Information Loss: arXiv:1703.0214
Part I: What is the problem?

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Unruh and Wald: there's no problem

Information Loss

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Abstract

The complete gravitational collapse of a body in general relativity will result in the formation of a black hole. Although the black hole is classically stable, quantum particle creation processes will result in the emission of Hawking radiation to infinity and corresponding mass loss of the black hole, eventually resulting in the complete evaporation of the black hole. Semiclassical arguments strongly suggest that, in the process of black hole formation and evaporation, a pure quantum state will evolve to a mixed state, i.e., there will be "information loss." There has been considerable controversy over this issue for more than 40 years. In this review, we present the arguments in favor of information loss, and analyze some of the counter-arguments and alternative possibilities.

Compère: there is a problem

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Are quantum corrections on horizon scale physically motivated?

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Abstract. This is a transcript of a talk given at the conference "Athens 2019: Gravitational Waves, Black Holes and Fundamental Physics". The aim of this note is to give an overview to non-specialists of recent arguments from fundamental physics in favor and disfavor of quantum corrections to black hole horizons. I will mainly discuss the black hole information paradox, its possible resolutions and shortly address its relevance or irrelevance to astronomy.
PS: If you are an expert, don't hesitate to send me your comments.

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Hawking's 1974 Information Paradox

Hawking's reasoning [4] can be loosely stated as follows. Around the horizon of a black hole, pairs are created in an entangled state

$$\psi_{pair} = \frac{1}{\sqrt{2}}(e^-_{in}e^+_{out} + e^+_{in}e^-_{out}). \tag{3.1}$$

Let say that either an electron gets in and a position comes out or a positron gets in and an electron comes out. In fact, neither happen, the state is a perfect superposition of the two. This is the result of a computation of quantum fields in the Schwarzschild or the Kerr geometry. When one particle is absorbed by the black hole, the mass of the black hole is lowered and the entanglement entropy of the outgoing radiation is increased by $\ln 2$. No information of the black hole is emitted.

The process goes on, until all the black hole has evaporated, leaving a radiation entangled with nothing, that is, a density matrix. This violates the unitary evolution of Quantum Mechanics of the exterior spacetime.

Two elements of problem:

- QFT in curved spacetime
- Quantum entanglement

QFT in curved spacetime: it's easy

".....Once a field theory is defined, applications in flat spacetime will naturally focus on the issue of interactions between the various fields, often treated as perturbations around the natural vacuum state. In curved spacetime, however, we are generally interested in the effects of spacetime itself of the fields for which the interactions are beside the point. We therefore can consider free (noninteracting) fields but we will have to take great care in defining what an appropriate vacuum state should be."
(Sean Carroll, *Spacetime and Geometry*)

Simple example: The Unruh effect: An accelerated photon detector sees "photons" even if a non-accelerated detector does not.

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Particle Creation by Black Holes

S. W. Hawking

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The approximation I shall use in this paper is that the matter fields, such as scalar, electro-magnetic, or neutrino fields, obey the usual wave equations with the Minkowski metric replaced by a classical space-time metric g_{ab}. This metric satisfies the Einstein equations where the source on the right hand side is taken to be the expectation value of some suitably defined energy momentum operator for the matter fields. In this theory of quantum mechanics in curved space-time there is a problem in interpreting the field operators in terms of annihilation and creation operators. In flat space-time the standard procedure is to decompose

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the field into positive and negative frequency components. For example, if ϕ is a massless Hermitian scalar field obeying the equation $\phi_{;ab}\eta^{ab}=0$ one expresses ϕ as

$$\phi = \sum_i \{f_i \boldsymbol{a}_i + \bar{f}_i \boldsymbol{a}_i^\dagger\} \qquad (1.1)$$

where the $\{f_i\}$ are a complete orthonormal family of complex valued solutions of the wave equation $f_{i;ab}\eta^{ab}=0$ which contain only positive frequencies with respect to the usual Minkowski time coordinate. The operators $\boldsymbol{a}_i$ and $\boldsymbol{a}_i^\dagger$ are interpreted as the annihilation and creation operators respectively for particles in the ith state. The vacuum state $|0\rangle$ is defined to be the state from which one cannot annihilate any particles, i.e.

$$\boldsymbol{a}_i|0\rangle = 0 \qquad \text{for all } i\,.$$

In curved space-time one can also consider a Hermitian scalar field operator ϕ which obeys the covariant wave equation $\phi_{;ab}g^{ab}=0$. However one cannot decompose into its positive and negative frequency parts as positive and negative frequencies have no invariant meaning in curved space-time. One could still

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Entanglement of systems of 2 spins

spin $1/2$ particles a and b:

$$|\psi\rangle = \alpha_{+-}|s_z^a = +,\ s_z^b = -\rangle + \alpha_{-+}|s_z^a = -,\ s_z^b = +\rangle$$
$$+\alpha_{--}|s_z^a = -,\ s_z^b = -\rangle + \alpha_{++}|s_z^a = +,\ s_z^b = +\rangle$$

