Quantum structure of gravity and black holes

Steven B. Giddings*

Department of Physics, University of California, Santa Barbara, CA 93106, USA

Abstract

Reconciling gravity with quantum principles is one of the most profound problems in theory. A key facet of this problem is the "unitarity crisis" for black hole evolution. This raises the important structural question of how to think about subsystems and localization of information in quantum gravity. Paralleling field theory, the answer to this is expected to be an important ingredient in the mathematical structure of the theory. If black holes behave similarly to familiar subsystems, unitarity demands new interactions that transfer entanglement from them. Such interactions can be parameterized in an effective approach, and merit further investigation. A related question regards possible observational probes of this, or other, proposed descriptions of unitary black hole evolution.

---

*`giddings@ucsb.edu`

The most profound remaining theoretical problem coming into this century is likely that of reconciling gravity with quantum principles. Since this is expected to involve a description of quantum spacetime, its resolution is critical for providing the basic foundation of the rest of theoretical physics. This LOI will briefly describe approaches to some key aspects of this problem.

In a large segment of the community, it is believed that string theory provides a solution to this problem. However, if this is true, it has become clear that we do not know *how* string theory answers a number of central questions, such as those of defining localized observables, cosmological evolution, and evolution of black holes. We should certainly pursue attempts, for example within AdS/CFT [1], to give complete answers to these. However, at the same time we should consider that answers may come from complementary approaches.

The unitarity crisis. The problem of reconciling the existence of black holes with quantum mechanics appears to be a "key" problem for quantum gravity, plausibly playing a role like explaining the atom did for quantum mechanics. Our current description, based on local quantum field theory (LQFT) evolving on a semiclassical geometry, produces a crisis in physics, commonly called the black hole information problem. Specifically, if we can to good approximation describe a black hole (BH) and its environment as quantum subsystems of a bigger system, LQFT through Hawking's calculation [2] implies that the BH builds up entanglement with its environment. Locality of QFT implies that this entanglement cannot transfer from the BH subsystem. If the BH disappears at the end of evolution, there is no longer a system to entangle with, and unitarity is violated. But, failure to disappear, *e.g.* by leaving a remnant, leads to other paradoxical behavior [3, 4]. Worse still, violation of unitarity is associated with catastrophic violations of energy conservation [5].

Mathematical structure of quantum gravity. The preceding description illustrates an important fundamental question: how do we mathematically describe subsystems, and localization of information, in quantum gravity? Indeed, various proposals for a resolution to the crisis rely on ideas that amount to challenging the view that a black hole is a quantum subsystem. One of these is the idea of soft quantum hair [6–10], suggesting that information does not localize in a BH but instead is present in features of its exterior gravitational field. Others include ideas associated with the proposal that entanglement generates spacetime connectedness, or ER=EPR [11, 12].

It is worthwhile to compare to the question of localization of information in other quantum systems. For finite or locally finite (*e.g.* lattice) systems, subsystems are described via factorization of the Hilbert space, $\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2$ and information localizes in factors. LQFT is more subtle, given the infinite entanglement existing between a region and its complement, associated with the von Neumann type III property. Instead, as described in *e.g.* [13], subsystems can be associated with commuting subalgebras of the algebra of observables, *e.g.* field operators convolved with test functions with compact support in a given region.

These subalgebras, describing subsystems, are in one-to-one correspondence with open sets of the background spacetime manifold. They also have inclusion, overlap, *etc.* relations mirroring those of the open sets. So, the structure defined on the Hilbert space by this "net" of subalgebras captures the topological structure of the manifold.

The property of commutativity also encodes the causal structure: commuting subalgebras correspond to spacelike separated regions. This is how the property of locality is hardwired into LQFT, which in flat space can be viewed as the answer to the question of how to reconcile the principles of quantum mechanics, the principles of relativity (Poincaré invariance), and the principle of locality.

Importantly, gravity behaves differently. First, there are no local gauge-invariant, or physical, observables [14]. One can perturbatively construct gauge-invariant observables that reduce to field theory observables in the weak-gravity limit, by "gravitationally dressing" an underlying LQFT observable; the condition for gauge-invariance is that it commute with the GR constraints [15]. These observables are now nonlocal, and generically do not commute at spacelike separation. Thus the basic locality property of LQFT is seen to be modified even at a leading perturbative level.

This raises the question of how to localize information, or define subsystems. Given that the answer to this in LQFT incorporates the key structural property of locality on the underlying manifold, one expects the answer to this question to be a key structural property in the mathematical description of quantum gravity.

