Quantum Gravity

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ABSTRACT

Quantum mechanics and general relativity, two of the most important branches of science explaining our world, are contradictory in nature. The search for a Grand Unified Theory of the universe that would be able to link these two branches so far with concrete foundations has been to no avail. So far, general relativity has successfully been able to describe the movement of planets and stars. Quantum physics describes the physics of the subatomic world. Unfortunately, gravity currently has no concrete basis in quantum theory; the most prevalent theories describing human understanding of the universe are incompatible. Using various research papers and articles, this paper reviews the different theories addressing the gap in our understanding, such as String Theory and Loop Quantum Gravity, and why they may fit with our expectations, as well as what shortcomings they have. By discovering a bridge between quantum physics and gravity, we would have a more complete general understanding of the mechanics of our universe. This review paper is aimed at helping to understand the development of the theory of quantum gravity and the various candidates for the Grand Unified Theory.

INTRODUCTION

For as long as humanity has existed, we have looked up in the sky and wondered what governs the structure of the universe. Modern physics tends to describe the structure of the universe in a remarkable yet incompatible way; general relativity governs the cosmic scales, and quantum mechanics governs the microscopic world. The need to combine these two frameworks gives us the motivation for the search for a theory of Quantum Gravity.

A problem that arises from Heisenberg's uncertainty principle[1] is that measurements at extremely small scales tend to disturb spacetime. Near the Planck length[2], spacetime cannot remain smooth, and the understanding of gravity as a curvature that is continuous becomes inadequate. Quantum gravity thus seeks to formulate a unified framework where gravity acquires a quantum nature, revealing a deeper and more accurate understanding of the universe.

This paper aims to explore the theory of quantum gravity and explain why a unified theory is necessary to understand the fundamental workings of our universe. It examines the theories of general relativity and quantum mechanics, highlighting when they contradict each other. The need for quantum gravity, along with its theoretical approaches and associated challenges, is then discussed.

THEORIES

General Relativity

General relativity [3], [4], a theory of Einstein, is the geometric theory of gravitation. It makes special relativity more applicable to non-inertial frames. It also provides a unified description of gravity as a geometrical property of space and time, or four-dimensional spacetime. General relativity expanded on the theories of special relativity. Special relativity [5] stated that space and time were interconnected, but the theory did not account for gravity. Einstein described gravity not as a force but as a result of spacetime curvature [5], [6]. Anything with mass bends the spacetime around it. For example, the Earth orbits the Sun because of the curvature caused in spacetime by the Sun. This theory also explains why light bends near stars and time gets slower as it approaches bodies with high mass.

Einstein's theory of general relativity altered our understanding of gravity; instead of a force, gravity was described as the curvature of space-time.

A popular analogy [7] to support Einstein's hypothesis of gravity as spacetime curvature was that it takes spacetime to be a rubber sheet that can be deformed (Figure 1 [8]). An object of relatively higher mass, when placed on the sheet (supposed to be the sun in the analogy), creates a depression, curving the space around it. A smaller object, like a marble, rolls down towards the depression caused by the bigger object, as if being pulled by a force. The smaller objects roll along the curved path of the sheet, following geodesics [9], not because of force but because of spacetime curvature.

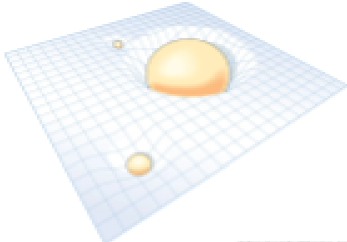

Figure 1-Analogy illustrating how objects of different mass curve spacetime, producing gravitational effects

According to general relativity, mass-energy, pressure, stress, and momentum are all capable of bending and deforming spacetime. In the presence of high pressure, pressure tends to play a big role and can even lead to the formation of black holes when limits are reached. This is closely related to intense gravitational fields associated with such conditions. Beyond shaping the paths of objects and light, the curved space-time fabric also affects the very nature of time.

