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Epistemology of Loop Quantum Gravity in the Context of Canonical Quantum Gravity

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Abstract

In the quest to comprehend the fundamental nature of the universe, physicists have delved into the realms of quantum mechanics and general relativity. However, joining these two pillars of modern physics into a unified framework has been a longstanding challenge. Canonical Quantum Gravity, particularly in the form of Loop Quantum Gravity, emerges as a prominent contender in this endeavor. The epistemology of Loop Quantum Gravity encompasses a diverse range of principles and methodologies, including empirical foundations, mathematical rigor, background independence, and philosophical implications, all of which contribute to our understanding of the theory and its implications for our conception of the universe.

This article explores the epistemological foundations of Loop Quantum Gravity, shedding light on its theoretical underpinnings, its approach to spacetime quantization, and the broader implications it holds for our understanding of the cosmos.

Keywords: Canonical Quantum Gravity, Loop Quantum Gravity, epistemology, tests, Planck constants

Epistemologia gravitației cuantice în buclă în contextul gravitației cuantice canonice

Rezumat

În încercarea de a înțelege natura fundamentală a universului, fizicienii au pătruns în tărâmurile mecanicii cuantice și ale relativității generale. Cu toate acestea, unirea acestor doi piloni ai fizicii moderne într-un cadru unificat a fost o provocare de lungă durată. Gravitația cuantică canonică, în special sub forma Gravitației Cuantice în Buclă, apare ca un candidat proeminent în acest demers. Epistemologia Gravitației Cuantice în Buclă cuprinde o gamă diversă de principii și metodologii, inclusiv fundamente empirice, rigoare matematică, independență de fundal și implicații filozofice, toate acestea contribuind la înțelegerea teoriei și a implicațiilor acesteia pentru concepția noastră despre univers.

Acest articol explorează fundamentele epistemologice ale Gravitației Cuantice în Buclă, evidențiind fundamentele sale teoretice, abordarea sa privind cuantizarea spațiu-timp și implicațiile mai largi pe care le presupune pentru înțelegerea noastră a cosmosului.

Cuvinte cheie: gravitație cuantică canonică, gravitație cuantică în buclă, epistemologie, teste, constante Planck

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Introduction

In the quest to comprehend the fundamental nature of the universe, physicists have delved into the realms of quantum mechanics and general relativity. However, joining these two pillars of modern physics into a unified framework has been a longstanding challenge. Canonical Quantum Gravity (CQG), particularly in the form of Loop Quantum Gravity (LQG), emerges as a prominent contender in this endeavor.

Canonical quantum gravity refers to approaches within theoretical physics that aim to quantize the gravitational field using methods similar to those employed in canonical quantization in quantum field theory. These approaches typically involve treating spacetime itself as a dynamical entity that can be quantized, leveraging the Hamiltonian formulation of the theory and the principles of quantum mechanics. At its core, CQG uses the concept of canonical quantization where classical phase space variables are promoted to quantum operators on a Hilbert space. The dynamics of these quantum systems are then described by the Schrödinger equation, with the

Hamiltonian operator derived from the classical Hamiltonian through a specific substitution of the phase space variables with their quantum counterparts².

CQG Tests

Carlip states, with reference to quantum gravity: "The ultimate measure of any theory is its agreement with Nature; if we do not have any such tests, how will we know whether we're right?"³

Usually, a new theory is constructed using the available experimental data, which attempts to match the phenomenological models, then verifying through predictions. Often, the conceptual and formal consistency is bypassed in an attempt to match reality. At quantum gravity everything happens very differently: it is almost entirely based on conceptual and formal consistency, along with the constraints imposed, and seems impossible to approach through experimental research. Dean Rickles states that the basic test of any scientific theory is an experimental test, without which the theory becomes entangled in pure mathematics or, even worse, in metaphysics.⁴

The epistemology of CQG, particularly in the context of LQG, involves a deep examination of the foundational, theoretical, and methodological questions underlying the attempt to quantize the gravitational field. An interesting aspect of CQG is its treatment of constrained theories, such as general relativity. In constrained theories, the phase space is divided into unrestricted (kinematic) phase space, where constraint functions are defined, and reduced phase space, where constraints are already solved. Canonical quantization in this context involves promoting phase space variables to quantum operators on a Hilbert space designed to accommodate these constraints. Notably, the approach to quantization can vary, with Dirac's approach being one popular method where the constraint functions are replaced by constraint operators. This has led

² Dirac, "Generalized Hamiltonian Dynamics."

