Epistemology of Canonical Quantum Gravity - Loop Quantum Gravity

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In the interpretation of canonical quantum gravity (CQG), gravity appears as a geometric pseudoforce, is reduced to spacetime geometry and becomes a simple effect of spacetime curvature. [1] (Maudlin[2]). Lehmkuhl[3] argues that canonical formalism does not confirm this interpretation. General relativity (GR) associates gravity with spacetime, but the type of association is not fixed. [4] Instead of the geometric interpretation, one can use the field interpretation (the spacetime geometry is reduced to a gravitational field, respectively the metric, considered as "just another field") or the egalitarian interpretation (a conceptual identification of gravity and spacetime in GR[5]). These alternative interpretations reduce the conceptual differences between GR and other field theories.

Instrumentalism allows the ignoring of quantum gravity, since it conceives scientific theories only as predictive tools. Canonical quantum gravity follows a nonperturbative quantum theory of the gravitational field. It is based on consistency between quantum mechanics and gravity, without trying to unify all fields. The main idea is to apply standard quantification procedures to the general theory of relativity. For this, it is necessary for general relativity to be expressed in canonical (Hamiltonian) form and then quantified as usual. This was (partially) successfully done by Dirac[6] and (differently) by Arnowitt, Deser and Misner. [7]

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[1] Kian Salimkhani, "Quantum Gravity: A Dogma of Unification?," in *Philosophy of Science. European Studies in Philosophy of Science, Vol 9.*, ed. Alexander Christian et al. (Cham: Springer, 2018), 23–41.

[2] Tim Maudlin, "On the Unification of Physics," *Journal of Philosophy* 93, no. 3 (1996): 129–144.

[3] D. Lehmkuhl, D. Dieks, and M. Redei, "Is Spacetime a Gravitational Field?, In The Ontology of Spacetime II, Volume 4 - 1st Edition," 2008, 83–110, https://www.elsevier.com/books/the-ontology-of-spacetime-ii/dieks/978-0-444-53275-6.

[4] Lehmkuhl, Dieks, and Redei, 84.

[5] Lehmkuhl, Dieks, and Redei, 84.

[6] Paul A. M. Dirac, *Lectures on Quantum Mechanics* (Mineola, NY: Snowball Publishing, 2012).

[7] R. Arnowitt, S. Deser, and C. W. Misner, "The Dynamics of General Relativity," *General Relativity and Gravitation* 40, no. 9 (September 2008): 1997–2027, https://doi.org/10.1007/s10714-008-0661-1.

Tests proposed for the CQG

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?" [8] 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 the 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. [9]

Giovanni Amelino-Camelia initiated a new research program called "quantum gravitational phenomenology", in which he tries 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: *h*, *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)**
Lungimea Planck length	$l_P = \sqrt{\hbar G/c^3}$	$1{,}616229(38)\times10^{-35}$ m
Planck mass	$m_P = \sqrt{\hbar c/G}$	$2{,}176470(51)\times10^{-8}$ kg
Planck time	$t_P = l_P/c = \hbar/m_Pc^2 = \sqrt{\hbar G/c^5}$	$5{,}39116(13)\times10^{-44}$ s
Planck charge	$q_P = \sqrt{4\pi\varepsilon_0\hbar c} = e/\sqrt{\alpha}$	$1{,}875\ 545\ 956(41)\times10^{-18}$ C

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[8] S. Carlip, "Quantum Gravity: A Progress Report," *Reports on Progress in Physics* 64, no. 8 (August 1, 2001): 64: 885, https://doi.org/10.1088/0034-4885/64/8/301.

[9] Dean Rickles, "Quantum Gravity: A Primer for Philosophers.," Preprint, October 2008, http://philsci-archive.pitt.edu/5387/.

Planck temperature	$T_P = m_P c^2/k_B = \sqrt{\hbar c^5/Gk_B^2}$	$1,416808(33)\times10^{32}$ K

Tabelul 3.1 Constantele Planck

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. [10] 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. [11]

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. [12] 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.

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[10] Rickles.

[11] B. S. DeWitt and Louis Witten, *The Quantization of Geometry, in Gravitation an Introduction to Current Research*, First Edition edition (John Wiley & Sons, 1962), 372.

[12] Rodolfo Gambini and Jorge Pullin, “Quantum Gravity Experimental Physics?,” *General Relativity and Gravitation* 31, no. 11 (November 1, 1999): 1999, https://doi.org/10.1023/A:1026701930767.

Loop quantum gravity

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.

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 Thiemann[13] on the one hand, and Christian Fleischhack[14] 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 semiclastic 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 general relativity in "canonical" or "Hamiltonian" form, [15] 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. [16] Thus, some constraints of the canonical variables imposed after quantification appear.