Gravity itself can affect time through a phenomenon called time dilation. In a stronger gravitational field (near a massive celestial object), time passes more slowly compared to time in a weaker gravitational field (far from the massive object). This implies that a clock on Earth ticks slower than a clock placed in space [10]. Mathematically, this effect is described as the Schwarzschild equation, which shows that as one moves closer to an object, the passage of time relative to an observer at some distance decreases. On extreme scales, as on the edge of a black hole, a few hours spent close to it correspond to years passing for someone far away. This effect illustrates the profound connection between gravity and time.

The Hafele-Keating experiment [11], [12], conducted in 1971 by Joseph C. Hafele and Richard E. Keating, tested Einstein's theory by flying four atomic clocks around the world in commercial airplanes (one in an eastward direction and the other in a westward direction). After their respective flights, the times on the clocks were compared with the time recorded on the clocks of the US Naval Observatory. The results were such that the clocks moving eastwards lost a significant amount of time relative to the stationary clock at the US Naval Observatory, while the clocks moving westwards gained time. These discrepancies were consistent with both general and special relativity. This experiment thus provided evidence of time dilation under practical conditions.

Just like how gravity influences time, it also bends light around massive objects, showcasing how closely linked space, time, and gravity are.

Gravitational lensing [13], [14], as proposed by Einstein's general theory of relativity, states that the bending of light emitted by an object bends as it passes near a massive object due to spacetime curvature (Figure 2 [15]). This bending of light makes the massive object act as a lens, as it magnifies and even distorts images of background sources. Since the source galaxy emits light in all directions, some light converges towards us, which makes the galaxy appear brighter than it would ordinarily appear from

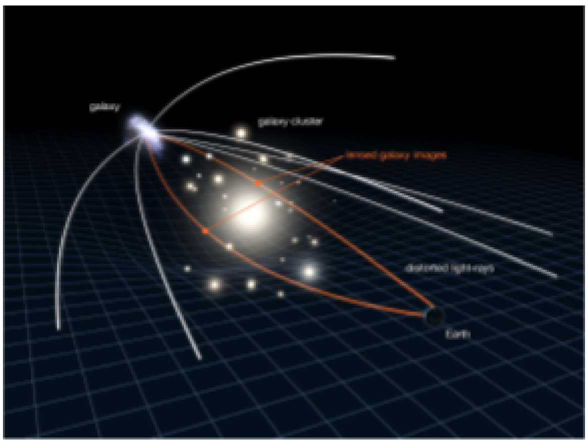

Figure 2-Gravitational lensing caused by spacetime curvature around a massive galaxy cluster

Earth. This effect is illustrated in Figure 2, where a galaxy cluster bends light from a distant galaxy, producing distorted images. This strong lensing effect makes gravity act as a telescope. The James Webb Space Telescope helps in observing gravitational lensing. Similar to bending light, gravity can also bend the paths of gravitational waves.

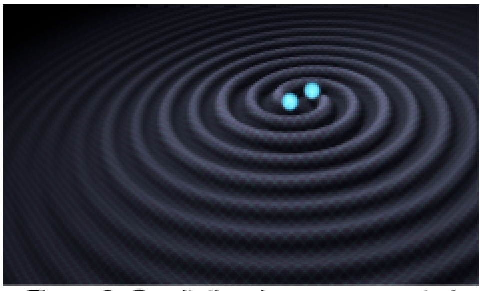
Figure 3- Gravitational waves generated by two massive objects.

Gravitational waves [16] are like ripples on the space-time fabric; they are primarily generated by the movement or collision of massive objects like neutron stars or black holes, and they travel outwards at the speed of light. It may result in stretching and squeezing of spacetime (Figure 3 [17]). Gravitational waves are a key feature to investigate quantum gravity, because they tend to reveal how gravity acts on the smallest of scales (quantum scales).

Experiments on General Relativity

<u>PERIHELION PRECESSION OF MERCURY</u>: it refers to the phenomenon where the closest point in Mercury's orbit around the Sun shifted slightly with each orbit; this shift occurred 43 arcseconds per century, causing Mercury's elliptical path. Newtonian physics was unable to explain this perihelion precession and the time required, but Einstein's theory of general relativity explained the anomaly by describing gravity as the curvature of spacetime rather than a force. It explained that Mercury's path was due to the curve in spacetime caused by the Sun's mass.