³ Carlip, "Quantum Gravity," 64: 885.

⁴ Rickles, "Quantum Gravity."

to significant developments, including a systematic approximation scheme for calculating observables in general relativity, which opens up new avenues for the quantization of gravity⁵.

Giovanni Amelino-Camelia initiated a research program called "quantum gravitational phenomenology", in which he tried to transform quantum gravity research into a true experimental discipline. The scale at which quantum gravitational effects occur is determined by the different physical constants of fundamental physics: \hbar , c and G , which characterize quantum, relativistic and gravitational phenomena. By combining these constants, we obtain the Planck constants at which the effects of quantum gravity must manifest.

These are many orders of magnitude beyond current experimental capabilities. But the scale argument applies to individual quantum gravitational events. The idea is to combine such events to amplify the effects that can be detected with current or near future equipment. Quantum gravity can also be studied by observing the opposite end of the scale spectrum, astronomical systems, by observing cosmic radiation, gamma ray generating explosions, Kaon explosions, particles, light and cosmic background radiation, through quantum gravitational effects that might manifest in these systems. In these systems, the Planck scale effects are naturally amplified.

Name	Formula	Value (SI)
Planck length	$l_p = \sqrt{\hbar G/c^3}$	$1,616229(38) \times 10^{-35}$ m
Planck mass	$m_p = \sqrt{\hbar c/G}$	$2,176470(51) \times 10^{-8}$ kg
Planck time	$t_p = l_p/c = \hbar/m_p c^2 = \sqrt{\hbar G/c^5}$	$5,39116(13) \times 10^{-44}$ s
Planck charge	$q_p = \sqrt{4\pi\epsilon_0 \hbar c} = e/\sqrt{\alpha}$	$1,875\,545\,956(41) \times 10^{-18}$ C

⁵ Dirac, "Generalized Hamiltonian Dynamics."

Planck temperature	$T_p = m_p c^2 / k_B = \sqrt{\hbar c^5 / G k_B^2}$	$1,416808(33) \times 10^{32}$ K
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Table 3.1 Planck Constants

But such effects can also be studied in experimental devices on Earth, also using "natural experiments", such as particles moving over large distances at enormous speeds.⁶ Bryce DeWitt argued that quantum gravitational effects will not be measurable on individual elementary particles, since the gravitational field itself does not make sense at these scales. The static field of such a particle would not exceed the quantum fluctuations.⁷

For the use of the universe as an experimental device, the idea is that light changes its properties over long distances in the case of discrete spacetime, which produces birefringent effects.⁸ The theoretical basis is that a wave propagating in a discrete spacetime will violate Lorentz invariance, which can be a "test" for quantum gravity models. But spacetime discrepancy is not a sufficient condition for Lorentz non-invariance: a counterexample is the causal sets which are discrete structures and do not appear to violate it.

Furthermore, there have been proposals for experimental tests of quantum gravity using cavity-optomechanical systems to detect quantum gravity corrections to canonical commutation relations. These proposals aim to enhance the precision of such measurements through sophisticated manipulation of phase space paths and the utilization of squeezed states of light, demonstrating resilience to experimental imperfections and suggesting the feasibility of testing quantum gravity with near-future technology⁹.

Some of proposed tests include:

⁶Rickles, "Quantum Gravity."

⁷DeWitt and Witten, *The Quantization of Geometry, in Gravitation an Introduction to Current Research*, 372.

⁸Gambini and Pullin, "Quantum Gravity Experimental Physics?," 1999.

⁹ Kumar and Plenio, "Quantum-Optical Tests of Planck-Scale Physics."

