Analysing Gravitational Models in Quantum Physics: Which Describes Our Universe Better, Loop Quantum Gravity or M-theory?

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Abstract

Gravity has a remarkable macro-scale description as put forth by the genius of Albert Einstein in 1915. However, modern physicists are conflicted by the many ideas of gravity that apply to quantum theories. Although Causal Dynamical Triangulation, Quantum Graphity, and Information Theory are all well-formed candidates for a quantum theory of gravity, this paper focuses on M-theory and Loop Quantum Gravity, the most researched of the five. To explore which theory describes our universe better, an analysis of its application to other parts of physics should be made with clarity. This should then be assisted with an explanation of gravity in the quantum scale, as done in this paper with particular emphasis on quantum cosmology and astrophysics.

Keywords

Loop quantum gravity, M-Theory, Quantum gravity, Effective field theory, String theory, Topology, Cosmological constant, Black hole information paradox, Spacetime, Quantum chromodynamics

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A brief introduction to Quantum Gravity

In his general theory of relativity, Einstein succeeded in depicting how gravity works by describing it as the curvature of spacetime (1, 2). Physicist John Wheeler famously remarked that spacetime tells matter how to move, and matter tells spacetime how to curve (3). This description of gravity is accepted without dispute. It has many observations to support it, such as the bending of starlight (4) and the detection of gravitational waves at the Laser Interferometer Gravitational-waves Observatory (LIGO) (5). However, even such a monolithic theory predicts singularities of infinite densities for black holes and the big bang. Wheeler believed that such infinities were the consequence of ignoring a quantum effect, which he thought, if appropriately applied, would resolve the issue and result in a perfect description of gravity that would apply to anything and everything (6).

Since the birth of quantum physics, where many interactions of elementary particles were studied carefully, we have a defined understanding of several phenomena in quantum physics that are validated by experimental evidence. One of these observations is that four fundamental forces exist: the strong force, the weak force, the electromagnetic force, and gravity. These fundamental forces, with the exception of gravity, are consequential to the exchange of force-carrier particles, or bosons. The Standard Model is an effective field theory (Appendix 1) that mathematically assigns the sets of bosons to forces: the gluon for the strong force, $W^{\pm}$, Z bosons for the weak force, and photons for the electromagnetic force (7). Even though this model has provided many accurate predictions observed experimentally, many quantum effects remain without explanation by the Standard Model that is called physics beyond the standard model (PBSM) (8). In the interest of this paper, the Standard Model does not incorporate general relativity and fails at the scale at which gravity plays a role in the quantum realm.

Gravity is a force with an infinite range like electromagnetism but is fundamentally different in its description, as already mentioned. It acts as an attractive force on all objects and as forms of energy in our universe, from planets orbiting a star, to atoms that make such magnificent celestial objects. A theory that fills the void of the Standard Model should include a quantum description of a given gravitational field that works coherently with the macroscopic description in general relativity. Furthermore, a theory that can describe such fields would resolve the problem of singularities that has excellent application in cosmology and astrophysics. It should also solve the black hole information paradox, which is expanded upon later in this paper. Such a theory is the holy grail of physics, otherwise known as the Theory of Everything. However, is such a theory even possible? This presents the problem of quantum gravity.

The problem of Quantum Gravity: A question persisting over several decades

The idea of quantum gravity introduces many "problems" that should be definitively answered by any proposed model without making many assumptions. The ultimate essence of such a theory is to prevent, and not create more ambiguity. This is the first and foremost problem encountered by theoreticians in approaching this problem. The scale at which gravity is relevant in quantum physics is the Planck scale (9) of time, t_p, length, l_p, mass, m_p, and temperature, T_p, such that:

$$t_p = \sqrt{\frac{G\hbar}{c^5}} 5.39 \times 10^{-44} s$$

$$l_p = \sqrt{\frac{G\hbar}{c^3}} 1.62 \times 10^{-35} m$$

$$m_p = \sqrt{\frac{c\hbar}{G}} 2.18 \times 10^{-8} kg$$

$$T_p = \sqrt{\frac{c^5\hbar}{G k_b^2}} 10^{32} K$$

At such scales, objects of any dimension would be indistinguishable from point-like particles, evincing practical experiments and observations to be impossible, at least with current technology. We can also observe two other key problems that must be overcome by a quantum model of gravity. Firstly, the theory should be consistent at such small scales and high energies as represented by the Planck scale, hence by definition should not be an effective theory, but a definitive one. Secondly, the constants that are used for the derivation of these scales should not arise solely from quantum theory such as " $\hbar$", or from general relativity like the gravitational constant "G". This highlights the fact that a quantum model of gravity should be an amalgamation of both general relativity and quantum theory, which share very few similarities, which by itself is a problem, causing multiple others (10).