<u>SHAPIRO TIME DELAY</u>: Radar signals sent nearer to the Sun take a longer time due to spacetime curvature; this effect was measured by Irwin Shapiro in 1970.

<u>EDINGTON EXPERIMENT</u> [18]: The Edington experiment, conducted in 1919 (during a total solar eclipse), tested Einstein's general relativity by bending of light emitted by a star around the Sun. According to the theory of general relativity, the Sun's massive gravitational field would bend light emitted by the star, which would cause its positions to shift relative to the viewer on Earth (Figure 4 [19]). The results confirmed that the Sun's gravity deflected the light as proposed by Einstein. This experiment provided strong proof of gravitational lensing.

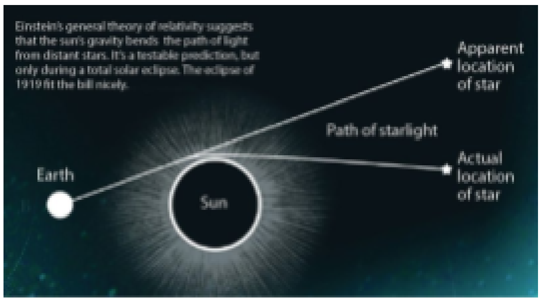

Figure 4-Deflection of starlight observed during the 1919 Eddington experiment.

<u>LIGO experiment:</u> It was the first experiment to detect gravitational waves (2015) from two black holes colliding billions of light-years away. Using laser interferometers, LIGO measured the tiny ripples in spacetime caused by the collision. This proved Einstein's prediction of gravitational waves.

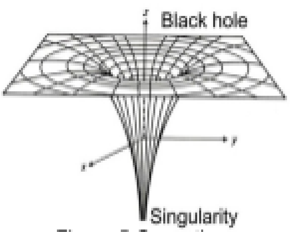

Figure 5-Spacetime curvature around a black hole and its event horizon.

General relativity, black holes, and quantum gravity are deeply connected. General relativity describes black holes as regions where nothing can escape beyond their event horizon due to their intense spacetime curvature (Figure 5[20]), which results in a very strong gravitational force.

Black holes form when a huge star collapses under its own gravity and creates what is known as a spacetime singularity, which is surrounded by a horizon, beyond which no matter can escape. The Event Horizon Telescope's imaging of the black hole provides us with

proof of general relativity's theory of light bending around massive objects.
Confirmed relativistic effects around black holes, like time dilation, are also predicted by General relativity.
At the event horizon, a phenomenon called Hawking Radiation [21], [22] is caused by quantum effects, where particle-antiparticle pairs are formed. One escapes as radiation causes the black hole to reduce in size. This process links gravity and quantum mechanics and also says that a black hole emits thermal radiation, and this discovery is very notable for the idea of quantum gravity.
General relativity predicts that black holes warp spacetime's fabric and thus influence the motion of nearby objects and also result in the bending of light around them (i.e., gravitational lensing).

Quantum Theory
Quantum theory[23] is one of the most transformative theories in modern science. Established in the 20th century, it was able to shift the focus from classical physics to the probabilistic framework and workings of atoms and subatomic particles. Classical physics failed to explain the science behind particles at the atomic scale, but quantum mechanics was able to explain such theories. The combination of classical physics with quantum physics explained and revealed how the universe operates on different scales.
As the quantum theory matured, it gave rise to the Quantum Field Theory, a theory that merges special relativity with quantum mechanics. Together, these theories tend to form the base of modern physics.
Quantum mechanics began with the concept of light. In 1905, Albert Einstein proposed that light behaves as small packets of energy called photons (to explain the photoelectric effect). This idea directly challenged the fact that light was considered a wave. Before the photoelectric effect, the double-slit experiment was performed, and it revealed that light (as well as matter) behaves both as a wave and as particles.
In the double-slit experiment (Figure 6[24]) [24], [25], when electrons were fired through two narrow slits onto a screen, a pattern emerged, indicating wave behaviour. However, when detectors were placed to determine which slit the electron passes through, the pattern tends to disappear, and electrons start behaving as particles. This experiment demonstrated wave-particle duality and stated that quantum particles cannot be described purely as waves or particles.