- Probabilities of the four possible spin combinations given by the $|\alpha|^2$'s
- The state cannot be determined is you only measure s_z^a and s_z^b. (No information on phases)

Entanglement of systems of 2 spins: an example

spin $1/2$ particles a and b:

$$|\psi_\pm\rangle = \frac{1}{\sqrt{2}}\left(|s_z^a = +,\ s_z^b = -\rangle \pm |s_z^a = -,\ s_z^b = +\rangle\right)$$

- Measurements of s_z^a or s_z^b give random $+$ and $-$.
  $\Rightarrow$Cannot distinguish $|\psi_+\rangle$ from $|\psi_-\rangle$ without measurements on both spins
- Measurements of s_z^a and s_z^b are always of opposite sign. $\Rightarrow$ Cannot distinguish $|\psi_+\rangle$ from $|\psi_-\rangle$ if you only measure s_z of a and b.

Note: Spin of particle a by itself is described as a "mixed state" where there is no well-defined phase between $|+\rangle$ and $|-\rangle$.

To distinguish $|\psi_\pm\rangle$, need to measure also s_x or s_y

$$|\psi_\pm\rangle = \frac{1}{\sqrt{2}}\left(|s_z^a = +,\ s_z^b = -\rangle \pm |s_z^a = -,\ s_z^b = +\rangle\right)$$

$$\begin{aligned}|\psi_\pm\rangle \propto & \,(|s_x^a = +\rangle + |s_x^a = -\rangle)(|s_x^b = +\rangle - |s_x^b = -\rangle) \\ & \pm(|s_x^a = +\rangle - |s_x^a = -\rangle)(|s_x^b = +\rangle + |s_x^b = -\rangle)\end{aligned}$$

- For $|\psi_-\rangle$, measurements of s_x^a and s_x^b are of opposite sign
- For $|\psi_+\rangle$, measurements of s_x^a and s_x^b are of the same sign

Entanglement of systems of 2 spins, summary

spin $1/2$ particles *a* and *b*:

$$|\psi_\pm\rangle = \frac{1}{\sqrt{2}}\left(|s_z^a = +, s_z^b = -\rangle \pm |s_z^a = -, s_z^b = +\rangle\right)$$

- The initial state can be reconstructed from multiple measurements of multiple components of *both* spins.
- One measurement not sufficient to reconstruct the initial state!
  Measurement process is also "non-unitary".
  Unitarity is only saved in an Everett multiverse.

Steven B. Giddings: arXiv:hep-th/9508151

To illustrate further, suppose the Earth were blown to bits by a powerful bomb. In that case, we know that, at least in principle, an advanced civilization could decipher our history right up to the explosion–this would of course require a very careful measurement of the outgoing quantum state of the fragments, and then a backwards evolution of it to the initial state before the explosion.

But according to Hawking, black holes are different. Here it would be impossible even in principle to reconstruct the initial state. To see this, consider the idealization where the initial state of the black hole (including the Earth) was a quantum-mechanical pure state:

Question: What constitutes a "very careful measurement of the outgoing quantum state of the fragments"?

U & W's statement of the problem

$t = constant > \tau_{BH}$ is not a "Cauchy surface".
(Because state of BH interior no longer measureable)

A. Violation of Unitarity

In scattering theory, the word "unitarity" has two completely different meanings: (i) Conservation of probability. (ii) Evolution from pure states to pure states. Failure of (i) would represent a serious breakdown of quantum theory (and, indeed, of elementary logic). However, it is (ii)—not (i)—that is being proposed by the semiclassical picture.

Failure of (ii) would be expected to occur in any situation where the final "time" is not a Cauchy surface. Such a failure of unitarity is entirely innocuous. For example, we get evolution from a pure state to a mixed state for a massless Klein-Gordon field in Minkowski spacetime if the final "time" is chosen to be a hyperboloid rather than a hyperplane, as illustrated in Fig. 3. This is because the state of the quantum field on the hyperboloid is

U & W's statement of the problem

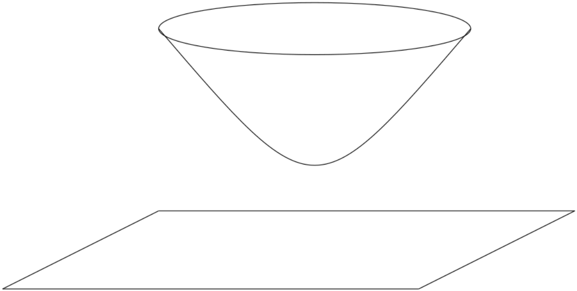

FIG. 3. A hyperboloid in Minkowski spacetime lying to the future of a hyperplane. If we consider the evolution of a massless quantum field that initially is in a pure state on the hyperplane, it will be in a mixed state on the hyperboloid.

entangled with the state of the quantum field on the portion of future null infinity that lies to the past of the cross-section of null infinity corresponding to its intersection with the hyperboloid. In this case, at the "time" represented by the hyperboloid, information has been "lost" to null infinity, leaving the field on the hyperboloid in a mixed state.

