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An Overview of Quantum Gravity Methods

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ABSTRACT

A theory of everything, or a theory of quantum gravity, refers to the unification of two of the most fundamental concepts in physics: quantum mechanics and general relativity. It was inspired by quantum field theory, which unifies quantum mechanics and special relativity. This literature review is an overview of the different approaches to this theory. The initial background theory provided is used to explain the gaps that need to be filled in order to develop a theory of quantum gravity. Loop quantum gravity and string theory are explained in detail in terms of the broad concept, their limitations, and a brief comparison to each other. A more general synthesis of other approaches, including and limited to asymptotic safety, quantum field theory on curved spacetime, and supergravity is covered. The method of research involved primarily reading journal articles, textbook chapters, and lecture notes. The paper concludes that a lack of experimental data is the key reason why it has not been determined which theory, if any of them, is correct. String theory and loop quantum gravity remain the top contenders, with minor theories, like the other three, being more helpful in gaining insights in mathematics and physics.

INTRODUCTION

Quantum mechanics, which explains particle behaviour on subatomic scales, and general relativity, which describes spacetime on cosmological scales, are two of the most fundamental theories developed in physics, and a successful theory of quantum gravity would be a coherent theory of everything: this would be an all-encompassing theory that unifies all the natural laws of physics into a single theory. Theories for quantum gravity have been proposed since the 1930s, though a completely successful theory has yet to be created [1]. This undertaking presents conceptual challenges, which will be examined in detail throughout the course of this paper. The review starts with presenting the necessary background theory on relativity and quantum mechanics. Then, it moves onto different approaches to quantum gravity, with emphasis on string theory [2] and loop quantum gravity [3].

This work is a literature review. The sources used largely consist of lecture notes from Cambridge University and Oxford University, textbook chapters, and research papers from sites such as arXiv that provide an introduction to the mentioned concepts. The scope and aim of this paper is to cover technical concepts that provide an understanding of this field of research in physics in a way that is accessible to high school students.

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RELATIVITY

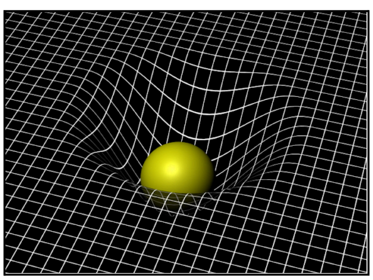
General relativity addresses how mass causes spacetime[1] to curve, with curves in spacetime causing gravitational force [4]. It is applied in concepts such as black holes and planetary orbits. The theory of special relativity describes how measurements of space and time are dependent on the velocity of an observer [5].

2.1 General Relativity

This section largely follows the content of Ref. [4]. The key principle of general relativity (GR) is that matter and the curvature of spacetime are dynamically related, in that matter tells spacetime how to curve, and the curvature of spacetime tells matter how to move. This idea is expressed in the Einstein field equation [6].

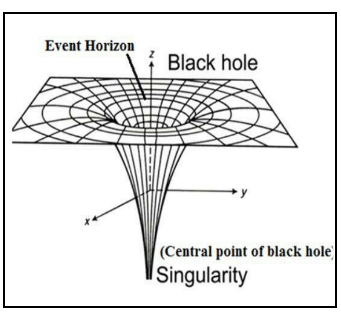
$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu} \tag{1}$$

On the left-hand side of this equation, $R_{\mu\nu}$ (Ricci curvature tensor) describes how volumes in spacetime change under curvature; R (Ricci scalar) summarises the overall curvature of spacetime; $g_{\mu\nu}$ (metric tensor) encodes the geometry of spacetime in terms of angles and distances. On the right-hand side, $T_{\mu\nu}$ (stress-energy tensor) encodes the distribution of matter and energy. This represents the relationship between spacetime and matter. The geometry of spacetime and gravitational effects are determined by deriving solutions to this equation for a given matter-energy distribution.



A schematic representation of how matter causes spacetime to curve is seen in Figure 2.1, where the grid lines represent spacetime, and the ball represents an object in space. This represents how the curvature of spacetime is dynamically linked to matter and energy in space.

Figure 2.1: A schematic representation of the curvature of spacetime [7].



Another phenomenon that was predicted using Equation (1) is the concept of singularities. In 1916, Karl Schwarzschild used Einstein's theory to predict the curvature of spacetime around a spherical object, assuming that the object is in a vacuum, that the mass is spherically symmetrical, and that it is not rotating. In such a case, at the point where r=0, or in other words, the centre of the spherical mass, is a point where the curvature of spacetime is infinite [4]. Near this point, the gravitational potential experienced by a particle increases to negative infinity, illustrating the inescapable nature of the force.