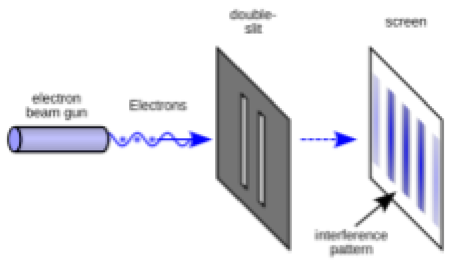

Figure 6- Double slit experiment demonstrating the wave nature of quantum particles.

To describe the dual behaviour, Erwin Schrödinger [26], [27] introduced the wavefunction in 1926. The wavefunction provided a complete mathematical description of the quantum system. The square of the magnitude of the wavefunction represented the probability of finding a particle at a given position in space.
Building on the probabilistic view, Heisenberg formulated the uncertainty principle in 1927. It stated that both the position and momentum of a particle can't exist simultaneously. The uncertainty principle guaranteed the stability of an atom; if electrons had definite position and momentum, they would collapse into the nucleus. This is true because when an electron is confined to a particular position, the momentum of the electron becomes so large (following the uncertainty principle) that

it prevents the electron from collapsing into the nucleus, thus, stabilising it.
Heisenberg also introduced the concept of zero-point energy, the smallest possible energy a system can have.
The uncertainty principle leads directly to the idea of quantum fluctuations, which are temporary changes in energy that occur (even in a vacuum). According to quantum theory, a space is not truly empty; it is filled with fluctuating fields where virtual particles and antiparticles constantly appear and disappear. These fluctuations can be measured. The Casimir effect [28], where 2 uncharged metal plates attract each other in a vacuum, arises from a shift in vacuum energy (Figure 7 [29]). Quantum fluctuations reveal that the vacuum is an active participant in physical processes, linking microscopic and cosmic scales. Quantum fluctuations show that space is not truly empty but is instead filled with short-lived particle-antiparticle pairs. Such effects take part in everything, from subatomic interactions to cosmic scales, such as vacuum energy and an accelerating expansion of the universe.

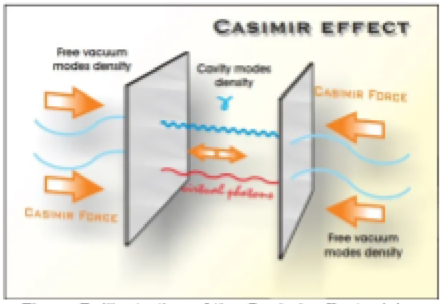

Figure 7- Illustration of the Casimir effect arising from quantum vacuum fluctuations.

Another fascinating feature of quantum particles is spin [30], an intrinsic form of angular momentum. Spin determines how a particle behaves under rotation and how it is affected by magnetic fields (Figure 8 [31]). Particles are classified based on their spins:
Fermions: They obey Pauli's exclusion principle, which prevents two fermions from occupying the same quantum state. This principle explains the stability of matter. Electrons, protons, and quarks are a few examples of fermions
Bosons: They have integer spins; they can share the same state. This leads to phenomena such as laser light and Bose-Einstein condensation (it is a state of matter formed when a gas of bosons is cooled to a few mK above absolute zero). Photons, gluons, and the Higgs boson are a few examples of Bosons.

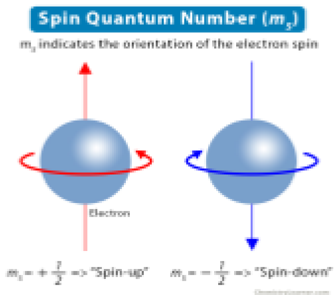

Figure 8- Electron spin quantum number and its orientations.