- Quantum gravity effects in the early Universe (cosmic microwave background radiation and primordial gravitational waves) for the quantum gravitational effects during the early universe.
- Gravitational wave observations, where quantum gravity effects might produce deviations from the predictions of classical general relativity.
- High-energy particle colliders that might reveal indirect evidence of quantum gravitational effects.
- Quantum entanglement and spacetime, for clues about the underlying quantum nature of gravity.
- Experimental tests of quantum gravity models, to test predictions made by various canonical quantum gravity theories.
- Astrophysical observations, such as the behavior of stars and galaxies, could provide constraints on theories of quantum gravity.
- Laboratory experiments, to probe the quantum properties of gravity at very small scales.

Overall, testing canonical quantum gravity theories presents significant challenges due to the extremely high energies and small scales involved. However, progress in experimental techniques and theoretical understanding continues to advance, offering hope for future insights into the nature of quantum gravity.

Particularly, there are challenges about quantization ambiguities in the dynamics of LQG. There's ongoing research inspired by Wilson's observation that renormalization methods, which are traditionally used in condensed matter physics, might offer a way to discern the relevant interaction terms among the many possible ones. He suggests that while a theory might appear non-renormalizable in a perturbative sense, it could be non-perturbatively renormalizable, an idea central to the asymptotic safety approach to quantum gravity¹⁰.

Loop Quantum Gravity

LQG attempts to unify gravity with the other three fundamental forces starting with relativity and adding quantum traits. It is based directly on Einstein's geometric formula.

¹⁰ Thiemann, "Canonical Quantum Gravity, Constructive QFT, and Renormalisation."

The epistemology of CQG, particularly in the context of LQG, encompasses several key principles and methodologies that guide our understanding of the theory and its implications.

Here's an overview:

- **Foundational Aspects:** CQG aims to reconcile the principles of quantum mechanics with the geometric description of gravity provided by general relativity. The granular structure of space-time at the Planck scale, the idea that space-time is quantized, and that these quanta of space-time are loop-like structures or spin networks, attempting to remain background-independent. Unlike other approaches, such as string theory, LQG takes a more direct route by quantizing the very fabric of spacetime itself ("quantum geometries"), a radical departure from classical notions of continuous spacetime. At the heart of LQG's epistemology lies a deep appreciation for the interplay between geometry and quantum principles.
- **Theoretical Underpinnings:** LQG places a strong emphasis on mathematical rigor. This focuses on the formal mathematical structures that LQG is built upon, such as the use of Ashtekar variables (a reformulation of general relativity using variables that simplify the description of the quantum properties of the gravitational field) and examines how LQG integrates with the principles of quantum mechanics, especially the quantization of the gravitational field and the implications for the nature of reality at the quantum level.
- **Canonical Quantization:** LQG typically involve the quantization of the gravitational field within the framework of canonical quantization, promoting the classical degrees of freedom, such as the metric tensor representing spacetime geometry, to operators that satisfy canonical commutation relations or Poisson brackets. The quantization of geometry replaces the classical notion of continuous spacetime by discrete entities ("spin networks"). Through the application of techniques from quantum field theory, such as spin foam models and loop quantization, LQG provides a rigorous framework for describing the dynamics of these quantum geometries.
- **Holism and background independence:** LQG often requires a pre-existing spacetime background, seeking to construct spacetime geometry from scratch in a way that does not presuppose any pre-existing structure. LQG also paves the way for a deeper understanding of the quantum nature of the universe as a whole.
- **Methodological questions:** The methods used to derive predictions from LQG and how these can be tested or observed (a challenging area due to the difficulty in testing quantum gravity theories with current experimental technology).
- **Interpretation and implications:** The epistemology of LQG involves philosophical considerations regarding the nature of space, time, and the quantum structure of the universe. LQG offers novel perspectives on these fundamental questions, challenging conventional notions and prompting philosophical reflection on the nature of reality at its most fundamental level. This involves the implications of LQG for our understanding of space, time, and the universe. It includes questions about the nature of time, the beginning of the universe, and the fate of singularities like those found in black holes. The interpretation of LQG also raises questions about the nature of reality at the most fundamental level and how it might differ from our classical intuitions.