One of the key differences between general relativity and quantum theory is background independence. A theory or framework is called background independent if it allows changes to happen to its background coordinate system (Appendix 1) (11). General relativity is quintessentially background independent, with a dynamic entity that warps due to presence of mass and energy. On the other hand, quantum background coordinate systems are consistently flat and quantum calculations cannot be attempted in non-flat geometry, because any successful attempt to do so requires assumptions to be made that are either not yet proven or are not representative of the universe in which we live. This shows that general relativity and quantum physics have significant differences that should be overcome by a supposed quantum model of gravity, which is a challenge. In the following sections, this paper will make comparisons between M-theory which is formulated with a fixed background and Loop Quantum Gravity (LQG), which is background independent.

The problem of time (12), as it is conventionally referred to, is very strongly connected to background independence. In quantum mechanics time is absolute and universal at any given point of space, which is at odds with general relativity, which treats time as an entirely new dimension, deeming it to be relative. Again, the crux of a quantum theory of gravity would have to have a new description of time that encompasses the diametric nature of both general relativity and quantum theory.

M-theory and Loop Quantum Gravity are both commendable frameworks that attempt to resolve many of the problems that are mentioned in this section. In order to compare and evaluate these contesting postulants of quantum gravity, this paper will gauge the merits of the theories in providing appropriate solutions, as well as their applications in other expanses of physics as discussed in the introduction.

Introduction to M-theory

To describe gravity in the quantum realm, theoreticians proposed that elementary particles may be vibrational states of a one-dimensional object, a string. With this idea, gravity can be quantised with a force carrying particle, or boson, called the graviton (13). The origin of this theory is attributed to the paper written by Gabrielle Veneziano which attempted to explain strong nuclear interactions, but interestingly gave rise to the idea of string theory. The strong nuclear interactions were better described by a better model called Quantum Chromodynamics (QCD), and string theory became a possible theory of quantum gravity (14).

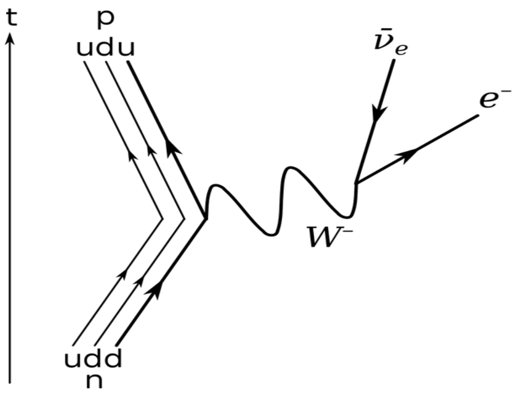

Figure 1: Feynman diagram showing beta-minus decay, sourced from Wikipedia. (2022). List of Feynman diagrams. [online] Available at: https://en.m.wikipedia.org/wiki/List_of_Feynman_diagrams [Accessed 18 Apr. 2022].

The physicist Richard Feynman developed a schema for the interactions between elementary particles called Feynman diagrams, shown in Figure 1. In such diagrams, the worldlines of particles are visualized through their progress in time. There are many philosophical significances to worldlines as well, the most interesting being J. C. Fields' "A Mathematical Fantasy" (15). He postulated that there could be a spiritual worldline that is traced throughout a person's lifetime from birth to death. He described these to be simple at juvenescence, developing into sophisticated worldlines later in one's life. This is somewhat analogous to the worldline of a particle, just a description of its interactions over time. M-theory expands on this idea by applying the aforementioned hypothesis that particles are one dimensional strings that have "worldsheets" as seen in Figure 2.

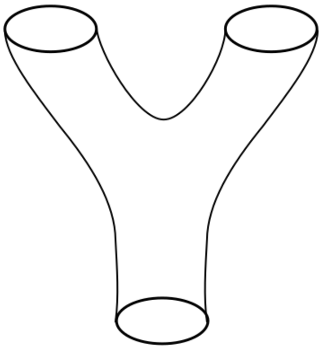

Figure 2: Representation of a worldsheet, sourced from commons.wikimedia.org. (n.d.). File:World lines and world sheet.svg - Wikipedia. [online] Available at: https://en.m.wikipedia.org/wiki/File:World_lines_and_world_sheet.svg [Accessed 18 Apr. 2022].

Feynman's representations are generally, grouped into Perturbative Quantum Field Theory, which remains one of the most rigorously and precisely tested theories in the entirety of physics, more so than general relativity itself. Its predictions correlate most precisely to empirical data, with an agreement of 10^{-8} decimal places (Appendix 1) (22). A non-perturbative definition of M-theory is still missing and will require a far deeper understanding of quantum physics, which we currently do not possess.

String Theories: The origin of a superstring theory

Initially, there were five descriptions of string theory named type I, type IIA, type IIB, SO (32) heterotic, and $E_{8\times}E_8$ heterotic (16). The different theories propose slightly differing description of strings that make up matter. For example, type I is the only version that proposes a string with endpoints, otherwise, not closed. Whereas all of the other versions propose closed strings which form loops (17).