Spin underlies the behaviour of matter and energy, linking quantum properties to macroscopic phenomena.

Quantum mechanics can successfully describe individual particles, but it fails to explain the processes where particles are created or destroyed, such as in high-energy collisions. To explain these effects and maintain consistency with special relativity, Quantum Field Theory was developed.
The theory explains that the particles are not independent objects but excitations of underlying fields that fill all of space. For example, the electromagnetic field gives rise to photons, while the electron field forms electrons. Interactions between particles occur when their corresponding fields interact. This theory helps unite quantum mechanics with relativity, providing a foundation for the Standard Model of particle physics [32].
All interactions in the universe arise from four fundamental forces:

- Gravitational force: acts between masses
- Electromagnetic force: acts between charged particles
- Weak nuclear force: governs radioactive decay and neutrino interactions
- Strong nuclear force: binds quarks inside protons and neutrons and atomic nuclei together

The Standard Model unites only three of the forces, which are the framework of quantum field theory. It classifies all particles into fermions and bosons. A grand unified theory, that is, quantum gravity, would unite all four fundamental forces. Quantum fields form the foundation of modern physics. Every point in space is associated with a field, and what we perceive as particles are vibrations in these fields.
The view unifies all of physics into an angular framework, rather than a universe made of particles moving through space; we live in a universe of interacting fields.

Need for Quantum Gravity
Quantum gravity is important because our current theories of general relativity and quantum mechanics are nearly incompatible in certain extreme situations and extreme areas. In regions like black hole singularities, general relativity breaks down, predicting incompatible measurements instead of meaningful ones. Quantum effects become more significant where the gravitational field becomes stronger. These situations lead to problems like the black hole information paradox, highlighting the need to form a unified framework that can combine gravity with quantum mechanics. General relativity explains the large structures of the universe, whereas Quantum mechanics describes the nature of minute microscopic particles. However, general relativity tends to break down in regions where these theories overlap.

Singularities [33] (at the centre of black holes) or at the Big Bang represent certain points where spacetime curvature is infinite and classical theories of physics stop giving meaningful measurements. This breakdown indicates that a quantum description of gravity is essential to represent such infinites meaningfully. Quantum effects in strong gravitational fields reveal the need for such a unified theory. One example is Hawking radiation (Figure 9 [34]), a quantum process in which black holes emit particles and slowly lose their mass. This phenomenon is a result of the overlap between theories of quantum field theory and curved spacetime. Hawking radiation is a theoretical phenomenon in which a black hole emits thermal radiation caused by quantum effects near the event horizon, leading to the eventual loss of mass (evaporation) of the black hole. The radiation temperature, called the Hawking temperature, is inversely proportional to the black hole's mass. This discovery of Hawking radiation led to the realisation that black holes possess thermodynamic properties, such as temperature and entropy, and raised the black hole information paradox, which questioned whether matter falling into a black hole is lost forever.

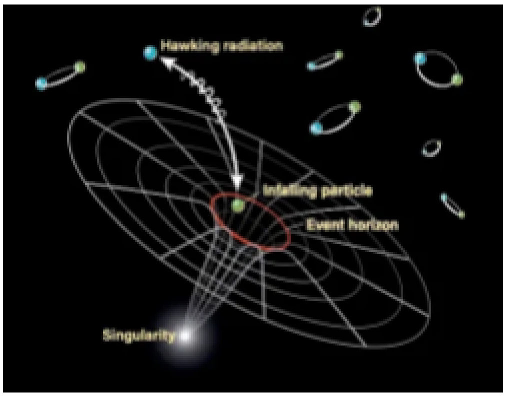

Figure 9-Hawking radiation produced by quantum effects near a black hole's event horizon.