[1] Spacetime: It is a mathematical model in which time and three-dimensional space are fused together in a four-dimensional continuum. As an analogy, we can imagine that it is a giant, stretchy blanket that fills the universe.

Such a singularity forms the central point of a black hole. Figure 2.2 is a true singularity, and represents one of the possible spacetime geometries derived from Equation (1). The event horizon, labelled on Figure 2.2, is the border of the black hole. The escape velocity at this point equals the speed of light. Since nothing can exceed this speed, everything gets sucked in [8].
Figure 2.2: An image of a black hole with the singularity and event horizon labelled [9].

Beyond the event horizon, all of spacetime is "sloping" towards the central point of the black hole; all possible future paths lead towards the centre. When a falling object reaches the singularity, the gravitational force crushes it to infinite density and zero volume. From the perspective of an outside observer, the falling object appears to move towards the event horizon at a slower and slower pace, without actually crossing it. This is because the gravitational field near the black hole is so strong that it stretches time, such that it takes longer and longer for light to reach the observer. Eventually, the signal stops reaching the observer, giving the appearance that the clock is stuck at the horizon. This phenomenon is known as gravitational time dilation [4]. The stronger the gravitational field, the slower a clock ticks when measured by a distant observer.

2.2 Special Relativity

This section largely follows the exposition of Ref. [10]. Special relativity (SR), developed by Albert Einstein, extends the theory of general relativity by stating that measurements of time and space are relative [10]. This theory is applicable in contexts where particles move at velocities approaching the speed of light, such as in particle physics experiments.

The two assumptions in special relativity are that the laws of physics are invariant in all inertial frames and that the speed of light in a vacuum is invariant in all inertial frames. This means that time ticks at different rates for observers in different inertial frames that are moving at different speeds. A Lorentz boost or Lorentz transformation describes a transformation from one inertial frame to another, allowing descriptions of the same event from different frames [11]. The Lorentz factor (γ)

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{2}$$

was derived to calculate how much time, length, and mass change for an object moving at a relative velocity to an observer. The velocity of the object is represented by v, and c is the speed of light. As v approaches c, γ approaches infinity.

The Lorentz factor is used to calculate special relativistic effects, such as time dilation.

$$\Delta t = \gamma \, \Delta t_0 \tag{3}$$

In Equation (3), Δt_0 is the time experienced by an observer who is stationary relative to the event, and Δt is the time experienced by an observer who is moving relative to the event. As γ approaches infinity, Δt increases, illustrating the stretching of time [10]. One of the famous examples that illustrates this point is the following thought experiment.

Such special relativistic effects are customarily displayed using Minkowski spacetime diagrams [10]. Minkowski spacetime is the simplest solution to the Einstein field equations described in Section 2.1. It describes the situation where spacetime is flat and there is no gravitational force. It is drawn showing one dimension of space is represented on the x-axis and time on the y-axis. Time is shown in terms of the distance travelled by light in one second. An illustration of a light cone is shown in Figure 2.3.

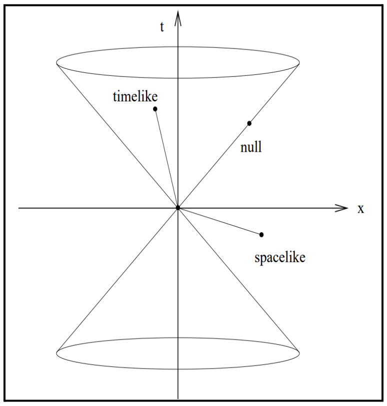


Figure 2.3: A light cone drawn on a spacetime diagram [10].

To understand a light cone, consider a point source of light emitting radiation uniformly in all directions. As time passes, the sphere gets larger and larger. In a spacetime diagram, the cross-section of this sphere is illustrated by a light cone. If an object moves at a speed lower than the speed of light, its worldline lies inside the light cone and is described as timelike. If an object moves at the speed of light, it moves along the light cone, and it is described as null or lightlike. Hypothetically, if an object were to move faster than the speed of light, its path would lie outside the light cone, and it would be described as spacelike. This diagram also allows us to represent the order in which events occur.

The Minkowski spacetime diagram allows us to examine how the concept of simultaneity, the idea that two things occur simultaneously, is affected by special relativity [10]. What occurs at a particular instant depends on the inertial frame of the observer. The first diagram in Figure 2.4 shows what is observed by a person who is at rest relative to an event. The second graph shows the event from the perspective of a moving observer - spacetime becomes squashed. The difference in perception of an event for different observers must be encoded in a theory of quantum gravity for it to be successful.