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The situation illustrated in Fig. 3 is not an artificial example but rather illustrates phenomena that occur around us all of the time. If an atom in your living room emits a photon, the state of that atom will be in entangled with the photon. If that photon escapes out the window and is not reflected/absorbed by clouds or any other intervening matter in the universe, it will be "lost forever" as far as you are concerned. The state of your living room and any additional portion of the universe that you observe will be mixed. "Information" will have been lost. An initial pure state in any experimentally accessible region around you will have been converted into a mixed state.

The pure state to mixed state evolution predicted by the semiclassical analysis of black hole evaporation is of an entirely similar character. It is a *prediction* of quantum (field) theory in any situation where the final "time" is not a Cauchy surface, not a *violation* of quantum theory.

Ways to avoid information loss

- No blackholes form (fuzzballs)
  Need modifications in classical regime
- Failure of semiclassical theory during evaporation (firewalls)
  Need modifications in classical regime
- Evaporation not complete (remnants)
  Need modifications only at Planck scale
- Information comes out in the final burst
  Need modifications only at Planck scale

U&W on AdS/CFT

C. AdS/CFT

During the 1980s and most of the 1990s, the main arguments given against information loss were "violation of unitarity" and "failure of energy conservation," as described in the above subsections. However, since the late 1990s, these arguments have largely been supplanted by the assertion that evolution from a pure state to a mixed state in the process of black hole formation and evaporation cannot occur since it would violate the "AdS/CFT correspondence."

The AdS/CFT correspondence is the assertion that quantum gravity (at least on asymptotically anti-deSitter spacetimes) is "dual" to a (non-gravitational) conformal field theory defined on the boundary of anti-deSitter spacetime. The one sentence version of AdS/CFT argument against information loss is that since the conformal field theory—being an ordinary quantum field theory in a fixed classical spacetime—presumably does not admit pure state to mixed state evolution, such evolution must also not be possible in quantum gravity, including when black holes form and evaporate.

Hawking: arXiv:0507171

Information Loss in Black Holes

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The question of whether information is lost in black holes is investigated using Euclidean path integrals. The formation and evaporation of black holes is regarded as a scattering problem with all measurements being made at infinity. This seems to be well formulated only in asymptotically AdS spacetimes. The path integral over metrics with trivial topology is unitary and information preserving. On the other hand, the path integral over metrics with non-trivial topologies leads to correlation functions that decay to zero. Thus at late times only the unitary information preserving path integrals over trivial topologies will contribute. Elementary quantum gravity interactions do not lose information or quantum coherence.

....

In 1997, Kip Thorne and I, bet John Preskill that information was lost in black holes. The loser or losers of the bet were to provide the winner or winners with an encyclopedia of their own choice, from which information can be recovered with ease. I gave John an encyclopedia of baseball, but maybe I should just have given him the ashes.

Compère

6. Final comments: quantum gravity physics with gravitational wave detectors?

According to the recent arguments advanced by the AdS/CFT correspondence, the process of black hole evaporation in the vacuum is unitary as seen by an exterior observer. In order to solve the Information Paradox, one is then led to the conclusion that either quantum black holes admit some new structure at the horizon scale, or, that effective field theory breaks down due to a new form of non-local physics, or, that quantum mechanics needs to be corrected. Today, there is no well-accepted model of a quantum black hole by quantum relativists. Known astrophysical black holes are very young relative to the timescale of black hole evaporation, which makes the role of such quantum considerations unclear for astrophysical purposes.

Echoes in gravitational wave observations have been proposed as potential signatures of new quantum horizon physics or of new exotic compact objects [49]. From the standpoint of fundamental physics, there is no first principle computation so far in quantum gravity showing that the absorption rate of a quantum black hole will be away from unity for astrophysical black holes, though it is not excluded. From the observational standpoint, it is worth looking at possible signatures, see e.g. [50].

An important problem to be faced by theorists that attempt to derive signatures of quantum black holes is degeneracy: even if there is a non-GR signal observed at LIGO/Virgo/ET/LISA, it will be very hard to distinguish a quantum black hole model from a classical black hole in alternative GR theories or a black hole mimicker.

U&W's summary of controversy

It is our hope that the AdS/CFT ideas can be developed further so as to make a math-

ematically precise argument regarding information loss in black hole formation and evaporation. A properly developed argument that AdS/CFT is in conflict with information loss would necessarily contain an explanation of how information is regained—and where the semiclassical behavior is violated—not just an assertion that it must happen somehow or other. With such an argument in hand, one would have to choose between AdS/CFT and information loss—and one would be in a position to do so intelligently. At the present time, we see no necessity of rejecting either alternative.