The black hole information paradox [35] is a fundamental problem in the unification of both theories. Hawking radiation was purely thermal and carried no information about the matter that originally fell into the black hole. This contradicted the theory of quantum mechanics. Thus, this paradox makes quantum gravity necessary because it exposes a conflict between general relativity and quantum mechanics. The destruction of information is acceptable in classical physics but not in quantum physics. This contradiction reveals that our understanding of gravity is incomplete at the quantum level. Thus, to explain what truly happens to information in and around the black holes, quantum gravitational theory is a necessity.

Why Black Holes serve as a testing ground for Quantum Gravity?

Black holes serve as the most promising testing grounds for quantum gravity. They provide a testing ground for quantum gravity because it is the black holes where the effects of extreme curvature and quantum fluctuations coexist. The study of black hole thermodynamics and entropy points toward a microscopic structure of space itself. In most regions of the universe, gravity is very weak for quantum phenomena. However, near a black hole's event horizon, spacetime curvature is enormous, and quantum phenomena cannot be ignored. This makes black holes an ideal testing ground for testing theories to unify general relativity and quantum theory.

The breakdown of general relativity and the emergence of quantum effects in a strong gravitational field point to the necessity of quantum gravity. Black holes provide not only the clearest evidence of the theory's need but also help in discovering the principle behind it.

APPROACHES TO QUANTUM GRAVITY

So far, the pursuit of a consistent theory of quantum gravity has been the inspiration for various distinct theoretical frameworks, each seeking to describe the basic features of spacetime and gravitation at the Planck scale, in which classical notions of geometry cease to be valid. Among the leading candidates are String Theory, Loop Quantum Gravity, Causal Dynamical Triangulations, and Emergent Gravity.

a. String Theory

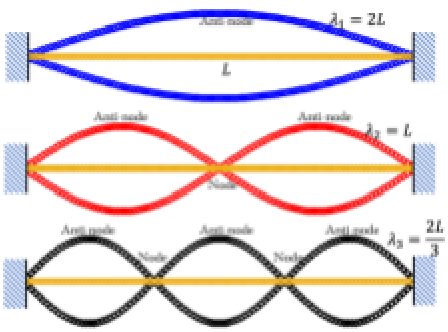

Figure 10-Vibrational modes of a one-dimensional string in string theory.

String theory [36] postulates that one-dimensional vibrating strings, rather than point-like particles, are the building blocks of everything that exists. The different modes of vibration (Figure 10 [37], where the modes correspond to particle properties like mass, spin, etc., and the vibrations occur at higher-dimensional spacetime) of these strings correspond to all the particles seen in nature. Notably, the theory naturally incorporates gravity through the existence of a massless spin-2 excitation, the graviton, the quantum mediator of the gravitational force.

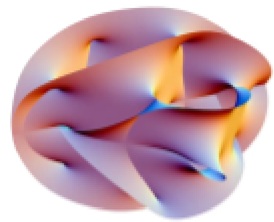
Figure 11-Representation of extra dimensions in string theory

One of the most profound features of String Theory is its dependence on higher dimensions (Figure 11[38]), usually ten in superstring theory or eleven in M-theory. This additional dimensionality provides a framework for the accommodation of all fundamental interactions, such as electromagnetism and the nuclear forces, within one theoretical framework. In addition, the extended nature of strings allows for the smoothing out of spacetime singularities, those occurring inside black holes or at the Big Bang, because the classical point-like divergences of general relativity get smeared out. Just as a finite-sized charge avoids a high electric field of a particle, strings smear interactions (with gravity) over a finite length, preventing the curvature from getting destroyed.

It remains the case that String Theory relies on supersymmetry (it relates bosons and fermions and improves the explanation of ultraviolet behaviour of gravitational theories, and also makes a consistent quantum description of spacetime possible) and extra dimensions, none of which have been experimentally verified so far. String theory was successful in providing a consistent mathematical framework that united gravity with the other forces and included quantum gravity but was unable to make testable predictions and experiments, as it mainly relied on extra dimensions not yet observed.

b. Loop Quantum Gravity (LQG)

