The future of quantum gravity

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What is the future of quantum gravity?

Short answer: nobody knows…

But one can guess some themes

- Locality and nonlocality
- Holography
- Perhaps deep connections with quantum physics (entanglement, etc.)
- Perhaps dimensional reduction
- Perhaps some form of “emergence” (but not a simple one!)

Locality

Torre (1993):

> "…there can be no observables for the vacuum gravitational field (in a closed universe) built as spatial integrals of local functions of Cauchy data and their derivatives."

But standard QFT relies on local observables —
Many of the problems of quantum gravity trace back to this

Related issues:
– diffeomorphism invariance vs. gauge transformations
– "everything couples to gravity"

Holography

– We know some observables in asymptotically flat spacetimes
(ADM energy, momentum, . . .)

– Quasilocal observables associated with surfaces
(Brown-York energy, momentum, . . .)

– AdS/CFT: many more in asymptotically AdS spacetimes
(Marolf: almost all perturbative AdS observables are boundary observables)

– Black hole area law for entropy. . .

$\Rightarrow$ Observables connected to *surfaces*

- How does one define relevant surfaces?
- Are these enough observables?
- Do they fit together consistently?

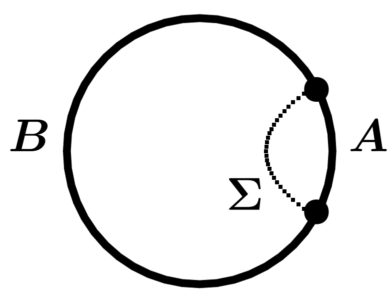
General boundary formalism in QM (Oeckl)

Locality and entanglement

Ryu, Takayanagi, Hubeny, Rangamani:

To compute entanglement entropy between two regions A and B divided by a curve $\mathcal{C}$ on (say) a sphere S^n:

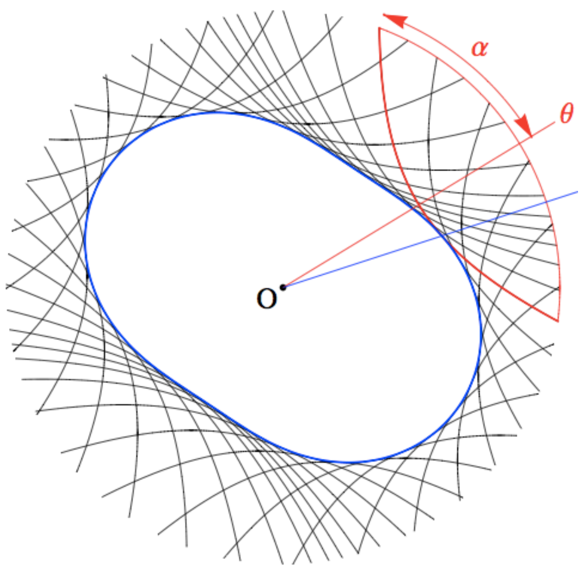
1. treat sphere as n-dimensional boundary of an $(n+1)$-dimensional time slice Σ of AdS^{n+2}
2. find minimal surface $\mathcal{S}$ in AdS^{n+2} whose boundary is $\mathcal{C}$
3. then $S = \dfrac{\mathcal{A}_{\mathcal{S}}}{4\hbar G_{n+2}}$



Really true (Lewkowycz and Maldacena)

To label a curve C on Σ:

1. consider a collection of minimal surfaces tangent to C
2. determine the corresponding boundaries and their entanglement entropies
3. reverse: determine the point from the entanglement entropies



drawing from Czech and Lamprou, arXiv:1409.4473

Points may be defined as limits of curves

Under what circumstances does a state of a field theory at the boundary determine entanglement entropies that (approximately) locate points?

Black hole information loss problems

Old problem: collapse a pure state to form a black hole, let it evaporate

What happens to unitarity?

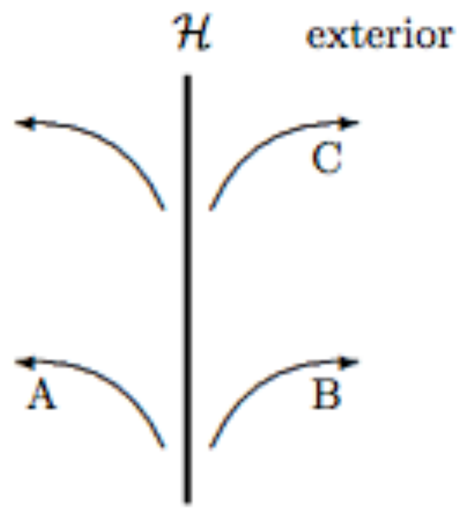
Newer emphasis (AMPS) connects to locality –

– QFT vacuum $\Rightarrow$ A and B are entangled

– Pure final state $\Rightarrow$ B and C are entangled

– Monogamy $\Rightarrow$ entanglement must be transferred

– But A and C are never in causal contact



Probably a unitary boundary description in AdS/CFT (with “precursors”?)

But how does one recover (approximate) spacetime locality?

Spontaneous dimensional reduction

Indications from a number of different approaches to quantum gravity that spacetime near Planck scale is effectively two-dimensional

- Causal dynamical triangulations: spectral dimension
- Asymptotic safety: anomalous dimension near UV fixed point
- High temperature string theory
- Strong coupling approximation of Wheeler-DeWitt equation
- Loop quantum gravity: area spectrum
- High temperature dispersion relations in noncommutative geometry
- Vacuum fluctuations near Planck scale $\Rightarrow$ Kasner/AVTD behavior (?)

Is quantum gravity a two-dimensional conformal field theory?

Emergent gravity?

1. Yes, obviously
2. But no, not in any simple way . . .

If space or spacetime are already present:

– background must decouple *very* strongly for Lorentz invariance
– principle of equivalence/universal coupling is not natural
  (though less problematic if Lorentz invariant)
– need same universal *self*-coupling
– emergent diffeomorphism invariance must be very nearly exact (Weinberg-Witten)

If spacetime is discrete:

– Lorentz invariance $\Rightarrow$ radical nonlocality

If spacetime itself emerges:

– OK, how? That's where we started. . .

Possible models

– AdS/CFT (and entanglement?)

– Causal sets

– Spin foams/group quantum field theory

But all still must confront same problem:

How to you reconstruct approximate locality/local QFT?