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[13] Jerzy Lewandowski et al., “Uniqueness of Diffeomorphism Invariant States on Holonomy–Flux Algebras,” *Communications in Mathematical Physics* 267, no. 3 (November 1, 2006): 267 (3): 703–733, https://doi.org/10.1007/s00220-006-0100-7.

[14] Christian Fleischhack, “Irreducibility of the Weyl Algebra in Loop Quantum Gravity,” *Physical Review Letters* 97, no. 6 (August 11, 2006): 97 (6): 061302, https://doi.org/10.1103/PhysRevLett.97.061302.

[15] Karel Kuchař, “Canonical Quantization of Gravity,” *Relativity, Astrophysics and Cosmology*, 1973, 237–88, https://doi.org/10.1007/978-94-010-2639-0_5.

[16] Steven Weinstein and Dean Rickles, “Quantum Gravity,” in *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, Winter 2018 (Metaphysics Research Lab, Stanford University, 2018), https://plato.stanford.edu/archives/win2018/entries/quantum-gravity/.

In loop quantum gravity, Ashtekar used a different set of variables with a more complex metric,[17] solving the constraints more easily. By the changes introduced in the program, all standard geometrical features of general relativity can be recovered.[18] 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 (spin network)[19] made from certain quantum numbers attached to it. The numbers determine the surfaces and volumes of space.[20] The problem of time in LQG is to incorporate time into this image.

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.[21] 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

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[17] Carlo Rovelli, "Notes for a Brief History of Quantum Gravity," *ArXiv:Gr-Qc/0006061*, June 16, 2000, http://arxiv.org/abs/gr-qc/0006061.

[18] Lee Smolin, "The Case for Background Independence," *ArXiv:Hep-Th/0507235*, July 25, 2005, 196–239, http://arxiv.org/abs/hep-th/0507235.

[19] The 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.

[20] Keizo Matsubara, *Stringed Along Or Caught in a Loop?: Philosophical Reflections on Modern Quantum Gravity Research* (Filosofiska Institutionen, Uppsala universitet, 2012).

[21] Christian Wuthrich, "In Search of Lost Spacetime: Philosophical Issues Arising in Quantum Gravity" (2011).

been resolved. The canonical quantization procedure is carried out according to Paul Dirac,[22] 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 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.[23]

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.[24] 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.[25]

A newer approach is the use of so-called "spin foam" models,[26] 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.[27] 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 states of spacetime. The theory was obtained by reformulating the general relativity with the help of the

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[22] Dirac, *Lectures on Quantum Mechanics.*

[23] Wuthrich, "In Search of Lost Spacetime."

[24] Wuthrich.

[25] Christian Wuthrich, "To Quantize or Not to Quantize: Fact and Folklore in Quantum Gravity," Published Article or Volume, Philosophy of Science, 2005, 72 : 777-788, http://www.jstor.org/stable/10.1086/508946.

[26] John W. Barrett and Louis Crane, "Relativistic Spin Networks and Quantum Gravity," *Journal of Mathematical Physics* 39, no. 6 (June 1998): 32:3296–3302, https://doi.org/10.1063/1.532254.

[27] Dirac, *Lectures on Quantum Mechanics.*

Ashtekar variables.[28] 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.

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.[29]

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

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[28] Abhay Ashtekar, "New Variables for Classical and Quantum Gravity," *Physical Review Letters* 57, no. 18 (November 3, 1986): 57 (18): 2244–2247, https://doi.org/10.1103/PhysRevLett.57.2244.

[29] Carlo Rovelli, "Relational Quantum Mechanics," *International Journal of Theoretical Physics* 35, no. 8 (August 1996): 35 : 1637-1678, https://doi.org/10.1007/BF02302261.

corrections. Other unresolved issues include dynamics of theory, constraints, coupling with matter fields, renormalization of graviton.[30]

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 semiclassic 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.[31]
- The difficulty of reconciling the discrete combinatorial nature of quantum states with the continuous nature of classical theory of the fields.
- Difficulties arising from the structure of the Poisson brackets that involve spatial diffeomorphism and Hamiltonian constraints.[32]
- The developed semiclassic 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.[33]

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.

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[30] Hermann Nicolai, Kasper Peeters, and Marija Zamaklar, “Loop Quantum Gravity: An Outside View,” *Classical and Quantum Gravity* 22, no. 19 (October 7, 2005): 22(19): R193–R247, https://doi.org/10.1088/0264-9381/22/19/R01.

[31] Thomas Thiemann, *Modern Canonical Quantum General Relativity*, 1 edition (Cambridge, UK ; New York: Cambridge University Press, 2008).

[32] Thiemann.

[33] B. Dittrich, “Partial and Complete Observables for Hamiltonian Constrained Systems,” *General Relativity and Gravitation* 39, no. 11 (November 1, 2007): 39 (11): 1891–1927, https://doi.org/10.1007/s10714-007-0495-2.

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