In the late 20th century, there was a period of great productivity for string theory known as the String Revolution. In 1995, Edward Witten proposed that the variants of string theory are merely different mathematical descriptions of the same theory, such that they can be unified under one grand and mysterious theory: M-Theory. The theories were consistent with one another by the relation of S and T dualities (18). S dualities are similarities in the description of interactions between particles. Strong interactions, as described in some of the theories, were weak interaction in others (19).

T dualities were based on topological consistency in between the different types of strings. One of the key principles that led to the unification of these theories is the mathematical notion that a string propagating around a circle of radius X is equivalent to that of a circle with radius $\frac{1}{X}$ (20).

This helped merge the heterotic string variations (SO(32) and $E_{8\times}E_8$) and also the type IIA with type IIB. T-dualities are also relationships between these theories as described by the phenomenon of compactification, which is explored in greater depth in the following subsections.

Geometry and topology

It is understood without much question that we live in a four-dimensional spacetime continuum, which is composed of three spatial dimensions and one time dimension. However, in many instances, working with extra dimensions results in a more flexible and amenable mathematical theory. This is majorly accounted for by quantum anomaly, which occurs in the attempt to give a perturbative definition to quantum gravity (refer to Introduction to M-Theory), where the classical and quantum applications of a theory do not correlate. Due to such restrictive conditions many theorists adamantly believe that quantum phenomena can only be explained by a model of quantum gravity if extra dimensions existed. Such is the case with M-theory which is comprised of 11-dimensions (Appendix 2). One of the main criticisms of string theory is that it makes such unsubstantiated assumptions (refer to Contributions and Criticisms of M-theory). This section covers how these extra dimensions came to be, and where they are if they exist.

Theodor Kaluza extended Einstein's general relativity to work in five dimensions, with an extra spatial dimension, but was lacking the idea of where exactly this 5th dimension could physically exist (Appendix 1) (21). Simultaneously, Oskar Klein, inspired by the works of Heisenberg and Schrodinger, introduced a quantum interpretation to Kaluza's classical theory (23). This is commonly known as the Kaluza-Klein theory and relies on the idea that extra dimensions could be "curled up" into microscales or compactified (Appendix 1) .

A generalisation of the Kaluza-Klein theory is importantly what describes all of the additional five additional spatial dimensions of M-theory. Through this topological process of dimensional reduction, we obtain complex manifolds called Calabi-Yau spaces (Figure 3) which can be used to represent the compactified dimensions (24). This can be taken as an important step towards the union of quantum theory and relativity and is arguably the most important mathematical reinforcement of M-theory.

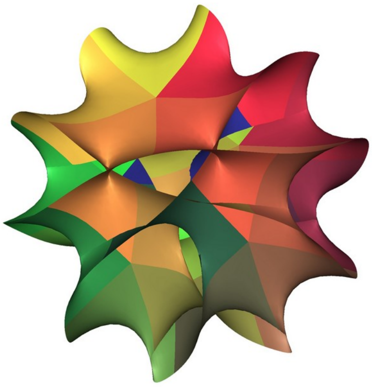

Figure 3: Calabi-Yau spaces, sourced from https://en.wikipedia.org/wiki/Calabi%E2%80%93Yau_manifold

M-theory Contributions and Criticisms

Extra dimensions themselves are a large criticism to M-theory. They are one of the many assumptions that are made in order to forcibly make M-theory function as a theory of quantum gravity. As seen in the previous section, string theorists point to the compactification of higher dimensions as a justification to the existence of higher dimensions. They claim that the limitations are introduced by the high amounts of energy required to access these small lengths (Appendix 2). An approach to warrant the existance of these extra dimensions is on the philosophical assumption that the observable universe is a four-dimensional subspace of a space that exists in higher orders of dimensions. This approach is called brane cosmology and remains unsupported by observations or experiments. The Randall-Sundrum model in brane cosmology (25) depicts bosons to be consequential to strings with endpoints attached to multiple four-dimensional subspaces. Gravity is then theorised to be closed strings that propagates in the extra-dimensional space, which provides a geometric depiction for an attractive force. The theory serves as an applicative model of quantum gravity as it provides us with an actual manifestation of quantum gravity in our physical universe. Such theories will deepen our understanding of the universe but do not have many ways by which they can be tested for validity, rendering them to be inept.

Moreover, string theory requires supersymmetry to be true, where all elementary particles have a sibling particle of a higher mass (26). Such particles have not yet been observed by any collider experiments and are not likely to be observed because incredible amounts of energy is required to find these particles. A clear comparison is made later in this paper, that discusses the issues of supersymmetry.

As shown in Figure 2, an abstract spacetime of moving strings results in gravitational fields and is known as Ads/CFT correspondence (appendix 1). This remains to be the only partially background independent interpretation of M-theory (27). This could be a successful formulation by which both quantum and classical physics can unite to form a background independent Quantum Field Theory (QFT), the benefits of which were deliberated upon in the beginning of this paper. While this may be true, in order for this to reflect reality, the existence of strings will need to be validated. This is yet to happen.

