at a specific frequency might behave like a photon, while another vibrating differently might represent a quark. Initially, this approach seemed promising for explaining constants like the electron's mass. However, it required ten dimensions instead of the four familiar ones. The extra six dimensions would only be visible from the strings' perspective, similar to how a powerline appears as a one-dimensional line to a distant bird but a three–dimensional object to an ant crawling on it.

String theory has evolved since the 1960s and 1970s, and researchers debate whether it remains the best candidate for a "theory of everything" or whether alternative frameworks should be pursued. Physicist John Schwarz noted that by the mid–1970s, many reasons existed to abandon string theory as interest shifted toward hadrons–particles made of quarks that strings could not explain. Consequently, string theory research saw a decline [3].

A small group of scientists continued exploring string theory, developing five different versions over the following decade. Connections between these versions led Edward Witten to suggest they were approximations of a more fundamental 11–11-dimensional theory, later called M–M-theory. The "M" might refer to higher–dimensional objects called membranes, but its exact meaning remains undefined. Taylor explained that this was "a parametrization of our ignorance."

While attempts to develop a comprehensive equation for all situations have made limited progress, the idea of a fundamental theory has driven the development of mathematical techniques applicable to different contexts. Though strings are too small to detect with current technology, string theory successfully described black hole entropy in a 1996 paper. Entropy measures the number of possible arrangements within a system. In the early 1970s, Stephen Hawking and others used thermodynamics and quantum mechanics to estimate black hole entropy, implying an internal structure. String theory provided a precise count of these possible configurations, suggesting an explanation for black hole interiors.

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Despite its successes, string theory faces challenges. It offers countless ways to compactify the extra dimensions, all consistent with the Standard Model of particle physics, making it challenging to identify the correct model. Furthermore, many of these models depend on supersymmetry–an equivalence between force and matter particles–which has not been observed in experiments.

It is uncertain whether string theory, including M–theory, aligns with our understanding of the expanding universe and dark energy. Critics, such as Peter Woit, argue that the lack of empirical support is a significant flaw. However, others, like Taylor, believe that future versions of string theory may incorporate currently unexplained features, such as cosmological expansion or the absence of supersymmetry.

While gravitational–wave astronomy may provide new insights into quantum gravity, Taylor believes that progress in understanding string theory will primarily come from deeper mathematical exploration: "I think the kind of breakthrough I'm describing would come from a chalkboard, from thought" [4, 5].

2.2. Loop quantum gravity (LQG)

LQG primarily describes a framework for general relativity that incorporates elementary particles through quantum mechanics. It seeks to address one of the most important questions of fundamental physics: how can the graviton, described by Einstein's general relativity, exist together with the three forces of nature incorporated in quantum mechanics? In contrast to string theory, which is concerned with the unification of all known forces and particles into a single theoretical framework, the main emphasis of LQG is retained quantum aspects of the spacetime [6].

General relativity must be an approximation to something new at the minor scales (e.g., in the center of black holes or during the Big Bang, universe space expansion Figure 2) where it fails; the need for a quantum theory of gravity illustrates this insight. In these areas, the effect of gravity is so intense that quantum effects can no longer be neglected. Quantum gravity theories, which try to combine general relativity and quantum mechanics at the quantum level, differ wildly in such high–energy domains.

General relativity treats spacetime as a continuous manifold that can be caused to curve by mass and energy. This contrasts with the other fundamental theory of physics: quantum mechanics. Quantum mechanics represents physical entities using particle-like units (quanta) but is generally in singular disrepute among relativists. LQG arises from this idea, suggesting that spacetime is not a smooth continuum but built up of minuscule discrete pieces or loops.

At the core of LQG is the concept that space is actually made out of loops, similar to a fabric woven with many separate threads. This network of loops is indeed a spin network, which is a mathematical representation of the quantum states of the gravitational field.

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Crucially, however, these networks are quantized: space has the smallest possible size, which cannot be divided below. This is a strongly non–local way to think about spacetime – as elements of the universe that can be used between regions of different sizes, not just infinitely divisible space–points.