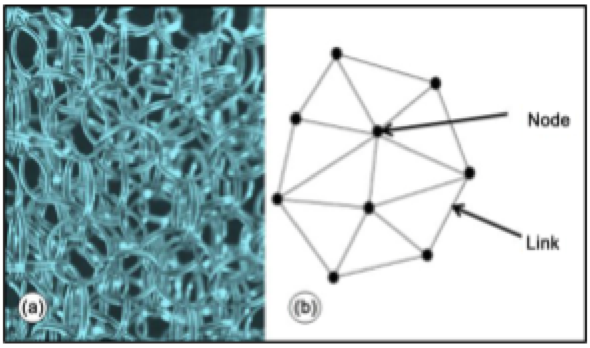

Figure 12-Spin Network representation of discrete spacetime in Loop Quantum Gravity

Loop Quantum gravity[39] is an approach to quantum gravity in which space and time are not continuous but are made of minute discrete chunks. At extremely small scales, the spacetime may have a granular structure (Figure 12 [40]) which prevents the infinite densities (singularities) predicted by the theory of general relativity.

Within Loop Quantum Gravity, the quantisation of spacetime itself is background-independent, without presupposing any fixed geometry. The theory reformulates general relativity in terms of the so-called Ashtekar variables, which allow for a non-perturbative quantisation with the result of a discrete structure of spacetime at the Planck scale.

In LQG, all geometric quantities, including area and volume, are quantised: they can take only discrete values. This quantisation means that spacetime is composed of finite, indivisible "chunks" described mathematically by spin networks. One of the notable successes of LQG lies in its application to the area of black hole entropy, where a statistical explanation of the Bekenstein-Hawking formula by counting microscopic spin network configurations associated with the event horizon can be provided.

While LQG is in accordance with general relativity and provides profound insight into quantum geometry, its relation to low-energy physics and matter fields is still a subject of ongoing research.

c. Causal Dynamical Triangulations (CDT)

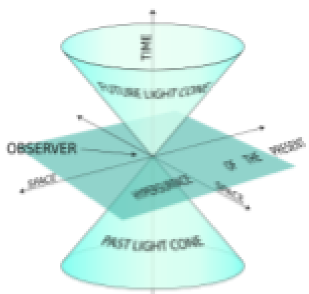

Figure 13- Light cone illustrating causal structure in spacetime

Causal Dynamical Triangulations [41] are a computational approach to quantum gravity in which spacetime is made up of discrete simplicial building blocks, higher-dimensional analogues of triangles, assembled so that causal structure (Figure 13 [42]) is preserved. Unlike other approaches based on discretisation, the causal ordering of spacetime elements is well defined in CDT. The CDT approach is used in quantum gravity because it enforces a well-defined causal structure while correctly quantising spacetime, preventing the formation of any unphysical geometries. This allows us to form a consistent and realistic framework that keeps classical spacetime consistent with general relativity to emerge at large scales.

CDT shows, by means of extensive numerical simulations, how classical spacetime naturally emerges at macroscopic scales – recovering in this way the familiar smooth geometry of general relativity from an underlying quantum, discrete substratum. This does indeed follow as strong evidence that spacetime continuity can actually be a result of fundamentally discrete dynamics.
CDT successfully reproduced general relativity at large scales while keeping the spacetime well-defined and continuous on quantum scales. However, CDT is unable to clearly connect particle physics or the Standard Model.

d. Emergent Gravity

Emergent Gravity[43] is a view that considers gravity as not being a fundamental force itself but rather an emergent, thermodynamic phenomenon due to the joint action of microscopic degrees of freedom. Drawing analogies with thermodynamics and statistical mechanics, this perspective, pioneered by Jacobson, Padmanabhan, and Verlinde, suggests Einstein's equations could actually be derived as an equation of state from underlying quantum information principles.