M-theoreticians have proved several theorems of certain abstract mathematical spaces, which has made tremendous improvements in the field of topology and pure mathematics. Even if so, these are not contributions that are specifically relevant to developing a quantum theory of gravity, nor do they have much purpose in other areas of physics. This once again emphasises on the beauty of the mathematics in string theory, which is very comprehensive, rigorous, and elaborate. It is undeniable that M-theory is very close to imitating QFT. The same mathematics used in string theory calculations can be used and applied to mechanisms regarding the interactions of particles in Standard Model physics or even in Perturbative QFT.

String theory is also key to the development of the holographic principle. In a time where relativity and quantum mechanics tussled in a scientific controversy of the black hole information paradox (Appendix 1), string theory was used to settle the debate. Leonard

Susskind correctly argued that the information lost in a black hole is conserved and stored in the boundary of a black hole, with a reference to the AdS spaces in AdS/CFT correspondence (27). This “wealth of anecdotes” as Sean M. Carroll calls it, was released in a book called The Black Hole War (30) written by Susskind, in which he theorised a holographic universe. This debate in turn led to the holographic principle, which differentiates between the lower dimensional CFT spaces and the higher dimensional AdS spaces and leads to a better understanding of black holes and spacetime geometry.

The biggest problem of M-theory is the fundamental flaw inherent to AdS/CFT correspondence. The term “Anti-de Sitter” describes a space with a negative cosmological constant. Essentially, there are three different descriptions to the universe in terms of its expansion and curvature which are de sitter, anti-de sitter, and Einstein-static. Due to observations of a distant supernovae in 1998 (28), it was concluded that the expansion of the universe is accelerated. This showed that the universe should have a positive cosmological constant. As AdS/CFT correspondence in M-theory requires a negative cosmological constant in order to work, it was then concluded that string theory can provide an explanation of quantum gravity for another universe, unfortunately not this one. However, the recent works of Gerard t' Hooft and Leonard Susskind, as previously discussed, show that the flaw of AdS/CFT correspondence has wider application in cosmology and astrophysics (29), where it has been used to resolve the black hole information paradox.

Introduction to Loop Quantum Gravity: A symphony of philosophy and mathematics

Loop Quantum Gravity (LQG) is an approach to quantum gravity which is comparatively newer than M-theory. The idea originates from a question that precedes the principles and laws that are relevant to quantum mechanics or general relativity; What is motion? What does it mean to move? What is stationery and what is not? All of these questions were attempted to be answered by many great physicists and philosophers like Newton, Leibniz, Descartes, among others. In relevance to this paper, Leibniz’s description of motion can be applied to quantum mechanics, whilst Newton’s and Einstein’s relativistic descriptions obviously describe motion with accordance to general relativity.

In quantum mechanics motion is described by the position and momentum of a particle’s wave-function in a background coordinate system and the manner in which it evolves over time. This means that quantum mechanics is not background independent (refer to The Problem of Quantum Gravity). The wave-function is the mathematical description of the distribution of possible positions and momenta of a given quantum object. The position and momenta distributions can be resolved into definite, measured values by applying specific operators to them. For example:

$$\hat{x}\Psi(x,t)=x\Psi(x,t)$$

$$\hat{p}\Psi(x,t)=-i\hbar\frac{d}{dx}\Psi(x,t)$$

Where $\hat{x}$ is a position operator and $\hat{p}$ is a momentum operator. The equations themselves contain a background dependent variable, x or are described by differentiating with respect to the said variables, as seen in the equations above.

On the other hand, motion in general relativity is described by morphing the background coordinate system, or spacetime. The relative motions of various objects are described as moving in geodesics that is caused by this curvature to spacetime, which is gravity. This highlights the fact that general relativity has to be background independent.

In Loop Quantum Gravity, spacetime is quantised and quantum operators act on it (like in the equations above), to make a background independent framework that incorporates general relativity in quantum mechanics. Even if a similar type of background independence emerges in M-theory (Ads-CFT formulations), this background independence is based on too many assumptions which are unlikely to represent reality (refer to Contributions and Criticisms of M-theory).

The following sections explore how effectively LQG resolves the background independence problem, and hence or otherwise, quantum gravity itself.

The Quantisation of Spacetime itself

In order to quantise spacetime, it is important to define it as a metric that encapsulates the background coordinate system in general relativity. As made clear in the previous subsection, the wave-function is a distribution of probability that presents uncertainties about the positions and momenta of an object against a fixed background. However, if the idea of uncertainty and superpositions were applied to the background itself, it is no longer "fixed" and can be thought of as a dynamical entity (31), which effectively can be used to describe gravitational waves in the quantum scale.

In order to satisfy that condition, we would have to mathematically describe the evolution of the metric over time, rather than the properties (like position and momentum) of a quantum object in the given metric. This was attempted by John Wheeler and Bryce DeWitt, now known as the Wheeler-DeWitt equations (32).