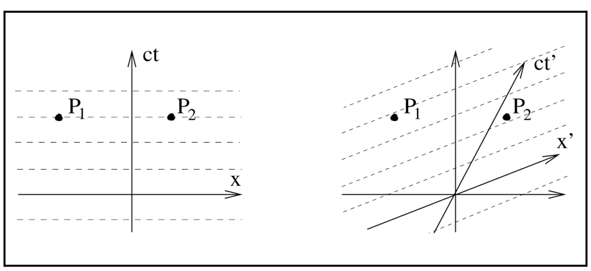


Figure 2.4: Spacetime diagrams that illustrate the concept of simultaneity in special relativity [10].

Though the concept of relativity is generally perceived as obscure, it has tangible, real-life applications, such as in GPS systems like Google Maps. A specific point on the Earth moves as the Earth rotates around an axis. Since a geostationary satellite would have to cover a longer distance in the same amount of time to track this rotating point, it must travel faster. The difference in speed implies that the satellite and the point on Earth will be in different inertial frames, so there are special relativistic effects, specifically time dilation: clocks on a GPS satellite tick about 7 microseconds slower than those on Earth. Additionally, as explained in Section 2.1, the object will experience time dilation caused by the curvature around the Earth. The gravitational force experienced by the satellite is much weaker than that experienced by an object on Earth. The effect of gravitational time dilation is weaker on the satellite, meaning that a clock on a satellite ticks faster than one on Earth. Specifically, it is about 45 microseconds faster. Considering the overall time dilation, location errors would be up to 10 km in the wrong direction if relativistic effects were not considered [12].

QUANTUM MECHANICS

Quantum mechanics (QM) cannot be experienced in the same manner as classical physics, rendering it counterintuitive [13]. An analogy compares classical physics to a clear, sharply defined image. Upon magnifying the image to the level of individual pixels, representing the quantum domain, the boundaries appear fuzzy and indeterminate. Quantum mechanics is a background-dependent theory because it was formulated on the assumption of a flat, fixed spacetime background.

3.1 Double Slit Experiment

This section is formulated along the lines of Ref. [13]. One of the most fundamental experiments in quantum mechanics that illustrates the key concept of wave-particle duality is the double slit experiment [13]. This is important, because it is one of the founding principles for string theory, which is discussed later. Traditionally, the double slit experiment refers to a diffraction experiment that is done with waves. A pattern of constructive and destructive interference is supposed to form on the screen on the other side of the slits.

The initial experiment was done with a gun that was used to fire bullets at varying angles towards two parallel slits. Since each bullet can only pass through one slit, the probability distribution of where the bullet lands is calculated using principles from classical physics, as shown in Figure 3.1.

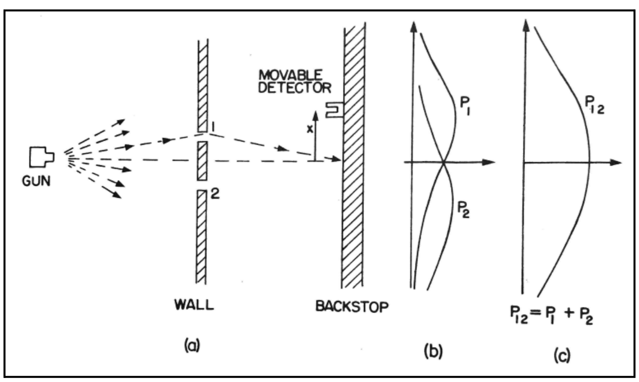
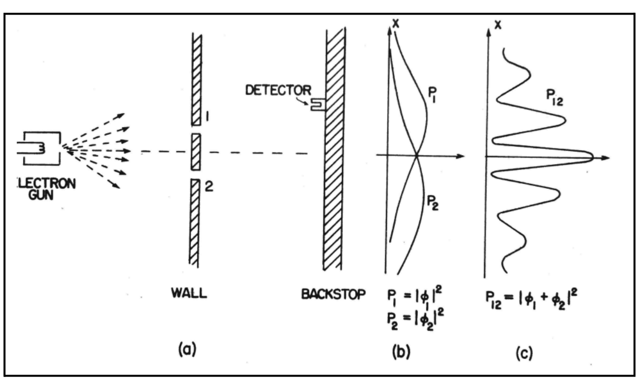


Figure 3.1: This figure illustrates the outcome of a double-slit experiment with bullets [13].



Then, the experiment was repeated using an electron-emitting gun. In the case where the slit through which the electron passed was tracked, the electrons still reach the detector in lumps, exhibiting particle-like behaviour. However, when the slit through which the electron passed was not tracked, the probability distribution resembled a wave interference pattern, as seen on the right side of Figure 3.2 [13].

Figure 3.2: This figure illustrates the outcome of a double-slit experiment with electrons [13].

The calculation of the probability distribution differs because it requires accounting for constructive and destructive interferences. This is done using so-called probability amplitudes [13]. This experiment demonstrated that electrons exhibit both particle-like and wave-like behaviour, a phenomenon known as wave-particle duality. The behaviour of the particle depends on whether or not a measurement of its position is made.