Perturbatively one can find a structure that begins to describe such localization. This is based on extending the notion of a splitting [13,16] in LQFT. Given neighborhood U and ϵ-extension of it U_ϵ, one can find an embedding of a product of Hilbert spaces associated to U and the complement $\bar{U}_\epsilon$ into the full Hilbert space, based on the "split vacuum," giving a different kind of definition of "subsystems." Including gravity, the gravitational field of excitations in U will extend into $\bar{U}_\epsilon$, making measurements outside U depend on its internal excitations. *However,* as shown in [17, 18] the gravitational field may be chosen in a "standard" form so that measurements in $\bar{U}_\epsilon$ only depend on the total Poincaré charges of the matter in U. This indicates that one has a set of Hilbert space embeddings, labeled by these charges, and provides a candidate subsystem structure.

An important problem for the future is to investigate this structure further, and improve our characterization of the localization of information, in terms of mathematical structure on Hilbert space. The nonperturbative extension of gravitational dressing, and of this structure, is also closely connected to the question of how we might explain holographic behavior of gravity [19]

Quantum consistency for BHs. Given such a construction, and an extension to BH backgrounds [20], it appears that one can perturbatively describe localization of information, and *e.g.* seemingly rule out the idea that the information in a BH is also present outside in its soft quantum hair. And, if subsystems can be defined in this fashion in gravity, that returns us to the question of how BH evolution is unitary. If a BH can be approximately described as a subsystem, and evolution is required to be unitary, that implies that interactions must be present that transfer entanglement from the BH to its environment. In a conservative approach, a question is to parameterize what such interactions "minimally" depart from the LQFT evolution, in an effective description. It has been proposed in particular that if such interactions are "soft," that is *e.g.* characterized by scales comparable to that of the BH rather than by microscopic scales, then they can have very limited effect on infalling observers, and thus preserve many of the essential features of BHs [21–25]. A contrasting possibility is that a BH is replaced by a new kind of "hard" object, such as a firewall [26] or fuzzball [27]. A newer approach to computing entropy curves [28–31] should also be investigated, to see if it provides unitary quantum amplitudes, perhaps with such a soft effective description.

It is important to further investigate and characterize entanglement-transferring interactions of this kind, and their possible role in restoring unitarity. If this is the resolution to the unitarity crisis, the structure of these interactions is also expected to provide important clues about the more complete underlying unitary dynamics of quantum gravity.

Observational probes. There is a now widespread view that resolution of the unitarity crisis requires new physics at horizon (or larger) scales. This scale is now being probed by gravitational wave and very long baseline interferometric observations. This coincidence of theoretical and observational developments begs further investigation. For example, the "nonviolent unitarization" scenarios [32] just described may have observable signatures [32–34]. It is also important to investigate possible observational consequences of other proposed resolutions to the crisis.

References

[1] J. M. Maldacena, "The Large N limit of superconformal field theories and supergravity," *Int. J. Theor. Phys.* **38** (1999) 1113–1133, `arXiv:hep-th/9711200`.

[2] S. W. Hawking, "Particle Creation by Black Holes," *Commun. Math. Phys.* **43** (1975) 199–220. [,167(1975)].

[3] S. B. Giddings, "Why aren't black holes infinitely produced?," *Phys. Rev. D* **51** (1995) 6860–6869, `arXiv:hep-th/9412159`.

[4] L. Susskind, "Trouble for remnants," `arXiv:hep-th/9501106`.

[5] T. Banks, L. Susskind, and M. E. Peskin, "Difficulties for the Evolution of Pure States Into Mixed States," *Nucl. Phys. B* **244** (1984) 125–134.

[6] S. W. Hawking, M. J. Perry, and A. Strominger, "Soft Hair on Black Holes," *Phys. Rev. Lett.* **116** no. 23, (2016) 231301, `arXiv:1601.00921 [hep-th]`.

[7] S. W. Hawking, M. J. Perry, and A. Strominger, "Superrotation Charge and Supertranslation Hair on Black Holes," *JHEP* **05** (2017) 161, `arXiv:1611.09175 [hep-th]`.

[8] A. Strominger, "Lectures on the Infrared Structure of Gravity and Gauge Theory," `arXiv:1703.05448 [hep-th]`.

[9] A. Strominger, "Black Hole Information Revisited," `arXiv:1706.07143 [hep-th]`.

[10] S. Haco, S. W. Hawking, M. J. Perry, and A. Strominger, "Black Hole Entropy and Soft Hair," *JHEP* **12** (2018) 098, `arXiv:1810.01847 [hep-th]`.

[11] M. Van Raamsdonk, "Building up spacetime with quantum entanglement," *Gen. Rel. Grav.* **42** (2010) 2323–2329, `arXiv:1005.3035 [hep-th]`. [Int. J. Mod. Phys.D19,2429(2010)].

