Chapter 8
Discussion

Any fair and balanced review paper on LQG should also mention at least a few of the many objections its critics have presented. A list of a few of the more important points of weakness in the framework and brief responses to them follows:

1. *LQG admits a volume extensive entropy and therefore does not respect the Holographic principle*: This criticism hinges upon the description of states of quantum gravity as spin-networks which are essentially spin-systems on arbitrary graphs. However, spin-networks only constitute the *kinematical* Hilbert space of LQG. They are solutions of the spatial diffeomorphism and the Gauss constraints but *not* of the Hamiltonian constraint which generates time-evolution. This criticism is therefore due to a (perhaps understandable) failure to grasp the difference between the kinematical and the dynamical phase space of LQG.
   In order to solve the Hamiltonian constraint we are forced to enlarge the set of states to include *spin-foams* which are histories of spin-networks. In a nutshell then, as we mentioned in Sect. 6.5, the kinematical states of LQG are the spin-networks, while the dynamical states are the spin foams. The amplitudes associated with a given spin-foam are determined completely by the specification of its boundary state. Physical observables do not depend on the possible internal configurations of a spin-foam but only on its boundary state. In this sense LQG satisfies a stronger and cleaner version of holography than string theory, where this picture emerges from considerations involving graviton scattering from certain extremal black hole solutions.
   In [1] it is shown that in the context of loop quantum cosmology of a radiation-filled flat FRW model, Bousso's covariant entropy bound [2] is respected. As one approaches the moment of the Big Bang, and quantum gravitational effects become large the bound is violated, however, far from the Big Bang, when geometry has become semiclassical the bound comes into force.
   As yet, there is no general proof of whether or not LQG respects Bousso's bound. However, one might argue that the structure of LQG is amenable to the spirit of

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Bousso's bound. The latter suggests that there is a fundamental limit to the number of degrees of freedom in any given region of spacetime. Such a fundamental limit is already present in LQG in the form of the quantized area and volume operators which tell us that any region of spacetime must contain a finite number of geometric degrees of freedom.

2. *LQG violates the principle of local Lorentz invariance/picks out a preferred frame of reference*: Lorentz invariance is obeyed in LQG but obviously not in the exact manner as for a continuum geometry. As has been shown by Rovelli and Speziale [3] the kinematical phase space of LQG can be cast into a manifestly Lorentz covariant form. A spin-network/spin-foam state transforms in a well-defined way under boosts and rotations. Similarly in quantum mechanics one finds that a quantum rotor transforms under discrete representations of the rotation group $SO(3)$.
3. *LQG does not have stable semiclassical geometries as solutions—geometry "crumbles"*: CDT simulations e.g. [4] show how a stable geometry emerges. As mentioned in Sect. 4.1, this involves calculating a sum over histories for the geometry of spacetime, between some initial and final state. The stability of the spacetimes studied in such simulations appears to be dependent on causality—that is, spacetime geometries develop unphysical structures in the Euclidean case, which are controlled when there is a well-defined past and future, as is the case in LQG. The question of exactly how similar CDT and LQG are to each other is a matter of continuing investigation.
4. *LQG does not contain fermionic and bosonic excitations that could be identified with members of the Standard Model*: The area and volume operators do not describe the entirety of the structures that can occur within spin networks. LQG or a suitably modified version which allows braiding between various edges will exhibit invariant topological structures. Recent work [5–10] has been able to identify some such structures with SM particles. In addition, in any spin-system—such as LQG—there are effective (emergent) low-energy degrees of freedom which satisfy the equations of motion for Dirac and gauge fields. Xiao-Gang Wen and Michael Levin [11, 12] have investigated so-called "string-nets" and find that the appropriate physical framework is the so-called "tensor category" or "tensor network" theory [13–15]. In fact string-nets are very similar to spin-networks so Wen and Levin's work—showing that gauge bosons and fermions are quasiparticles of string-net condensates—should carry over into LQG without much modification.
5. *LQG does not exhibit dualities in the manner String Theory does*: Any spin system exhibits dualities. A graph based model like LQG even more so. One example of a duality is to consider the dual of a spin-network which is a so-called 2-skeleton or simplicial cell-complex. Another is the star-triangle transformation, which can be applied to spin-networks which have certain symmetries, and which leads to a duality between the low and high temperature versions of a theory on a hexagonal and triangular lattice respectively [16].
6. *LQG doesn't admit supersymmetry, wants to avoid extra dimensions, strings, extended objects, etc.*: Extra dimensions and supersymmetry are precisely that—

"extra". Occam's razor dictates that a successful physical theory should be founded on the *minimum* number of ingredients. It is worth noting that at the time of writing of this paper, results from the LHC appear to have ruled out many supersymmetric extensions of the standard model. By avoiding the inclusion of extra dimensions and supersymmetry, LQG represents a perfectly valid attempt to create a theory that is consistent with observations.

7. *LQG has a proliferation of models and lacks robustness*: Again a lack of extra baggage implies the opposite. LQG is a tightly constrained framework. There are various uniqueness theorems which underlie its foundations and were rigorously proven in the 1990s by Ashtekar, Lewandowski and others. There are questions about the role of the Immirzi parameter and the ambiguity it introduces however these are part and parcel of the broader question of the emergence of semi-classicality from LQG (see Simone Mercuri's papers [17, 18] in this regard).
8. *LQG does not contain any well-defined observables and does not allow us to calculate graviton scattering amplitudes*: Several calculations of two-point correlation functions in spin-foams exist in the literature [19]. These demonstrate the emergence of an inverse-square law.

As well as discussing criticisms of LQG, it is also fair to consider what role this theory may have in the future. We would not have written a paper reviewing the formulation of LQG if we did not consider it an important and interesting theory—one which we feel is probably a good representation of the nature of spacetime. However it is wise to remember that most physical theories are ultimately found to be flawed or inadequate representations of reality, and it would be unrealistic to think that the same might not be true of LQG. Questions linger about the nature of time and the interpretation of the Hamiltonian constraint, among other things. What is the value then, in studying LQG? Perhaps LQG will eventually be shown to be untenable, or perhaps it will be entirely vindicated. As authors of this paper, we feel that the truth will probably lie somewhere in the middle, and that however much of our current theories of LQG survive over the next few decades, this research program does provide strong indications about what some future (and, we hope, experimentally validated) theory of "quantum gravity" will look like.

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