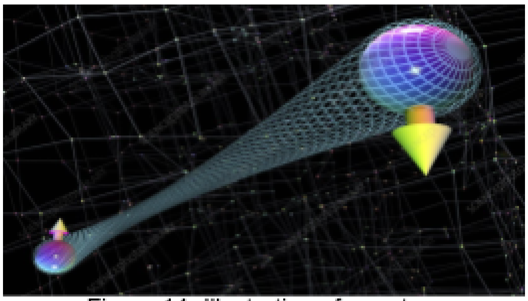
Figure 14- Illustration of quantum entanglement between two particles

In emergent gravity, spacetime and gravity arise from quantum entanglement (Figure 14 [44]) between fundamental degrees of freedom. Patterns of entanglement determine spacetime geometry, like a strong entanglement corresponds to a strong connection in spacetime, while a weak one gives rise to curvatures (which we perceive as gravity). In this approach, the geometry of spacetime and gravitational dynamics emerge from the structure of entanglement or, equivalently, the information content of quantum fields. This view links gravity to profound questions in quantum information theory and thermodynamics; therefore, it may allow a reconciliation of quantum mechanics and general relativity without requiring a quantised gravitational field.

These varied approaches represent the multifaceted nature of the problem of quantum gravity. While string theory seeks unification in higher-dimensional frameworks, LQG and CDT focus on the quantisation of spacetime itself, and emergent gravity reinterprets gravity as a macroscopic manifestation of microscopic information dynamics. Each offers unique insights into the structure of spacetime and brings us closer to grasping the true quantum nature of gravity.
Among these quantum gravity approaches, string theory is the most widely studied and aims to be a unified theory connecting all 4 fundamental forces. Loop Quantum gravity mainly aims at quantising spacetime and does not aim at providing a unified framework. Emergent gravity is more of a conceptual theory in which gravity arises from quantum correlations and geometries. The Causal Dynamic Triangulation provides an independent description of quantum spacetime that preserves causality but is not a unified theory.

Challenges in Quantum Gravity

One of the challenges in quantum gravity is the inaccessibility of Planck scale units and energies. The energy levels at which the quantum nature of spacetime is expected to become prevalent are much higher in magnitude than what current experimental technology can reach. As a result, it is difficult to test theories of quantum gravity or to obtain adequate evidence that could guide theoretical development.
For example, the maximum energy of collision by the Large Hadron Collider is 1.3×10^{13} eV, whereas the Planck energy is nearly 1.22×10^{28} eV. This shows that the Planck energy is 10^{15} times the maximum energy we can attain.[45]

The lack of experimental data creates a second major problem. Without observational constraints, proposed models rely solely on mathematical calculations and a few untested theories rather than empirical support. This makes it challenging to distinguish between competing theories, such as string theory, loop quantum gravity, causal dynamical triangulations, and other approaches that attempt to support quantum mechanics with general relativity, making the experimental foundation of general relativity a challenging one

There is also a conceptual difficulty in defining time within the framework of quantum scales. In general relativity, time is dynamic and connected with the geometry of spacetime. In quantum mechanics, time is treated as a constant external parameter. Combining these differing roles of time has proven to be a major problem.

A further challenge arises from the incompatibility between the smooth spacetime of general relativity and the quantised structures expected in quantum theory. General relativity models spacetime as a continuous geometric manifold, while quantum mechanics suggests that at minute scales, physical quantities, including the geometry itself, may be discrete. Developing a consistent mathematical framework and firm theories that incorporate both theories' perspectives remains a problem.

Conclusion

Current research in quantum gravity reflects significant progress but also substantial limitations. Theoretical models have grown more sophisticated and mathematically robust, yet the absence of experimental evidence limits our ability to evaluate their physical validity. Researchers continue to explore pathways that combine quantum principles with gravitational dynamics, but many fundamental questions remain unresolved.

Despite these challenges, the outlook for quantum gravity research remains promising. Advances in observational cosmology, high-precision experiments and theoretical techniques may eventually provide clues about quantum aspects of spacetime. New ideas such as holography, spacetime emergence, and quantum information-based approaches are reshaping how scientists think about the problem, offering new avenues for investigation.

Resolving the problem of quantum gravity carries a lot of scientific significance. Scientifically, it would unify our understanding of the fundamental forces and provide a complete description of nature at all scales. Achieving a theory of quantum gravity would represent one of the most profound milestones in modern science.

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