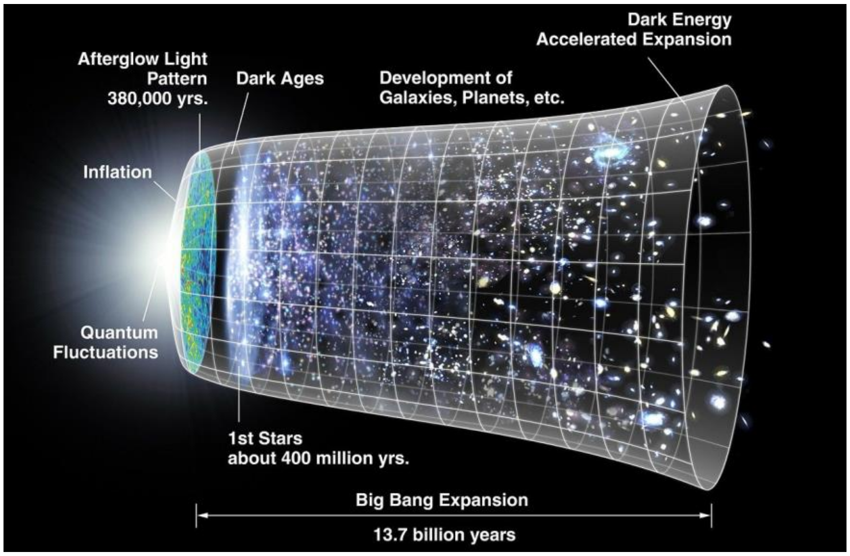

Figure 2. Universe space expansion[2]

Loops of this much more basic kind are combined – and the space is then built up from such loops; the geometry of spacetime will be realized as a web of these loop–like structures connected, with each connection being "a quantum" of space. This theory amounts to a quantization of space by giving these loops an area and a volume (not unlike the discretized energy levels of particles in quantum mechanics). The quantization of space is one of the deepest hints from LQG.

LQG uses two central mathematical tools to describe the quantum nature of space: spin networks and spin foams.

1. Spin networks. These are graphs made of nodes and links that represent the quantum states of the gravitational field. Each link represents a quantum of space, and the nodes where the links meet represent quanta of volume. Spin networks are static structures that provide a snapshot of the quantum geometry of space at a given moment.

2. Spin foams. While spin networks represent space, spin foams represent their evolution through time. Spin foams are essentially a way of describing how spin networks evolve, providing a bridge between quantum states of geometry at different times. They describe the dynamics of spacetime and offer a way to model how the fabric of spacetime changes at the quantum level.

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[2] Figure is original work of WikiImages, available at Pinterest. Please consider supporting this author by visiting the following link https://pixabay.com/illustrations/universe-space-expansion-big-bang-11636/

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One of the groundbreaking implications of LQG is the quantization of both space and time. According to the theory, there is the smallest possible unit of space (often referred to as the Planck length) and the smallest possible unit of time (the Planck time). This contrasts with classical physics, where space and time are continuous and can be divided infinitely. In LQG, the discrete nature of spacetime leads to the idea that the geometry of the universe is granular. This granularity means that spacetime is not smooth but instead composed of finite, indivisible "atoms" of space and time. The quantization prevents the occurrence of singularities, such as the infinite density predicted by general relativity at the center of black holes or the Big Bang. In LQG, these singularities are replaced by finite quantum states, suggesting that the universe may have a more complex structure than previously thought.

LQG has significant implications for some of the most perplexing phenomena in the universe, such as black holes and the Big Bang. One of LQG's important achievements is the resolution of the singularity problem. In classical general relativity, black holes contain singularities–points where the spacetime curvature becomes infinite, and the laws of physics break down. Similarly, the Big Bang is thought to have started from a singularity, where all matter and energy were concentrated into an infinitely dense point.

In LQG, however, the quantized nature of spacetime means that these singularities are avoided. Instead of an infinitely dense point, the center of a black hole or the beginning of the universe is described by a quantum state of spacetime. For example, in the case of black holes, LQG suggests that the core of a black hole may not collapse into a singularity but instead form a highly dense quantum state, possibly leading to a "bounce," where the black hole transitions into another phase or universe.

Likewise, the Big Bang may not have been the beginning of time but rather a "bounce" from a previous contracting phase of the universe. This idea is often referred to as the "Big Bounce" model, in which the universe undergoes cycles of expansion and contraction, with LQG providing the mathematical framework to describe these transitions.