Arnowitt-Deser-Misner (ADM) formalism and Canonical Quantum Gravity

The Wheeler-DeWitt equations are based on ADM formalism, which is briefly a formulation of general relativity that describes abstract ideas that are key to LQG. In this formalism, abstract spaces of 3D metrics form the 4D spacetime that we know of. This allows a change to occur to the geometry of spacetime as an object moves on it, providing a background independent framework. To build on these primary principles, the Wheeler-DeWitt equations quantise the abstract space times and derive the background independent properties to be quantum operators, as previously defined. Even if this was a promising attempt to quantising spacetime and general relativity, the Wheeler-DeWitt equations remained unsolvable and impossible to verify, which led to many physicists abandoning the idea of LQG, or canonical quantum gravity; as it was known then.

In LQG, the space of metrics is methodised into spaces of so-called connections. These are mathematical functions that describe the evolution of a property vector, like position or momentum over its movement in space. It is known that, when a vector is shifted along a non-flat coordinate system, its properties may change (33). Einstein noticed that by the use of topology, the change that occurs to the background coordinate system from the transport of a vector, can be deduced. In his final years he attempted to rewrite general relativity with this new idea in mind but failed to do so. A widely celebrated breakthrough occurred when in 1986, Abhay Ashtekar introduced a variation of the aforementioned connections. He reasoned that an additional property vector; the angular momentum, could be used to rewrite general relativity. This was a grand success and resulted in the Ashtekar variables (34). When these were applied to the space of metrics, the consequential formulation tended towards a space of fields, like in quantum field theory.

Later, Lee Smolin and Carlo Rovelli realised that the Wheeler-DeWitt equation could be fully solved when representing the 3D slices of space using the Ashtekar variables. This was a feat of great success for LQG and was an accomplishment in theoretical physics that placed LQG as a plausible postulate for a theory of quantum gravity. As Smolin and Rovelli appraised this new discovery for physical significance, they found that 3D spaces could be described as a large interlacing of several loops. The loops serve as a unitary and elementary circuit of gravitational fields that could be used to describe gravity in a quantum realm. As a result, what is obtainable is a regular spacetime that begins to pixelate into circuits of gravitational fields at the Planck scale as expected (refer to The Problem of Quantum Gravity).

Contributions and criticisms of LGQ

Firstly, it is important to note that LQG has considerably less amount of resources and scientists researching it, as expanded upon later in this paper (refer to “Conclusion”). It is possible that many of the breakthroughs relevant to the field are yet to be made. Therefore, the future may behold many exciting discoveries to happen in this relatively unexplored, yet promising framework. It is appreciable that LGQ makes testable hypotheses that can be compared to measured observation, which is very important for a physical theory. One of these is that LQG predicts that quantised spacetime manifests itself to have very small differences in the speed of light for different colours of light (35). With improvement in facilities and investment into research, we can devise several experiments that can test the validity of these claims. Secondly, loop quantum gravity allows us to predict the entropy of a black hole, which provides valuable insights in astrophysics and cosmology (Appendix 3).

The no-hair conjecture of general relativity characterises a blackhole by mass, charge and angular momentum (Appedices 1, 3) . A violation of the second law of thermodynamics can occur if a system of non-zero entropy were to be sucked in by a blackhole, whereupon the entropy of that system would appear to decrease. Hawking and Beckenstein assigned each blackhole an entropy that is dependent on its area, *A*, of the event horizon (Appendix 3).

$$S_{BH}=\frac{K_B A}{4 l_p^2}$$

Loop Quantum Gravity associates a quantum, geometrical interpretation of the area and topology of the event horizon to the microstates of a blackhole. This explains entropy in blackholes. The theory's main success is from a direct computation of the entropy of several blackholes and agrees with the work of Hawking and Beckenstein (36), providing a fundamental explanation to blackhole thermodynamics.

LQG also resolves the blackhole information paradox and provides an explanation for the Blackhole Firewall; the gruesome postulation that an observer passing the event horizon of a blackhole would die by being quantised into Planck scale densities. In 2014, Carlo Rovelli and Francesca Vidotto proposed that there is a "plank star" inside every blackhole which eliminates the idea of a singularity and provides a quantum explanation to the blackhole information paradox.

Even so, Loop Quantum Gravity remains to be an underdeveloped theory that does not incorporate fermions in its description of a quantised spacetime. In simple words, LQG quantises space time to solve the problem of quantum gravity, but heavily relies on QFT for the explanation of the existence of matter in our universe. This violates the idea of an all-encompassing grand unification of quantum and classical physics.

Earlier, this paper presented evidence that there could exist effective field theories that are only applicable to certain scales or conditions. Since we do not know much about general relativity at the quantum scale, it could remain to be an effective field theory. This is a valid criticism to LGQ, as quantising general relativity would be ignoring the basic degrees of freedom given to merit general relativity if it is only an effective field theory (37). This would mean that the very base upon which LQG is built, is inapplicable to the universe. However, current consensus on this matter is missing, and the idea of incorporating general relativity to quantum mechanics would be ineffectual if general relativity were only an effective field theory.