The difference in the probability distribution seen in Figure 3.1 and Figure 3.2, illustrates the difference between classical and quantum mechanics. This explains how there are bridges that must be crossed in order to unite the two.

When the position of a particle is not tracked, it exists in a cloud of probability. However, upon measurement, a definite position is obtained, and all other possibilities are eliminated. This instantaneous and discontinuous jump is referred to as wavefunction collapse or collapse of wavepacket [14], which is represented visually in Figure 3.3

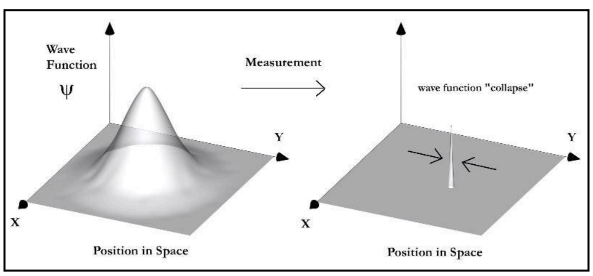


Figure 3.3: Quantum calculations of the position of a particle in space [15].

3.2 Mathematics

In this section, we follow the conception discussion given in Ref. [16]. The mathematics described in this section is used to explain a mathematical condition of quantum mechanics. Firstly, the measurable physical quantities, such as the position of a particle, are represented using mathematical objects known as operators. The state[2] of a particle is represented by vectors. Operators act on vectors to transform them from one state to another. For example, a scaling operator with a factor of 2 would double the length of a given vector.

$$A \quad x \quad = \quad \lambda \quad x$$

[2] State: the condition/set-up of a system. This often comes from the set-up of an experiment.

↓ ↓ ↓ ↓ (4)
Matrix (n×n) Eigenvector Eigenvalue Eigenvector

If an operator A transforms a vector v into a scalar multiple λ of itself, then v is an eigenvector of A, with an eigenvalue of λ. Physically, an eigenvector (or eigenstate) corresponds to a state in which measurement of the observable quantity A will, *with certainty,* give the result λ [16]. This is a mathematical condition for quantum mechanics.

However, many vectors are not eigenvectors due to superposition, where a quantum state is expressed as a combination of multiple eigenvectors rather than a single one. In such cases, the value of an observable A cannot be predicted with certainty. Rather, possibilities and probabilities can be calculated [16]. Upon measurement, a single outcome is obtained, leading to a wave function collapse, as discussed previously.

Another consequence of this rule is the uncertainty principle, which concerns determining which measurements can be taken simultaneously with certainty. Consider the case where two observables, O_1 and O_2, of a particle are measured to obtain their respective eigenvalues λ_1 and λ_2. This can only occur when the order in which the two observable quantities are measured does not affect the measurement. In mathematical terms, the operators must commute [16]. An example where the order of measurement does affect the result is explained in Section 3.3. In these cases, the uncertainty of the measurements must be accounted for.

3.3 Heisenberg Uncertainty Principle in Measurement

There is more uncertainty at a quantum level because measurement introduces additional uncertainty. This is because the act of observation disturbs the system. Hypothetically, a gamma microscope could be used to determine the position of a particle with high accuracy. However, the use of such short-wavelength radiation means that the photons have more energy, so a collision between a photon and the particle disturbs the particle's momentum [16][17]. This principle is illustrated mathematically in the following equation,

$$\Delta x \cdot \Delta p \geq \hbar/2 \qquad (5)$$

which quantifies the extent to which position (x) and momentum (p) can be known simultaneously.

3.4 Spin

Spin, unlike the concepts explained above, is an internal property of particles that dictates how they interact with one another [18]. Spin allows particles to form stable structures. According to the Pauli exclusion principle, no two identical fermions[3] (such as electrons) can occupy the same quantum state simultaneously [19]. Forces of electrostatic attraction cause physical separation between particles.

On the other hand, bosons (such as photons) have integer spin values that allow them to occupy the same quantum state simultaneously. This concept is applied in lasers [20]: All photons align perfectly, their wave crests and troughs are aligned, and they work together, creating a superwave which is used to cut metal without needing high power levels. Spin is an important property of particles that must be encoded in a successful theory of quantum gravity.

QUANTUM GRAVITY

4.1 Relativistic Quantum Mechanics

In the late 1920s, quantum mechanics was united with relativity for the first time in a theory known as quantum field theory (QFT) [21]. QFT specifically unites special relativity SR and QM.