Despite its promising features, LQG faces several challenges. One of the main difficulties is the lack of experimental evidence. While LQG provides a mathematically consistent framework for quantum gravity, it has yet to make concrete predictions that experiments or observations can test. This challenge is shared with other quantum gravity theories, such as string theory, as the scales at which quantum gravitational effects become significant are far beyond the reach of current technology.

Moreover, the complexity of the mathematics involved in LQG makes it challenging to apply the theory to many practical problems in physics. The theory also does not naturally include the other forces of nature (such as electromagnetism or the strong and weak nuclear forces), which means that it cannot yet be considered a complete theory of everything.

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However, LQG remains an active area of research, with ongoing efforts to develop the theory further and find ways to test its predictions. Some theorists are exploring potential connections between LQG and other areas of physics, such as cosmology, quantum field theory, and black hole thermodynamics.

LQG offers a unique and compelling approach to the problem of quantum gravity. By quantizing spacetime itself, LQG challenges the traditional view of space and time as continuous entities and provides new insights into the structure of the universe at the most minor scales. While still a developing theory, LQG has already produced critical conceptual advances, particularly in its treatment of black holes and the Big Bang.

As the search for a quantum theory of gravity continues, LQG stands as one of the leading contenders, offering a novel way to understand the fabric of spacetime and the nature of the universe. Whether it will ultimately succeed in providing a complete description of quantum gravity remains to be seen, but its contributions to our understanding of the quantum nature of spacetime have already had a profound impact on the field of theoretical physics [7].

2.3. Non–linear quantum mechanics

Nonetheless, quantum mechanics, at its heart, is a very effective theory that accounts for the motion and interaction of matter and energy in the micro–world from particles to atoms and molecules. One of its axioms is linearity which is inbuilt in the Schrödinger equation of fame. This linearity is necessary for the calculation of the superposition states, which are the basis of most of the quantum effects, such as interference, correlation, and collapse. However, there have been few proposals and discussions on the possible change of this straight structure, which led to what is referred to as non–linear quantum mechanics.

Non–linear quantum mechanics is the generalization of the linear quantum mechanics model, in which non–linear considerations have been added. Depending on the type of quantum mechanics used, linear and the Schrödinger is linear in terms of the wave function and non–linear quantum mechanics, and the Schrödinger is non–linear in terms of the wave function. This non–linearity results from the interaction of quantum systems, which produces quantum chaos, quantum solitons, and non–linear quantum phase transforms. Possible use of non-linear quantum mechanics is found in experiences where linear quantum mechanics may not be adequate, for instance, in superconductivity, superfluidity, and quantum gravity.

It is therefore argued that while quantum mechanics (DM), presents a strictly linear framework, hence amenable to linear algebra even in its manifestation of wave particle dualism, this reality and nonlinear phenomena can be reconciled by ascribing to emergent behavior. Even though quantum mechanics is linear on its base level involving the fundamental equations of a quantum system, the composed systems of several quantum systems or the dynamic of many particles does not result in linear phenomena.

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On the microscopic level, the time evolution of quantum mechanical systems is described using linear Schrodinger equations. Yet, suppose the interaction is put together, and the quantum systems participate in this interaction. In that case, it does not necessarily mean that the system of behavior that coincides with the participation of several quantum systems will depict a linearity of the same degree. This is so due to complex entangling, coherency, and interactive feedback that come with the operations of many Quantum entities at once.

For instance, in condensed matter physics, for example, the movement of electrons in a solid where specific physical properties can be exhibited, such as superconductivity, which shows nonlinear transport characteristics. Likewise, in quantum optics, with reference to Electromagnetic interaction, valid when light is close to a material medium, and its behavior induces changes in the atomic or molecular systems, this paper confirms that new optical phenomena such as optical bistability and self–focusing can occur from the complex relativity.

Moreover, any measurement and observation in quantum mechanics can also be a source of non–linearity. Measuring or attempting to obtain information about a quantum system forces the wavefunction of a system, which makes it a non–linear operation, to collapse, thus interrupting the system's linear flow.

The apparent contradiction between quantum mechanics' linearity and the observation of non–linear phenomena is resolved by the recognition that the collective and emergent behaviors of complex quantum systems can give rise to non–linear effects despite the underlying linear nature of the fundamental quantum mechanical equations [8].