Conclusion

There is a certain *hamartia* inherent for any quantum model of gravity, which is that we do not currently know much about even the very rudiments of our universe. There are many unanswered questions in theoretical physics, such as the continuity of spacetime, the existence of unfound particles that may be merely a result of the lack of technology and the entirety of physics beyond the standard model as explored earlier in this paper. It is therefore important that a new framework of quantum gravity is fabricated to be parsimonious with the assumptions it makes.

M-theory was originally developed as a way to describe interactions in the strong force, where particles seemed to form bonds by certain characteristics that made them analogous to a string, hence the term "string theory". When string theory was outdated by a better description of strong interactions, Quantum Chromodynamics, it became an obvious model for a quantum theory of gravity. Loop Quantum Gravity, on the other hand was formulated solely towards solving quantum gravity and in some sense was bound to run into the same issues unresolved by the much older M-theory. Certainly, Loop Quantum Gravity addresses and solves these issues with conditions that are pre-existent whereas string theory is reliant on more abstract ideas, that may or may not be true.

One of such issues is the large number of assumptions made by string theory which includes supersymmetry and many extra-dimensions. On the contrary, Loop Quantum Gravity only requires the 4D in which we live and does not require any further abstraction than the idea of quantised spacetime, which is yet to be disproven (Appendix 1). This makes Loop Quantum Gravity a relatively better scientific framework, as it does not force the universe to fit its description, instead it is built upon unambiguous facts, that we know are absolutely true.

M-theory is a far more well-established theory that is much more developed than LQG. M-theory manages to provide an explanation for the matter that makes up the universe, which would be required by a theory as fundamental as one that depicts quantum gravity. Proponents of M-theory may consider it to be a much better unification of gravity with the other forces, as it describes gravity as being manifested by hypothetical bosons called gravitons. If all of the other fundamental forces have a specific and correspondent boson, why should gravity not? Contrarily, LQG provides a description of gravity by explaining it as the result of gravitational fields produced by elementary quantisation of spacetime in the form of loops. One can see that LQG does not attempt to fully complete the standard model, like M-theory, but sufficiently unifies general relativity to quantum mechanics. Perhaps gravity is not like the other fundamental forces and so does not require the existence of certain force carrying particles.

At the same time, M-theory does not make any testable hypotheses and lacks the consistency needed for a scientific theory. As seen, it makes many assumptions that cannot be tested for validity or falsified, and therefore cannot present itself to be a solution for quantum gravity when it naturally creates more ambiguity than it resolves. Nevertheless, it has improved our understanding of the universe in which we live and has presented solutions elsewhere in physics. It has remarkable mathematical and philosophical applications in cosmology, standard model physics, quantum field theory, and even topology and pure mathematics. Then again, what does it mean to have a physical theory? It is very clearly not only the rigour of mathematics that defines a theory of quantum gravity, despite it being an important aspect. The mathematics of string theory is exquisitely elegant but does not contribute greatly to developing the reality of a quantum model of gravity. Karl Popper's Conjectures and Refutations reviews the principle of falsification (38), which quite appropriately, applies to M-theory. When criticised, M-theory persists to avoid root problems caused by its underlying assumptions by simply presenting an alternative interpretation of the theory. A theory that does not provide us with any testable hypothesis suffers from the same issue. This makes M-theory impossible to falsify, as expressed very articulately by theoretical physicist, Peter Woit, in his book "Not Even Wrong." (39).

It can so be said that Loop Quantum Gravity has the potential to make several more breakthroughs when provided with the right resources, even becoming a prepossessing model of quantum gravity. More so than M-theory, which fails to provide any conclusive, complete, or fully formed predictions that are vital for a scientific theory as fundamental as the Theory of Everything.

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Appendix I: Subject Relevant Terminologies

1. **Spacetime** is the fabric of the universe, which is composed of the three spatial dimensions and one time dimension. It denotes the idea that travelling through space and travelling through time are not two separate actions independent of each other. Many Loop theorists are working towards a testable hypothesis that can be used to check for the validity of a quantised space time, however no such methods yet exist.

2. **Starlight** is the light emitted from a distant star. Einstein showed that light moves in curved paths that are caused by the warping of spacetime.

3. **Singularities** are the origin or centre of a blackhole, where there is an assumed infinite density.

4. **Bosons** are the force carrying particles. An exchange of these particles, results in a field of a correlating force being generated.

5. **An Effective Theory** is an approximation that works only in certain boundary limits, does not apply to all conditions and may not work at all orders of magnitude. An Effective Theory is used as a standard model and is not universal.

6. **Plank's constant** is the proportionality of the energy of a photon to its frequency.

7. $\hbar$ **(h-bar)** is Planck's constant divided by 2π.