The challenge involved understanding the behaviour of particles moving at relativistic speeds at quantum scales. Both special relativity and quantum mechanics were constructed on fixed spacetime (such as Minkowski spacetime), as described in Sections 2.2 and 3. QFT enables the description of particle interactions using mathematical equivalent Hamiltonian or Lagrangian equations [22]. Feynman diagrams, of which Figure 4.1 is an example, represent these interactions more simply [23]. In these, different kinds of lines represent different particles. Vertices are the points where these particles interact.

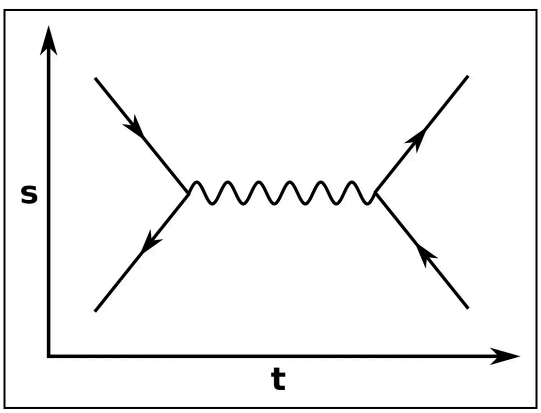


Figure 4.1: Simple Feynman diagram [24]

This theory was further developed to enable the approximation of quantities that otherwise could not be calculated, due to the uncertainty principle. It incorporates concepts from quantum mechanics, such as path integrals. This theory was constructed to be inherently Lorentz invariant, ensuring consistency with the principles of special relativity. However, calculations using this theory often lead to infinities, which are divergences that do not give meaningful answers. Renormalisation [25] is the technique to remove these infinities by adding new, artificial parameters, or counterterms, to the equation. A theory is renormalisable, as long as it only requires a finite number of counterterms to cancel out all divergences. Quantum field theory is renormalisable. A theory is non-renormalisable when it requires an infinite number of counterterms to cancel out all divergences.

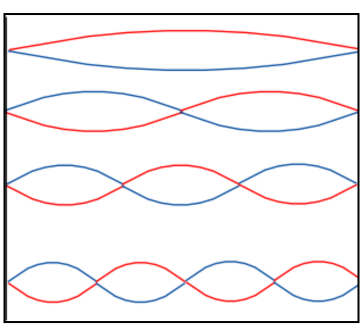
[3] Fermiones: subatomic particles that are the building blocks of matter and have a half-integer spin (eg. ½)

Inspired by the success of QFT, attempts were made to combine general relativity with quantum mechanics, leading to the development of quantum gravity. There are certain points of contrast between QM and GR. These are with regards to the scale on which they are usually applied, and that GR is background independent, whereas QM is background-dependent. A successful theory of quantum gravity must be background-independent [26]. This means that its equations must not rely on a fixed, constant structure of spacetime; there should be no specific geometric background or coordinate system that the theory relies on. Rather, various configurations of the geometry of spacetime should emerge as solutions to the equations in quantum gravity. This would be in line with general relativity, where solutions to the Einstein field equations give certain spacetime geometries, one of which is a singularity.

Additionally, the fundamental nature of the two theories is different, as GR relies on discrete measurements, whereas QM works with probability. In GR, time is considered as an additional dimension, whereas in QM is treated differently from other variables, as no probability wavefunction is associated with it. Initially, gravitational effects were not considered at microscopic scales in quantum mechanics because the gravitational force of individual particles was assumed to be negligible. However, at very small, dense, and energetic scales like the Planck scale [27], current frameworks break down because both quantum and relativistic effects become equally significant. To explain this further, the Planck length (1.616 x 10^{-35} meters) is the scale at which the Compton wavelength[4] meets the Schwarzschild radius[5]. When attempting to quantize gravity using the method in QFT, it was found that the quantization of gravity is non-renormalisable at the Planck scale [28].

The behaviour of matter under such conditions is not understood, such as in the case of black hole singularities or even the Big Bang singularity. This is why the development of a theory of quantum gravity is needed - a “theory of everything” that explains physics at scales ranging from the Planck scale to the scale of the observable universe.

4.2 String Theory



Quantum mechanics has successfully described three of the four fundamental forces: electromagnetic, weak nuclear, and strong nuclear forces. Interactions between certain bosons that are force carriers (such as photons, W and Z bosons, and gluons) give rise to these forces [29]. A consideration was to add an additional particle, gravitons, that would account for the fourth fundamental force, gravity. Unfortunately, this inclusion caused the mathematical framework of QFT to break down, because it became nonrenormalisable [2].

[4] The Compton wavelength is a limit to how precisely we can measure the quantum mechanical position of a particle.
[5] If mass is compressed to a point smaller than the Schwarzschild radius a black hole forms.

Figure 4.2: Strings vibrating at different frequencies [30].