2.4. Extended theories of quantum dynamics

Deformed Heisenberg uncertainties refer to the introduction of modifications in the conventional Heisenberg uncertainty in quantum mechanics through a mathematical formula. The uncertainty principle, as postulated by Werner Heisenberg, states that it is impossible to know both the position of a particle and its momentum accurately at the same time. Non-zero deformations shift this limit by means of covariance for the uncertainties of positions and momenta. It has been studied in order to understand such effects as quantum noise, mesoscale, and some intrinsic components of quantum mechanics. Researchers employ the deformed uncertainties to develop new theories and models suitable for various fields.

Heisenberg's Uncertainty Principle applies effectively in the study of atomic energy spectra and characteristics of particles in high energies or at lower scales. In these domains of the quantum world, the particle's dual wave-particle duality is observed where the exact measurement of the position (or energy) of the particle limits the possible range of momentum and vice versa. The principle states that the product of uncertainty in energy

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(ΔE) and time (Δt) must be larger or equal to a specific value ($h/4\pi$). This sets an intrinsic constraint on the joint measurement of energy and time, thus leading to fluctuations and nonclassical behavior in the spectra of atoms and particles as well as their interactions.[9,10]

2.5. Emergent phenomena and holography

A brief look at the meaning of emergent space-time highlights a vast complex of new and unique ideas and theories in the context of space-time relations, which cuts across science domains within the physical, mathematical, astronomical, and philosophic realms. These notions are often realized at the intersection of different disciplines and with the help of progressive technologies, which can challenge the conventional perception. Some of them are Einstein's theory of relativity, which shifted the perception of gravity and time, and wormhole and multiverse theories, which hint at the possibility of existing shortcuts in spacetime and infinite parallel universes, respectively. New space-time concepts may, therefore, let us question the previous understanding of the universe's architecture, which is so new and so radical. Here are the steadily developing theories that may one day alter not only humankind's perception of the universe but also how the entity of space and that of time transpire.

Present-day physics is experiencing a shift in viewing atomic properties as the result of operations separated at a higher level of order. On the most fundamental level, an atom consists of protons, neutrons, and electrons obeying the laws of quantum mechanics and subjected to intense and weak nuclear forces. The electron, for instance, how it scans, or it releases, or how it absorbs, is not an inherent characteristic of an atom. Still, it is one of the behaviors of particles that are in formations and in their complex interactions. From this point of view, characteristics that we attribute to atoms as elementary particles, for instance, solidity, color, chemical activity, and other physical characteristics, are actually emergent phenomena that result from complex processes within an atom, including quantum and nuclear interactions. Hence, what we consider as a permanent and constant state of matter in terms of atoms and molecules are, in fact, the reflection of numerous processes that always regulate the particles' activity. This is a broader approach to the atomic structure as it shows the layered structure of the world where the nuclear interactions give rise to higher-order characteristics [11].

3. Conclusions

The search for post-quantum models, as a contemporary paradigm, represents a revolution in terms of the paradigms of reality. These theoretical frameworks, including String theory, LQG, and non–linear quantum mechanics, aim to unify the profound contradictions between quantum mechanics and general relativity theories—the two best theories in physics but in conflict. These models are frontier breakers in conventional

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science; they create horizons for the understanding of space, time, and matter. As has been discussed earlier under string theory, the notion of vibrating string in place of point particles integrates all forces, including gravity, in a multidimensional schema. Despite its lack of empirical evidence, the beauty of its mathematical framework has let it make predictions in areas such as black hole formation, entropy, and even the geometry of space-time. On the other hand, LQG presents a picture of the universe in which spacetime is granularized, consisting of loops that form the basis of continuity. It has the potential to reunify the singularities that live in black holes and the Big Bang, replacing them with finite quantum states and disputing the prevailing paradigm for the universe. Thus, as these theories develop, they also expand the field of study, which is new to most students beyond mere atomic and subatomic activity. The change in atomic nuclei, the shift in electron orbital states and discretization, and the possibilities of new forms of symmetry and new conservation laws point to a much richer and deeper structure to reality. Physicists have been able to discuss and provide extrapolations of entities that are non–local, entangled, and so oftentimes appearing holographic, which gives perhaps a glance into a universe having a physics behavior far different from what a three–dimensional experience suggests.

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