8. **G** is the **Gravitational constant** and I commonly involved in calculations that involve an effect of a gravitational field.

9. **c** is the universal constant for the speed of light.

10. K_B **(Boltzmann's constant)** is the ratio of the molar gas constant to the number of molecules of a substance in a gram molecule

11. **Background independence** is the property of a theory that allows it to have a dynamic background coordinate system. If planets and other celestial bodies were actors, spacetime would be the stage and the background coordinate system. One could analyse that background independence makes a theory more deterministic, since such a theory requires fewer inputs to make a prediction on the development of a system. This is exemplary of the requirement of an elegant theory to be one with fewer free parameter, at least in a hypothetical theory of everything.

12. **Worldlines** are traces of interactions of a particle that is represented diagrammatically in Feynman diagrams.

13. **S dualities** are connections drawn between various theories on the basis of their descriptions of interactions.

14. **T dualities** are connections drawn between theories on mathematical basis of similarities in topology.

15. **Topology** is the study of geometry in spaces that are invariant under any continuous deformation.

16. **Strong interactions** are interactions of elementary particles that happen under the influence of the strong force.

17. **Weak interactions** are interactions of elementary particles that happen under the influence of the weak force.

18. **Compactification** is a topological process in which multiple dimensions are "curled" into smaller scales, that make them indistinguishable from lower dimensions at regular scales. An analogy to understand compactification is as such: a garden hose appears to be tube-like (3D) when looked at from a close distance, but by moving further, it begins to look more like a one-dimensional line.

19. **The Gauge Coupling Parameter** is a numerical value that determines the strength of the force exerted in an interaction of two or more particles. Theodor Kaluza extended Einstein's general relativity to work in five dimensions by introducing the idea of a dilaton field. When combined with the Gauge Coupling Parameter, it renders statistical probabilities of strings breaking and reconnecting.

20. **Supersymmetry** is the notion and assumption made in M-theory, that all particles must have a similar particle of much higher mass.

21. **AdS/CFT correspondence** is another type of duality that is found within superstring theories. It expands to, and is comprised, of the two ideas of Anti-de Sitter spaces (AdS) and Conformal Field Theories (CFT).

22. **The Blackhole Information Paradox:** when Stephen Hawking discovered hawking radiation, he proposed that information is lost in black holes, and is not preserved by hawking radiation. In both classical and quantum mechanics, the state of a system at a given point of time could be used, if needed, to determine its state at any other time. This contradicts Hawking's prediction, as information loss in black holes imply that the system's whose information is lost could not have a defined state in its past, present, or future.

23. **ADM formalism** or **Canonical Quantum Gravity** is a framework in which LQG is developed from. It depends on the idea that 4D spacetime is a superposition of multiple slices of 3D spaces.

24. **Entropy** is the measure of disorder in a system. The higher the entropy, the more information is stored in the system. The The no-hair conjecture of general relativity presents a blackhole to be of perfect order, implying no entropy. However, there are multiple combinations of microstates of a blackhole, arguing that every blackhole must have a non-zero entropy that is caused by this uncertainty.

25. **Property vectors** are mathematical descriptions of the momentum, position, angular momentum, etc of an object in a given space.

26. **Connections** are mathematical functions that describe the evolving of a property vector over its movement in a given space, such as the surface of a sphere.

27. **Spin foams** are topological structures that configure in manners that result in Feynman's path integral. They are essential quantum fluctuations of spacetime in Loop Quantum Gravity.

28. **The Second Law of Thermodynamics** states that the entropy of a system should be ever increasing for a system progressing through time.

29. The **wave-function** is an important principle upon which much of quantum mechanics is built. It posits that quantum objects cannot always have a definite position on a field until a measurement is made. In simple terms, the wave function of a quantum object describes the probability of the object being present in a given space.

30. **Perturbative Quantum Field Theory** Credited to the theory's prediction is the comparison of the anomalous magnetic dipole moment of an electron and the Rydberg's constant, which was measured by Gabrielse, G. et al. (2007) at Harvard, from an electron captured within a Penning trap.

Appendix 2: Eigenstate Equations Proof for The Unobservable Nature of Extra Dimensions

Introduction

In this paper, several references have been made to the multiple dimensions required in M-theory. The following is mathematical proof that the hypothetical extra-dimensions required may never be accessible to mankind.