A key assumption in QFT is that particles are zero-dimensional points. This allowed us to do calculations involving particles, accurately predict how they would behave, and contributed to technological developments. However, in an effort to make the inclusion of gravitons renormalisable, string theory (ST) proposes that particles are one-dimensional strings [2]. Different particles would correspond to different frequencies of vibration, as shown in Figure 4.2, a concept drawn from wave-particle duality (Section 3.1) in quantum mechanics.

In the first version of string theory, known as Type 1 [2], separate equations were developed for high-energy and low-energy particles. To make the equation for high-energy particles renormalizable, it was necessary to assume that 26 dimensions exist in the universe. Despite this, the equations for high-energy and low-energy particles were mutually inconsistent.

The second version of string theory, Type 2A, is based on the concept of supersymmetry [2]. It was posited that the number of low-energy particles is doubled by assigning each boson (force-carriers) a complementary fermion,[6] and vice versa. For example, electrons (fermions) are paired with selectrons (bosons) as supersymmetric counterparts. The mathematics is consistent, and this theory is therefore referred to as superstring theory. It requires the existence of 10 dimensions. However, it is purely theoretical, since no experimental evidence of supersymmetry has been found. Currently, particle accelerators are used to search for proof of this theory.

Though this theory was mathematically consistent, the additional dimensions proposed have not been observed. To solve this problem, a mathematical model known as the Calabi-Yau manifold [31] was used to compactify the additional dimensions, explaining why they have not been observed. An analogy: up close, a pipe is visibly 3-dimensional, but from afar, it appears as a 2-dimensional line.

After Type 2A, three more versions of string theory were proposed, each with varying conditions and dimensions. In 1995, Edward Witten put forward M-theory [2] that coalesced the 5 versions of string theory into one coherent theory that requires 11 dimensions. While this theory is mathematically consistent, there are no experimental procedures to test it [32]. Though supersymmetry could be confirmed through particle accelerators, and cosmological observations could support the theory of additional dimensions, these experiments would be supportive, not confirming. In the event that it is an invalid theory, its development still led to translatable mathematical progress.

4.3 Loop Quantum Gravity

Loop quantum gravity (LQG) is a theory of quantum gravity where space is quantised into discrete units, as opposed to the smooth continuous space described in GR. It involves spin networks that encode the

[6] Fermiones are matter particles. As discussed earlier, they obey the Pauli Exclusion Principle, so two of them cannot be in the same state in the same place at the same time.

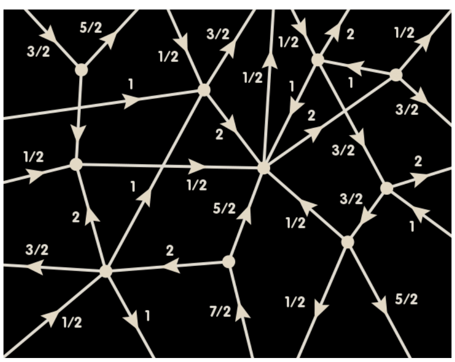
dynamic relationship between particles and the deformations they cause [33], making it background-independent. String theory is not as background-dependent as quantum mechanics, but it is not a fully background-independent theory. Deformations caused by objects on Minkowski spacetime can be encoded; it is difficult to encode dynamic change, and two interrelated systems of equations are required.

4.3.1 Background

LQG was fundamentally formed from already established principles in QM and GR, making it largely consistent with known physics. Research in this theory began in the late 1980s, with Lee Smolin, Abhay Ashtekar, and Carlo Rovelli [33] as key scientists who played a role in its development.

The birth of this theory was when Lee and Rovelli solved the Wheeler-DeWitt equation[7] [34] using the Ashtekar variables [35]. The Ashtekar variables are a rewritten, quantised form of GR. The physical property of position is represented in terms of connections that encode the spacetime curvature, and momentum is represented by triads that encode area and volume. Spinors, a mathematical object, were used to encode the quantum property of spin (Section 3.4).

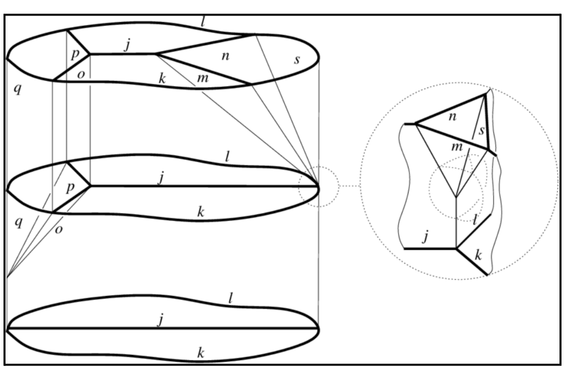
4.3.2 The Structure of Space



As stated earlier, in this theory, space is created by discrete units of space that are connected to each other by spin networks in a graph-like structure, illustrated in Figure 4.3. The minimum volume of a unit of space is the Planck length cubed.