- **Comparative analysis:** The epistemology of LQG often involves comparing and contrasting it with other approaches to quantum gravity, such as string theory. This comparison is not only in terms of the theoretical framework and predictions but also in terms of the philosophical and foundational assumptions each approach makes about the nature of the universe.

In LQG, space and time are quantified just like energy and momentum in quantum mechanics. Space and time are granular and discrete, with a minimal size. The space is considered to be an extremely fine fabric or network of finite loops, called spin networks or spin foam, with a size limited to less than the order of a Planck length, about 10^{-35} meters. Its consequences apply best to cosmology, in the study of the early universe and Big Bang physics. Its main, unverified prediction involves an evolution of the universe beyond the Big Bang (Big Bounce).

Any theory of quantum gravity must reproduce Einstein's theory of general relativity as a classical limit. Quantum gravity must be able to return to classical theory when $\hbar \rightarrow 0$. To do this, quantum anomalies must be avoided, in order to have no restrictions on Hilbert physical space without a correspondent in classical theory. It turns out that quantum theory has less degrees of freedom than classical theory. Lewandowski, Okolow, Sahlmann and Thiemann¹¹ on the one hand, and Christian Fleischhack¹² on the other, have developed theorems that establish the uniqueness of the loop representation as defined by Ashtekar. These theorems exclude the existence of other theories in the LQG research program and so, if LQG does not have the correct semiclassical limit, this would mean the end of the LQG representation as a whole.

The canonical quantum gravity program treats the spacetime metric as a field and quantizes it directly, with space divided into three-dimensional layers. The program involves rewriting the

¹¹Lewandowski et al., "Uniqueness of Diffeomorphism Invariant States on Holonomy–Flux Algebras," 267 (3): 703–733.

¹²Fleischhack, "Irreducibility of the Weyl Algebra in Loop Quantum Gravity," 97 (6): 061302.

general relativity in "canonical" or "Hamiltonian" form,¹³ through a set of configuration variables that can be encoded in a phase space. The evolution in time of these variables is then determined, the possible physical movements in the phase space, a family of curves, are quantized, and the dynamic evolution is generated with the help of the Hamiltonian operator.¹⁴ Thus, some constraints of the canonical variables imposed after quantification appear.

In loop quantum gravity, Ashtekar used a different set of variables with a more complex metric,¹⁵ solving the constraints more easily. By the changes introduced in the program, all standard geometrical features of general relativity can be recovered.¹⁶ The advantage of this version is a greater (mathematical) control over the theory (and its quantification).

The LQG program requires that a theory of spacetime be independent of the background, as opposed to the string theory where spacetime is treated as a fixed background. LQG uses the Hamiltonian or canonical formulation of GR. The advantage of a canonical formulation of a theory is the ease and standardization of quantification. The loops in the LQG give us a description of the space. At the intersection of the loops there appear nodes that represent basic units of the space, which is thus discretized; two nodes connected by a link represent two space units side by side. The surface is determined by the intersections with the loops. Thus, one can imagine a graph (spinnetwork)¹⁷ made from certain quantum numbers attached to it. The numbers determine the surfaces and volumes of space.¹⁸ The problem of time in LQG is to incorporate time into this image.

¹³Kuchař, "Canonical Quantization of Gravity."

¹⁴Weinstein and Rickles, "Quantum Gravity."

¹⁵Rovelli, "Notes for a Brief History of Quantum Gravity."

¹⁶Smolin, "The Case for Background Independence," 196–239.

¹⁷The spin network is a graph whose nodes represent "slices" of space and whose links represent surfaces that separate these pieces, representing a quantum state of the gravitational field or space.