Eigenstate Equation Proof

Let's consider that there is a particle in a box, the particle has a wave-function and a pure energy Eigenstate given by,

$$E\Psi = \frac{-\hbar^2}{2m}\nabla^2\Psi$$

If the box was considered to be our universe, the work-function outside the box and on the boundaries of the box could be made to be zero. Then, using partial differential equations involving the separation of variables, as work-function in certain conditions equals zero,

$$\Psi = A\prod_{i=1}^{n}\sin\left(\frac{m_i \pi x_i}{L_i}\right)$$

The operator Π shows that, the wave-function is a sine term of all m integers as an infinite series of products. Re-inserting this equation back to the Schrodinger's Eigenstate equation to obtain the energy state of the box, and only the box:

$$E = \frac{\hbar^2}{2m}\left(\sum_{i=1}^{n}\frac{m_i^2}{L_i^2}\right)$$

By assuming, rightly, that for the first d numbers of dimensions, the box has a large magnitude of width L, and in the last $(n - d)$ dimensions, the box has a small width l. Then the sum above can be divided into two, as such,

$$E = \frac{\hbar^2}{2m}\left(\sum_{i=1}^{d}\frac{m_i^2}{L^2} + \sum_{i=d+1}^{n}\frac{m_i^2}{l^2}\right)$$

When $L \gg l$, there is a small energy cost in traversing the bigger d dimensions, whilst there is a much greater energy cost with regards to the smaller ($n - d$) dimensions. It is mathematically understandable that the smallest energy cost is proportional to the inverse square of the widths of the dimensions. If the lengths associated with l were small enough, the energy cost associated with traversing at such small dimensions (possibly at the Planck scale, even if M-theory does not directly predict this) would be unattainable by any experiments mankind has conducted before. Therefore, these extra dimensions remain inaccessible and therein their existence, unprovable.

Appendix 3: Blackhole Thermodynamics

Introduction

To understand much of the ways in which the proposed theories of quantum gravity are applicable to the wider range of physics, several key references have been made to black holes and to how both M-theory and LQG resolve issues and paradoxes that are relevant to this field of study. This appendix is an expansion on the key principles of a black hole that give rise to the many problems that are encountered in the manuscript.

Black Body Radiation

It is understood that a vacuum is not truly empty due to phenomena like the Casimir Effect. Virtual particles and antiparticles can spontaneously appear and annihilate, conserving the time-averaged energy of the universe. When such an interaction occurs near the event horizon of a blackhole, the antiparticle is sucked into the blackhole, while the particle is ejected with a high enough velocity. This means that there is no annihilation of the particle and antiparticle. As interactions like these happen over and over, it appears that the black hole is radiating such particles like photons and neutrinos, whilst it loses mass by the absorption of antiparticles.

Even if this is a conceptually intuitive way of understanding black body radiation, Stephen Hawking proved through rigorous mathematics that the radiation can be a result of the extreme curvature to spacetime caused by a black hole. In essence, this is because of the indeterminacy of particle population and energy density caused by such steep curvatures. Hawking then coined the term black body radiation, which is also now called Hawking's radiation.

The Paradoxical Temperature and Heat Capacity Problem

The temperature of a blackhole due to black body radiation is given by the equation:

$$T_{BH}=\frac{\hbar c^3}{8\pi GM\,K_B}$$

Where M is the mass of a blackhole.

From the equation, the mass and temperature are inversely proportional to each other. This supports the hypothesis on black body radiation as discussed earlier.

Using the famed energy-mass equivalence principle of Eisenstein, we get,

$$T_{BH}=\frac{\hbar c^3}{8\pi GM\,K_B},\, E=Mc^2$$

$$T_{BH}=\frac{\hbar c^5}{8\pi GE\,K_B}$$

$$E = \frac{\hbar c^5}{8 \pi G T_{BH} K_B}$$

By taking the partial temperature derivative of the energy, we can get an expression for the specific heat capacity of a blackhole,

$$C_v = \frac{\partial E}{\partial T_{BH}} \vee v, p$$

$$C_v = \frac{-\hbar c^5}{8 \pi G T_{BH}{}^2 K_B}$$

A negative heat capacity is an absurdity as it shows that the temperature of a blackhole decreases with the amount of energy input into it. This simultaneously correlates with both the inversely proportional relationship of temperature to mass and the black body radiation.

The Entropy of a Blackhole

Entropy can be thought of as a measure of disorder of the amount of information in a system. The entropy of a blackhole can be thought of as the store of information within the blackhole, which intuitively should increase with size. To calculate the entropy of a blackhole we use the following identity :

$$\frac{\partial S}{\partial E} = \frac{1}{T_{BH}}$$

By the use of elementary calculus, and using expressions that were derived previously , we get:

$$\partial S_{BH} = \frac{1}{T_{BH}} \partial E$$

$$\int d S_{BH} = \int \frac{1}{T_{BH}} dE$$

$$S_{BH} = \int \frac{8 \pi G E K_B}{\hbar c^5} dE$$

$$S_{BH} = \frac{8 \pi G E^2 K_B}{2 \hbar c^5}$$

However, the idea of entropy is very confusing when applied to blackholes, which are not within the scope of the question at hand regarding quantum gravity. The many paradoxes presented by a blackhole are a few of the unsolved mysteries in physics and can potentially redefine our understanding of the universe in which we live.

The equations above are the works of Hawking and Beckenstein as mentioned in the manuscript. Loop Quantum Gravity also formulates the same equations in its own, separate way. This provides a fundamental theory for the aforementioned works of Stephen Hawking.