Nodes, the central points seen in Figure 4.3, add to the volume of space. The edges that connect nodes are labelled with a specific spin that encodes the surface area covered. Physical quantities like area and volume have a discrete spectrum, which means that they can only take on certain values. The connections of nodes and edges form loops of LQG that encode information about the curvature of spacetime [36].

Figure 4.3: A mathematical model of a spin network [37]



Over time, these spin networks evolve as new nodes and edges form, and edges make different connections. This evolution is illustrated by spin foam. Spin foam displays the different frames of a spin network over a period of time [36]. The points where evolution occurs are the vertices, as magnified in Figure 4.4.

[7]Wheeler Dewitt equation: a timeless, background-independent equation that describes the quantum state of the universe.

Figure 4.4: Spin foam [38]

4.3.3 Consistencies

LQG has been used to accurately compute the amount of entropy in a black hole, such that it is consistent with the Bekenstein-Hawking theory [39]. The Bekenstein-Hawking theory states that the entropy[8] of a black hole is directly proportional to one quarter of its surface area. This brings validity to LQG.

4.3.4 Experiments

As seen with string theory, due to uncertainty about how to conduct experiments on the Planck scale, no experiments have confirmed LQG completely. Still, certain observations could indicate that it is valid [33].

Explosions caused by mergers of binary neutron stars or black holes release ultra-high-energy cosmic waves or gamma ray bursts. The particles possess a lot more energy than what is produced in a particle accelerator, and have travelled long distances. The journey to Earth can take billions of light-years, amplifying small effects. Additionally, the expansion of the universe causes small fluctuations at the Planck scales to become larger and detectable [33]. Detecting these small effects could provide data that gives insight into the validity of LQG.

4.3.5 Limitations

4.3.5.1 Special Relativity

Though LQG was developed based on established principles in relativity, it is surprisingly inconsistent with some special relativistic principles. Specifically, the speed of light may not be constant. Due to the granular structure of LQG, high-energy photons may interact differently with the structure of space than low-energy photons. The indication is that high-energy photons travel slower than low-energy photons [40]. Additionally, an object travelling at relativistic speeds, does not only appear shorter, but the apparent size of space chunks is also affected. This would lead to contradictions with the assumption that the laws of physics are the same in all inertial frames [41].

These inconsistencies could have certain implications, such as:

- Special relativity is not an accurate theory,
- Experimental data have proved special relativity, and the data were collected by highly precise instruments, such as atomic clocks, that would have accounted for the effects of quantum gravity, or

[8] Entropy: The number of different ways in which something can be arranged on the inside, provided it appears the same on the outside. A system with a high amount of entropy has a lot of disorder and randomness. An example would be that a messy room has a high amount of entropy, contrasted with a neat room that has a low amount of entropy.

- Special relativity must be modified such that the theory holds even when the speed of light is dependent on its energy.

4.3.5.2 The Problem of Time

The problem of time refers to how the Wheeler-Dewitt equation does not incorporate time as a variable, as introduced in Section 4.3.1. Hence, the passage of time, causality, and dynamic changes in the universe are not represented clearly. In LQG, time is incorporated in spin networks as an equal partner to space [36]. It is directionless in this incorporation. However, in spin foam structures, time is reintroduced when considering how spacetime has changed over time. This is a problem, since over here time is unidirectional, which would make it a "special" dimension, since dimensions usually do not have a specific direction. Additionally, time would be accounted for twice in LQG, which is another problem. There is a debate about how time should be represented, which is as much a philosophical issue as a scientific one.

4.3.5.3 GR on Large Scales

A theory of quantum gravity must reproduce GR on large scales. This same principle is seen in the way QM is reduced to Newtonian mechanics for large masses, and SR reduces to classical kinematic equations at speeds much smaller than the speed of light. At present, it is uncertain if the granular structure of LQG resolves into the smooth, continuous geometry of GR [36]. This is because it is a mathematically difficult problem to solve. Some believe that further investigation could resolve this gap, while others argue that LQG is fundamentally flawed.

4.3.6 Connection to String Theory

Having two competing theories may be essential to the evolution of science and new discoveries. Indeed, some have suggested that joining forces is the way forward [42]: LQG studies parts of space itself, whereas string theory focuses on how objects would behave within space.

Others believe LQG is a method that can be applied by string theorists [33]. Mathematical methods developed in both theories can be applied to each other. An alternate view is that if the additional dimensions in string theory are validated, they could be incorporated into LQG.