¹⁸Matsubara, *Stringed Along Or Caught in a Loop?*

The LQG considers GR as a starting point, at which it applies a quantification procedure to arrive at a viable quantum theory of gravity. In the quantification procedure, called canonical quantization, it is necessary to reformulate the GR as a Hamiltonian system, thus allowing a time evolution of all the degrees of freedom of the system. The respective Hamiltonian formulas divide the spacetime in a foliation of three-dimensional space hypersurfaces, through a formalism called ADM after its authors (Richard Arnowitt, Stanley Deser and Charles Misner). ADM formalism assumes metrics induced on spatial surfaces as "position" variables and a linear combination of the outer curvature components of these hypersurfaces encoding their incorporation into 4-dimensional space-time as canonically conjugated "momentum" variables with metrics.¹⁹ The resulting Hamiltonian equations are not equivalent to the Einstein field equations. To make them equivalent, restrictions must be introduced, resulting in certain conditions for the initial data. The first family of constraints encodes the freedom of choosing the foliation (Hamiltonian constraint), and the second set of constraints concerns the freedom to choose the coordinates in the 3-dimensional space (vector constraints), resulting in a total of four constraint equations. In the LQG there is a family of additional constraints related to internal symmetries. So far, only two of the three families of constraints have been resolved. The canonical quantization procedure is carried out according to Paul Dirac,²⁰ transforming the canonical variables into quantum operators that act on a space of quantum state.

The use of ADM formalism was hit by insurmountable technical complications, so in the 1980s Abhay Ashtekar introduced new variables that simplified the equations of constraints, with the disadvantage of losing the direct geometric significance of ADM variables. In this case the spacetime geometry is captured by a "triad field" which encodes the local inertial frames defined

¹⁹Wuthrich, "In Search of Lost Spacetime."

²⁰Dirac, *Lectures on Quantum Mechanics*.

on spatial hypersurfaces, rather than the metrics. The transition from ADM to the Ashtekar variables represents a reinterpretation of the Einstein field equations. The generalized theory of reinterpreted relativity is then subjected to the canonical procedure as above.²¹

In many approaches to quantum gravity, including string theory and LQG, space is no longer a fundamental entity, but merely an "emergent" phenomenon that results from basic physics.²² Christian Wüthrich states that it is not clear whether we can formulate a physical theory in a coherent way in the absence of space and time.²³

A newer approach is the use of so-called "spin foam" models,²⁴ which use path integration to generate spacetime. The evolution in time of spin networks is assumed to represent spacetime in terms of spin foam.

LQG is a vast active research program, developed in several directions with the same hard core.²⁵ Two directions of development are more important: the more traditional canonical LQG, and the covariant LQG, called the spin foam theory.

The loop quantum gravity resulted from an attempt to formulate a quantum theory independent of the background. This takes into account the general relativity approach that spacetime is a dynamic field and, therefore, a quantum object. The second hypothesis of the theory is that the quantum discreteness that determines the behavior similar to the particles of other field theories also affects the structure of space. The result is a granular structure of space at Planck length. The quantum state of spacetime is described by means of a mathematical structure called a spin network. Spin networks do not represent quantum states of a field in space, but quantum

²¹Wüthrich, "In Search of Lost Spacetime."

²²Wüthrich.

²³Wüthrich, "To Quantize or Not to Quantize," 72 : 777-788.

²⁴Barrett and Crane, "Relativistic Spin Networks and Quantum Gravity," 32:3296–3302.

²⁵Dirac, *Lectures on Quantum Mechanics*.

states of spacetime. The theory was obtained by reformulating the general relativity with the help of the Ashtekar variables.²⁶ Currently, there are several positive heuristics based on which the dynamics of the theory develop.

The black hole thermodynamics tries to reconcile the laws of thermodynamics with the black hole event horizons. A recent success of the theory is the calculation of the entropy of all non-singular black holes directly from the theory and independent of other parameters. This is the only known derivation of this formula from a fundamental theory, in the case of generic black holes that are not singular. The theory also allowed the calculation of quantum gravity corrections at entropy and radiation of black holes.

In 2014, Carlo Rovelli and Francesca Vidotto suggested, based on LQG, that there is a Planck star inside a black hole, thus trying to resolve the protection of the black hole and the paradox of the black hole information.

Loop quantum cosmology (LCC) predicted a Big Bounce before the Big Bang. LCC was developed using methods that mimic those of LQG, which predicts a "quantum bridge" between contracting and expansive cosmological branches. Through the LCC, the singularities of Big Bang, Big Bounce, and a natural mechanism for inflation were predicted. But the results obtained are subject to restriction due to the artificial suppression of the degrees of freedom. The avoidance of singularities in the LCC is done through mechanisms available only in these restrictive models; the avoidance of singularities in the complete theory can only be achieved by a more subtle feature of the LQG.