[12] J. Maldacena and L. Susskind, "Cool horizons for entangled black holes," *Fortsch. Phys.* **61** (2013) 781–811, `arXiv:1306.0533 [hep-th]`.

[13] R. Haag, *Local quantum physics: Fields, particles, algebras.* (Texts and monographs in physics). Springer, Berlin, Germany, 1992.

[14] C. G. Torre, "Gravitational observables and local symmetries," *Phys. Rev.* **D48** (1993) R2373–R2376, `arXiv:gr-qc/9306030 [gr-qc]`.

[15] W. Donnelly and S. B. Giddings, "Diffeomorphism-invariant observables and their nonlocal algebra," *Phys. Rev.* **D93** no. 2, (2016) 024030, `arXiv:1507.07921 [hep-th]`. [Erratum: Phys. Rev.D94,no.2,029903(2016)].

[16] S. Doplicher and R. Longo, "Standard and split inclusions of von Neumann algebras," *Invent. Math.* **75** (1984) 493–536.

[17] W. Donnelly and S. B. Giddings, "Gravitational splitting at first order: Quantum information localization in gravity," *Phys. Rev.* **D98** no. 8, (2018) 086006, `arXiv:1805.11095 [hep-th]`.

[18] S. B. Giddings, "Gravitational dressing, soft charges, and perturbative gravitational splitting," *Phys. Rev. D* **100** no. 12, (2019) 126001, `arXiv:1903.06160 [hep-th]`.

[19] S. B. Giddings, "Holography and unitarity," `arXiv:2004.07843 [hep-th]`.

[20] S. Giddings and S. Weinberg, "Gauge-invariant observables in gravity and electromagnetism: black hole backgrounds and null dressings," *Phys. Rev. D* **102** no. 2, (2020) 026010, `arXiv:1911.09115 [hep-th]`.

[21] S. B. Giddings, "Models for unitary black hole disintegration," *Phys. Rev.* **D85** (2012) 044038, `arXiv:1108.2015 [hep-th]`.

[22] S. B. Giddings, "Black holes, quantum information, and unitary evolution," *Phys. Rev.* **D85** (2012) 124063, `arXiv:1201.1037 [hep-th]`.

[23] S. B. Giddings, "Nonviolent nonlocality," *Phys. Rev.* **D88** (2013) 064023, `arXiv:1211.7070 [hep-th]`.

[24] S. B. Giddings, "Modulated Hawking radiation and a nonviolent channel for information release," *Phys. Lett. B* **738** (2014) 92–96, `arXiv:1401.5804 [hep-th]`.

[25] S. B. Giddings, "Nonviolent unitarization: basic postulates to soft quantum structure of black holes," *JHEP* **12** (2017) 047, `arXiv:1701.08765 [hep-th]`.

[26] A. Almheiri, D. Marolf, J. Polchinski, and J. Sully, "Black Holes: Complementarity or Firewalls?," *JHEP* **02** (2013) 062, `arXiv:1207.3123 [hep-th]`.

[27] S. D. Mathur, "Fuzzballs and the information paradox: A Summary and conjectures," `arXiv:0810.4525 [hep-th]`.

[28] P. Saad, S. H. Shenker, and D. Stanford, "JT gravity as a matrix integral," `arXiv:1903.11115 [hep-th]`.

[29] G. Penington, S. H. Shenker, D. Stanford, and Z. Yang, "Replica wormholes and the black hole interior," `arXiv:1911.11977 [hep-th]`.

[30] A. Almheiri, T. Hartman, J. Maldacena, E. Shaghoulian, and A. Tajdini, "Replica Wormholes and the Entropy of Hawking Radiation," `arXiv:1911.12333 [hep-th]`.

[31] D. Marolf and H. Maxfield, "Transcending the ensemble: baby universes, spacetime wormholes, and the order and disorder of black hole information," `arXiv:2002.08950 [hep-th]`.

[32] S. B. Giddings, "Black holes in the quantum universe," *Phil. Trans. Roy. Soc. Lond.* **A377** no. 2161, (2019) 20190029, `arXiv:1905.08807 [hep-th]`.

[33] S. B. Giddings and D. Psaltis, "Event Horizon Telescope Observations as Probes for Quantum Structure of Astrophysical Black Holes," *Phys. Rev. D* **97** no. 8, (2018) 084035, `arXiv:1606.07814 [astro-ph.HE]`.

[34] S. B. Giddings, "Astronomical tests for quantum black hole structure," *Nature Astron.* **1** (2017) 0067, `arXiv:1703.03387 [gr-qc]`.