4.4 Other Approaches

4.4.1 Asymptotic Safety

Asymptotic safety is a method that focuses on a new approach to deal with the problem of nonrenormalisability in quantum gravity [43]. Asymptotic safety suggests that when there are very high amounts of energy, like in the Planck scale, the strength of a gravitational field reaches a fixed point - it is no longer responsive to changes in energy [44]. If this fixed point exists and the behaviour of matter at this point can be described using a finite number of physical parameters, the behaviour of gravity can be predicted at all scales. This theory by itself may not be sufficient in finding a theory of everything. Rather, it is likely to coexist or be related to other quantum gravity approaches, such as ST or LQG.

4.4.2 Quantum Field Theory on Curved Spacetime (QFTCS)

QFTCS is an approach that combines QFT and GR in a very direct manner. It takes the theory of QFT, which explains how particles interact on flat spacetime, and instead applies it to a situation where spacetime is curved [45]. However, this theory does not consider the fundamentally dynamic relationship between mass and the curvature of spacetime as described in Section 2.1. The background is still fixed. For this reason, it is only valid in scenarios where the gravitational feedback is negligible. It cannot be applied to situations where gravitational feedback is essential, such as Hawking radiation [45]. Hawking radiation suggests that a black hole loses mass with time. This loss of mass should alter the curvature of spacetime in the black hole, but this change is difficult to account for. One of the key criteria of a successful theory of quantum gravity is that it is background independent, so this theory is incomplete and invalid.

Still, it has been useful to study some cosmological phenomena, such as spontaneous particle creation, so it does still provide some conceptual insights.

4.4.3 Supergravity

The theory of supergravity is strongly linked to string theory, since it combines supersymmetry with GR [46]. As explained in Section 4.2, supersymmetry is the idea that each boson has a partner particle that is a fermion. In this way, the particle that is responsible for gravitational force, gravitons, must have a gravitino counterpart. Adding a gravitino partner is a way to make the theory renormalisable and more mathematically consistent. Additionally, the compactified extra dimensions mentioned earlier are reduced to 4-dimensional spacetime in this extension of the theory. The primary concern, as seen with string theory, is that supersymmetry is unproven, and supersymmetry must be true for a theory of supergravity to be valid.

DISCUSSION

The purpose of this paper was to provide an introduction to the different approaches to quantum gravity. It started with an overview of quantum mechanics and relativity, and then went deeper into where the conflict between them lies, and looked at different ways in which these conflicts could be resolved.

In string theory, the way particles are viewed changed from zero-dimensional points to one-dimensional strings. Though it initially seemed like a promising theory, since it was mathematically consistent and it united the four fundamental forces, there are still many gaps: There is no experimental data to confirm it, and there is no proof of supersymmetry or additional dimensions. Supergravity is an extension of string theory that introduces a graviton-gravitino pair, but it relies on supersymmetry. Some believe that supersymmetry is unlikely to be true because they believe proof of it would have been discovered by now.

Loop quantum gravity may be a more promising approach. It is focused on quantising the structure of space or spacetime, and it is an inherently background-independent theory, which are both important aspects of a theory of quantum gravity. In this theory, space is constructed using nodes (chunks of space) and edges (connecting the chunks) as a way to encode quantum properties (spin). It was formulated on well-established principles and is workable in 3 spatial dimensions + time. It is also more reliant on cosmological observations and data than string theory is, making it easier to validate. Still, like with string theory, there is no experimental data that explicitly confirms it. Furthermore, there are some inconsistencies with special relativity, the problem of time, and the uncertainty that LQG appears as smooth, continuous spacetime on large scales.

Some less prominent approaches include asymptotic safety and QFTCS. Asymptotic safety is an example of a less prominent approach. Even though gravity is nonrenormalisable, it suggests that there is a finite point, which would make mathematical calculations easier. It is unlikely to be used as a complete theory of quantum gravity. With QFTCS, its background dependence makes it difficult to account for dynamic changes to the curvature of spacetime. Unlike ST and LQG, it is not a fundamental theory and does not start from the first principles.

Though there is no dearth of ideas, the key current limitation is with testing theories of quantum gravity. A lack of prospective experimental procedures means that it is difficult to validate these potentially successful theories.

CONCLUSION

This paper provides a scientifically accurate and accessible overview of the key approaches to quantum gravity, explaining the strengths and weaknesses of each theory. Centrally, experimental data is key for determining which theories are valid. Since there is a lack of this, there is more room for speculation about whether ST or LQG is correct. There is agreement that less prominent theories are not by themselves contenders of a theory for QG.

Still, the theories that have been developed are largely mathematically consistent. Even if they are not successful theories, their development can lead to useful insights. An example of this would be that QFTCS was useful to study spontaneous particle creation. Furthermore, the mathematical tools that have been developed for each theory are transferable across the other. Some say that collaboration and combining ST and LQG to form a complete theory is a potential possibility, since LQG can accommodate the additional dimensions posed by ST. In the end, scientific observations shall guide the path to a well-grounded theory of everything.

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