The GR reproduction as a low-energy limit in LQG has not been confirmed yet, and the scattering amplitudes have not yet been calculated.

²⁶Ashtekar, "New Variables for Classical and Quantum Gravity," 57 (18): 2244–2247.

The most pressing problems of the LQG are our lack of understanding of the dynamics (the inability to solve the Hamiltonian constraint equation), and the failure to explain how the classic smooth space appears (how GR succeeds in this case).

Another LQG problem is a general problem of quantum mechanics: time. Carlo Rovelli and Julian Barbour tried to formulate quantum mechanics in a way that does not require external time, replacing time by relating events directly with one another.²⁷

The effects of quantum gravity are difficult to measure because the Planck length is much too small, but we try to measure the effects from astrophysical observations and gravitational wave detectors. It has not yet been shown that the LQG description of spacetime on the Planck scale has the correct continuous limit described by the general relativity with possible quantum corrections. Other unresolved issues include dynamics of theory, constraints, coupling with matter fields, renormalization of graviton.²⁸

There is still no experimental observation for which LQG made a different prediction from the Standard Model or general relativity. Due to the lack of a semiclassical boundary, LQG did not reproduce the predictions made by general relativity.

The LQG has difficulties in trying to allow the theory of general relativity at the semiclassical limit, among which:

- There is no operator that responds to infinitesimal diffeomorphisms, it must be approximated by finite diffeomorphisms and thus the structure of the Poisson brackets of classical theory is not exactly reproduced. The problem can be circumvented by introducing constraints.²⁹
- The difficulty of reconciling the discrete combinatorial nature of quantum states with the continuous nature of classical theory of the fields.

²⁷Rovelli, "Relational Quantum Mechanics," 35 : 1637-1678.

²⁸Nicolai, Peeters, and Zamaklar, "Loop Quantum Gravity," 22(19): R193–R247.

²⁹Thiemann, *Modern Canonical Quantum General Relativity*.

- Difficulties arising from the structure of the Poisson brackets that involve spatial diffeomorphism and Hamiltonian constraints.³⁰
- The developed semiclassical mechanisms are only suitable for operators who do not change the graph.
- The problem of formulating observables for general relativity due to its nonlinear nature and the invariance of spacetime diffeomorphism.³¹

LQG is a possible solution of quantum gravity, just like string theory but with differences.

In contrast to the string theory which postulates additional dimensions and unobserved additional particles and symmetries, LQG is based only on quantum theory and general relativity, and its scope is limited to understanding the quantum aspects of gravitational interaction. In addition, the consequences of LQG are radical, fundamentally altering the nature of space and time.

Conclusion

This blend of theoretical development and experimental proposals showcases the vibrant, albeit challenging, landscape of research in CQG. The work towards resolving theoretical ambiguities and devising experimental tests underscores the dynamic interplay between theory and experiment in the quest to understand the quantum aspects of gravity.

In conclusion, the epistemology of CQG, particularly in the form of LQG, offers a radical reimagining of our understanding of spacetime and gravity. By embracing the quantum nature of the cosmos and departing from classical notions of continuous geometry, LQG provides a fertile ground for exploring the fundamental principles that govern the universe. As physicists continue to probe the depths of quantum gravity, the insights gleaned from LQG promise to illuminate new pathways towards a unified theory of physics.

Overall, the epistemology of LQG encompasses a diverse range of principles and methodologies, including empirical foundations, mathematical rigor, background independence,

³⁰Thiemann.

³¹Dittrich, "Partial and Complete Observables for Hamiltonian Constrained Systems," 39 (11): 1891–1927.

and philosophical implications, all of which contribute to our understanding of the theory and its implications for our conception of the universe.

The epistemological inquiry into LQG is an ongoing process, as the theory itself is under continuous development and refinement. As such, it encompasses a broad and evolving discussion among physicists, mathematicians, and philosophers of science.

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