QUANTUM GRAVITY

Physics from geometry

Two recent developments suggest how familiar properties of gravity and matter may emerge from the quantum geometry that underlies loop quantum gravity.

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General relativity is the best theory of space–time structure available today. Its basic premise is that geometry is not an inert arena. Rather, it is a physical entity that acts on and can be acted upon by matter. It then stands to reason that, like matter, geometry may have a quantum nature, and it is widely expected that this is so at the Planck scale, $\ell_P \sim 10^{-33}$ cm. By contrast, the standard perturbative methods of quantum field theory assume a classical space–time continuum at all scales. When applied to quantum gravity, then, they are fraught with difficulties.

The situation changes in loop quantum gravity — a non-perturbative attempt to unify general relativity with quantum physics, now developed further in a series of recent papers[1–5]. Here, matter as well as geometry are treated quantum mechanically. Fundamental excitations of geometry are one-dimensional and the familiar continuum arises only with suitable coarse-graining. This perspective emerges from a precise mathematical framework, analogous to that of ordinary quantum mechanics. Geometrical operators such as areas of physical surfaces turn out to have only discrete eigenvalues. In a precise sense then, geometry is quantized.

In everyday situations, and even in current high-energy accelerators, this discreteness is totally irrelevant because even the radius of a single proton, for example, is some twenty orders of magnitude larger than the Planck length. It is at times close to the Big Bang and in the vicinity of black holes that quantum geometry becomes crucial. In the former case, it creates a new repulsive force, resolving the singularity and extending space–time. Similarly, quantization of area has been used to show that the statistical mechanical entropy of black holes is proportional to their surface area, in accordance with the celebrated thermodynamic arguments of Jacob Bekenstein and Stephen Hawking. Thus, because of its in-built quantum geometry, loop quantum gravity has had successes with some long standing and conceptually difficult problems.

However, precisely because of this emphasis on Planck-scale discreteness, familiar properties of gravity and matter that can be easily derived using the space–time continuum are now difficult to obtain. For instance, in the traditional perturbative framework the gravitational attraction between two point masses arises from an exchange of virtual gravitons, described by the Feynman propagator. In the non-relativistic limit, the propagator yields Newton's inverse square law of gravitation. Loop quantum gravity, on the other hand, has no background metric. Therefore one cannot even begin to calculate the propagator along these traditional lines.

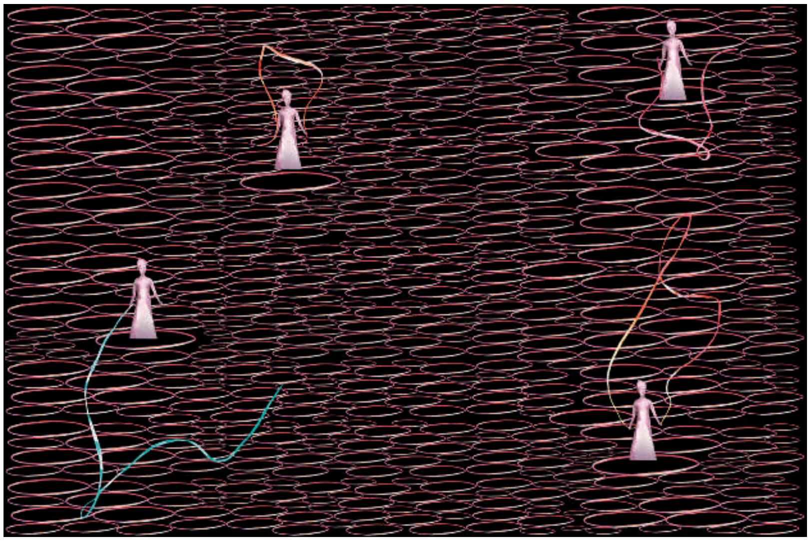

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Figure 1 Is space loopy? In loop quantum gravity, space is fundamentally discrete and continuum is only an approximation. The fabric of space is woven by one-dimensional threads, represented here by loops.

The recent work of Rovelli, Speziale and others[1–3], however, carves out a new way to do the calculation, tailored to quantum geometry. One first observes that the propagator between two points x and y can be evaluated using path integrals. Now, because of fundamental discreteness, path integrals based on quantum geometry — called spin foams — are finite, unlike their counterparts in perturbative treatments. The missing element was a geometry to measure the distance between x and y. Rovelli *et al.*[1] consider a surface S passing through x and y and fix on it a semi-classical state of quantum geometry in which S is a sphere of radius L, much larger than the Planck length ℓ_P. They then use spin foams to calculate the propagator by summing over all quantum geometries in the interior that are compatible with the boundary state.

The calculation is well-defined; there are no infinities. The leading term in the expansion in ℓ_P/L is then the candidate propagator, and explicit calculation shows that it has the correct dependence on L to yield the inverse square law. Thus, Rovelli *et al.* have developed a conceptual framework that bridges Planck-scale quantum geometry to large-scale continuum physics. This opens the door for more ambitious calculations of scattering amplitudes from first principles. However, several technical issues still remain in the propagator calculation, most notably a dynamical determination of the boundary state.

The second development, reported by Bilson-Thompson and colleagues[4,5], relates to particle physics. Einstein famously said that, whereas the geometrical, left-hand side of his equations has a pristine character like marble, the right-hand side describing matter resembles wood. Since then several researchers have attempted to make matter emerge from geometry. For example, in the 1970s John Wheeler proposed that elementary particles may only be manifestations of topological fluctuations of space–time, so that particle physics may in the end resemble the 'chemistry of geometry'. However, this suggestion remained qualitative. But, using ideas inspired by loop quantum gravity, Bilson-Thompson *et al.* have now made a more concrete proposal.

They first imagine the one-dimensional excitations of quantum geometry as two-dimensional 'ribbons'. They then interpret the braids obtained by suitably twisting these ribbons as the quarks, leptons and gauge bosons of the standard model of elementary particles (Fig. 1). The attractive feature of this bold idea is that the uncomfortably large list of 'elementary' particles now results from just two fundamental constituents, which, furthermore, have their origin in the topological features of the fundamental excitations of quantum geometry.

However, as with any radical suggestion, this proposal can only be regarded as preliminary. Much work lies ahead, in particular, to get a handle on the dynamics and to account for the masses of elementary particles, especially as they are significantly smaller than the Planck mass. However, as Richard Feynman[6] said in a lecture, on his way back from Stockholm in 1965: "It's necessary to increase the amount of variety … and the only way to do it is to implore you few guys to take a risk with your lives that you will never be heard of again, and go off in the wild blue yonder and see if you can figure it out."

REFERENCES

1. Rovelli, C. *Phys. Rev. Lett.* (in the press); preprint at <http://arxiv.org/abs/gr-qc/0508124> (2006).
2. Bianchi, E., Modesto, L., Rovelli, C. & Speziale, S. *Class. Quantum Grav.* (in the press); preprint at <http://arxiv.org/abs/gr-qc/0604044> (2006).
3. Livine, E. & Speziale, S. Preprint at <http://arxiv.org/abs/gr-qc/0608131> (2006).
4. Bilson-Thompson, S. O. <Preprint at http://arxiv.org/abs/hep-th/0503213> (2005).
5. Bilson-Thompson, S. O., Markopoulou, F. & Smolin, L. Preprint at <http://arxiv.org/abs/hep-th/0603022> (2006).
6. Gleick, J. *Genius: The Life and Science of Richard Feynman* 382 (Patheon, New York, 1992).